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Logistical considerations in the development of on-farm anaerobic digestion systems in Ireland

Thesis presented by

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for the degree of

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Declaration

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.

Signature: 

Date: Friday, 7th April 2023

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Abstract

Ireland has 4 million ha of grassland, and over 6.56 million cattle, including over 1.4 million dairy cows. The potential resource of grass silage and animal slurry can be considered significant if utilised in anaerobic digestion for the production of biogas (and biomethane). On-farm anaerobic digestion (AD) can provide a renewable, sustainable fuel (in the form of biogas) that can decarbonise the energy system and reduce emissions from the agricultural sector. However, cattle in Ireland spend the majority of the year outdoors in pasture-based farming systems, leading to intermittent slurry collection by the farmer. Thus, there is an inherent seasonality with regards to feedstock availability. On-farm AD plants may also have no gas grid infrastructure access, and therefore may be required to facilitate a seasonal gas demand of a large energy user in their vicinity. Although the Irish biomethane industry is emerging, there are no significant virtual pipeline or biogas pipeline networks. The work herein assesses these logistical characteristics such as on-farm biomass resources, their location with respect to both gas grid infrastructure and large industry energy users, and how seasonal feedstock availability and seasonal gas demand can affect the operation of an on-farm AD plant. Furthermore, this work investigates the logistical considerations in the development of virtual pipelines and biogas pipelines serving on-farm AD plants, and how to optimise them.

The findings from this work indicate that the total on-farm biomethane resource in Ireland is estimated to be 67 PJ a^{-1}. Approximately 17% of this resource is more than 15 km away from gas grid infrastructure whilst also within 15 km of a large industry energy user. Seasonal slurry availability on an Irish dairy farm can lead to a 21% reduction in total biomethane production, whilst increasing the carbon intensity of the biomethane produced (as compared to year-round availability) by 11 g CO_2 MJ^{-1}. Seasonal gas demands may be facilitated without significant effect to biomethane sustainability. Liquid digestate must be recirculated during times of no slurry availability to keep the solids content of the digester low and thus ensure sufficient mixing takes place. In the delivery of the energy to the end user, virtual pipelines serving on-farm AD plants may reduce the total routing requirements and emissions by opting for larger biomethane haulage vehicles. The use of mobile-upgrading and compression units may be logistically unfeasible due to the slow upgrading speed of current technologies. Heuristics (practical methods to solve very complex problems)

used in GIS software may be employed to quickly find optimal biogas pipeline layouts which either follow the shortest possible path (Steiner minimum spanning tree (MST)) or follow the road network. Commercial software was used to design and cost 20 Steiner MST and 20 road network biogas pipeline layouts. A road network pipeline layout connecting 10 AD plants to the biogas user costs 26% more than a Steiner MST would. Multi-criteria decision analysis revealed that the designed Steiner MSTs always outperformed road network layouts, except when pipeline material cost was of no importance. This work highlights the potential of on-farm anaerobic digestion to provide a source of sustainable, renewable fuel source for decentralised areas and industries in Ireland, whilst highlighting the logistical considerations and challenges associated with feedstock location, seasonal feedstock availability, seasonal gas demand, and the development of gas delivery methods such as virtual biomethane pipelines or biogas pipelines.

Thesis output

Chapters published as papers or currently under review in peer-reviewed journals for which I am principally responsible:

Chapter 3:

Ó Céileachair, D., O'Shea, R., Murphy, J.D., and Wall, D.M. (2021). Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane. Applied Energy, 303, p.117627. doi:10.1016/j.apenergy.2021.117627.

Chapter 4:

Ó Céileachair, D., O'Shea, R., Murphy, J.D., and Wall, D.M. (2022). The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant. Journal of Cleaner Production, 368, p.133129. doi:10.1016/j.jclepro.2022.133129.

Chapter 5:

Ó Céileachair, D., O'Callaghan, S., Wall, D.M., Goulding, D., O'Connor, D., Murphy, J.D., O'Shea, R. (2023). Logistical considerations and challenges in deploying virtual biomethane pipelines to serve on-farm biogas plants. Journal of Cleaner Production, 407, p.137075. doi:10.1016/j.jclepro.2023.137075

Chapter 6:

Ó Céileachair, D., O'Shea, R., Murphy, J.D., and Wall, D.M. A methodology for designing biogas pipelines. (to be submitted to Energy Conversion and Management).

Contribution to papers

Chapter 3:

I was the first author of the paper. I was responsible for the data collection, processing, analysis, and interpretation of results. I developed the GIS methodology to conduct the analysis.

Chapter 4:

I was the first author of the paper. I developed the Excel tool for tracking an anaerobic digestion plant's characteristics through 52 weeks and how seasonal feedstock supply and gas demand affected such characteristics. I conducted the analysis and interpretation of results.

Chapter 5:

I was the first author of the paper. I was responsible for the data collection, processing, analysis, and interpretation of results. I calculated the feedstock availability and gas output at each AD site, and the chosen vehicle parameters for each scenario.

Chapter 6:

I was the first author of the paper. I was responsible for the data collection, processing, analysis, and interpretation of results. I developed the GIS heuristics to create Steiner nodes, and the heuristics to choose which sites to add to each pipeline layout. I adapted SNAP for use as a biogas pipeline tool, calculating the pipeline material cost of each layout. I conducted the MCDA comparing each layout's material cost to biogas flow-rate.

Nomenclature

AD	Anaerobic digestion
AER	Annual environmental report
BMP	Biomethane potential
C	Constant
CAP	Climate action plan
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CSTR	Continuously-stirred tank reactor
CVRP	Capacitated vehicle routing problem
DEFRA	Department of environment, food, and rural affairs
DM	Dry matter
DS	Dry solids
ED	Electoral district
EJ	Exajoule
FFC	Fossil fuel comparator
GHG	Greenhouse gas
GJ	Gigajoule
GNI	Gas Networks Ireland
HDD	Heating degree days
HGV	Heavy goods vehicle
HRT	Hydraulic retention time
LEU	Large energy user
LPG	Liquefied petroleum gas
MCDA	Multi-criteria decision analysis
MJ	Megajoule
MST	Minimum spanning tree
MW	Megawatt
NO_X	Nitrogen oxides
NP-hard	Non-deterministic polynomial-time hard

OLR	Organic loading rate
PB	Pasture-based
PJ	Petajoule
PM_2	Particulate matter 2.5 (less than 2.5 microns in width)
PSA	Pressure-swing absorption
RED	Renewable energy directive
RES	Renewable energy share
RHI	Renewable heat incentive
S	Summer
SMY	Specific methane yield
SO_2	Sulphur dioxide
TJ	Terajoule
TS	Total solids
TW	Terawatt
VRP	Vehicle routing problem
VS	Volatile solids
W	Winter
ZG	Zero-grazing

1 Introduction

1.1 Background to thesis

Signatories of the Glasgow Climate Pact at COP26 have agreed to reduce their greenhouse gas emissions and invest further in decarbonisation measures (UNFCCC and UN, 2021). However, global energy consumption is projected to increase by almost 50% from 2020 to 2050, with natural gas consumption alone projected to increase by more than 30%, to over 56,600 TWh in the same period (U.S. Energy Information Administration, 2021). Despite the recent geopolitical crises which threatened supply, natural gas is considered an important transitionary fuel towards the decarbonisation of energy systems. Biogas (more specifically biomethane) offers a renewable alternative to natural gas. In response to these crises, the EU has launched the REPowerEU scheme, where the bloc plans to reduce its dependence on Russian fossil fuels and transition to sustainable alternatives whilst also saving energy, diversifying supplies, and increasing investments and reforms in the energy sector (European Commission, 2022). Consumption of biogas is expected to increase from 35 to 340 billion cubic metres equivalent (3,400 TWh) from 2020 to 2050 (IEA, 2022). It can thus be assumed that sustainably sourced biomethane has a significant role to play in the EU's energy future.

Ireland's Climate Action Plan (CAP) commits the country to achieving an ambitious target of 51% reduction in overall greenhouse gas emissions by 2030, and net-zero emissions by 2050 (Department of the Environment Climate and Communications, 2021). In achieving these emissions reductions, the government have set out sub-targets to reach by 2030: an 80% share of renewable energy in the electricity sector, a 75% reduction in emissions in the electricity sector, a 35% reduction in emissions from industry, a 40-45% reduction in emissions from buildings, a 50% reduction in emissions in the transport sector, and a 25% reduction in emissions in the agriculture sector (Department of the Environment Climate and Communications, 2022). The CAP also promotes circular economy practices, such as the reintroduction of residues and wastes, like slurry, back into the value chain.

Irish GHG emissions amounted to 61.53 million tonnes carbon dioxide equivalent (Mt $CO_{2\text{-eq}}$) in 2021, and the agriculture sector accounted for over 37% of these emissions (Environmental Protection Agency, 2022). Slurry management practices accounted for over 11% of those agricultural emissions (see Figure 1-1).

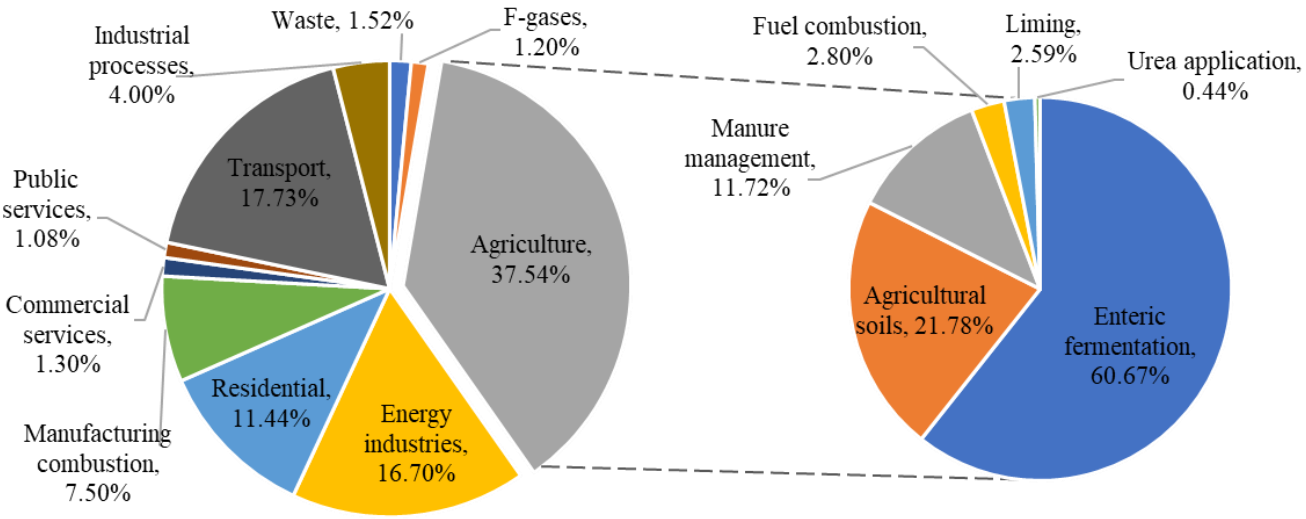


Figure 1-1: Ireland's GHG emissions by sector, and agricultural emissions (Environmental Protection Agency, 2022).

On-farm anaerobic digestion (AD) is a method in which renewable, sustainable biomethane and biofertiliser can be produced using organic residues such as manures (slurries) and crops. In particular, the use of slurries as a feedstock may be favourable as it may reduce the fugitive emissions resultant from current slurry management practices. As such, on-farm AD can be viewed as a circular economy practice that can be integrated into the agriculture sector in Ireland.

Biogas is comprised of mostly methane (50-60%), carbon dioxide (40-50%), and trace amounts of other gases, such as hydrogen sulphide. The process of cleaning the biogas and leaving only the higher-value biomethane is known as upgrading. Biogas may be burned directly for heating or electricity generation, but it must be upgraded to natural gas quality (biomethane) before compression and use as a transport fuel, or prior to gas grid injection. Biomethane is similar in composition to fossil fuel natural gas and can be used as same. Digestate, the biofertiliser product from AD, can also be used as a synthetic fertiliser substitute on the farm.

In general, energy crops and residues are the primary feedstocks of AD plants. Whilst maize is the energy crop of choice in Germany, it is likely that an on-farm AD plant in Ireland would use surplus grass silage (silage available after livestock feeding requirements are met) as well as animal slurries and manures. There are plentiful grass resources in Ireland, with over 4 million ha dedicated to grassland (CSO, 2020). Slurry is also a plentiful resource, with over 1.4 million dairy cows in Ireland (6.56 million cattle in total) (CSO, 2019).

The logistical considerations of on-farm anaerobic digesters will be a major consideration in the deployment of such systems. Such considerations include, but are not limited to, the location and temporal availability of the feedstock, the end use of the gas and whether the gas demand varies throughout the year, and how to deliver the gas to the end user. This thesis of work investigates these logistical considerations for on-farm AD, focusing on dairy slurry and surplus grass silage as the primary feedstocks.

The location of available feedstocks will in essence dictate the location of the AD plant itself, as hauling feedstocks over long distances will become economically and environmentally unfeasible. This is particularly true when hauling high water content feedstocks such as dairy slurry. The seasonal availability of such feedstocks must be considered if they cannot be stored long term, or if the AD plant operator desires to use certain feedstocks immediately as they become available. Once more this may be of importance to dairy slurries where their immediate use may minimise fugitive emissions. If an AD plant is not connected to gas grid infrastructure, it may have to supply gas to a local large energy user, which may have seasonal gas demands; this may have an influence on the operational characteristics and logistics of an on-farm AD plant. Without gas grid access, the delivery method of gas from the on-farm AD plant to the end user will involve complex logistical considerations in how the gas is transported, whether it is upgraded or not, and what the end-use of the biogas will be.

1.2 Aims and objectives

This thesis aims to describe the logistics of on-farm AD systems from a quantitative perspective. Through logistical analysis, this thesis will examine the implications of on-farm AD systems and how they may operate in Ireland in the future.The aims and objectives of this thesis were as follows:

i. Quantify and locate the on-farm biomethane resources in Ireland and their location with respect to national gas grid infrastructure. Resources outside certain distances of the gas grid may then be designated as decentralised.
ii. Determine whether decentralised resources may be used by decentralised end users, replacing fossil fuels with locally sourced biomethane.
iii. Investigate the effects of seasonally available feedstocks, and seasonal gas demand, in terms of the operational characteristics of an on-farm AD plant.

iv. Calculate whether seasonally available feedstocks and seasonal gas demand affects the sustainability of the biomethane produced from on-farm AD.
v. Investigate the logistical considerations of the operation of a virtual biomethane pipeline serving on-farm AD plants.
vi. Assess the logistical feasibility of using mobile-upgrading and compression units in a virtual biomethane pipeline serving on-farm AD plants.
vii. Determine the optimal layout of biogas pipelines serving AD plants.
viii. Develop methods to assess the optimal asset utilisation efficiency of biogas pipeline layouts.

1.3 Outline and link between chapters

The thesis is comprised of seven chapters and additional appendices. The theme of each of the chapters is the production of biogas and/or biomethane, and the logistical implications resulting from either the feedstock choice, seasonal feedstock availability, seasonal gas demand, the gas delivery method and gas end use. Chapter 2 discusses previous literature and reviews previous works which have discussed these topics, highlighting developments in the logistical considerations involving on-farm AD plants, as outlined in section 1.1. Chapters 3 and 4 discuss the location and seasonal availability of the feedstocks, as well as the effects that seasonal gas demand may have on an on-farm AD plant. Chapters 5 and 6 discuss two competing gas delivery methods: virtual biomethane pipeline and biogas pipeline, respectively. Chapters 3, 4, and 5 are peer-reviewed journal papers, and their methodology, results, and discussion appear in the thesis as per published manuscripts. Chapter 6 is currently under review for publication. The thesis follows the academic paper model: a succession of published journal papers that can be read independently, or as part of a whole. Chapter summaries are included below.

Chapter 2: *The logistics of on-farm anaerobic digestion: feedstock, plant type, and energy end-use considerations*

This chapter outlines the literature review conducted during the writing of this thesis. Ireland's on-farm agricultural feedstocks, the profile of on-farm AD plants, common uses of biogas sourced from on-farm AD, Ireland's seasonal farming practices, and delivery methods for biogas and biomethane are discussed. Developments in the areas of on-farm AD, resource assessments, feedstock seasonality, gas demand

seasonality, virtual pipeline optimisation and biogas pipeline optimisation are examined.

Chapter 3: *Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane*

This chapter assesses the biomethane resource available from on-farm feedstocks specifically and conducts a spatial analysis of the resources with respect to gas grid infrastructure and large energy users. The resource assessment and gas grid spatial analysis were conducted with the most up-to-date data available at the time of publishing. The gross theoretical biomethane resource from on-farm feedstocks was estimated at 67 PJ a^{-1} (surplus silage 72%, hay 13%, dairy slurry 3%, straws 11%). Around 33% of this resource is situated more than 12.5 km away from gas grid infrastructure. An origin destination matrix showed that 17% of the total resource (11.6 PJ a^{-1}) was 15 km away from the gas grid whilst also within 15 km of a large energy user. Two case studies showed that within the vicinity of two large energy users (LEUs) enough biomethane could be sourced as a replacement for fossil fuel use to decarbonise their energy requirements.

Chapter 4: *The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant*

This chapter describes Ireland's pasture-based farming system; dairy cows in Ireland are only indoors for around 18 weeks of the year, often less. The effects of this seasonal slurry availability on the operational characteristics of an on-farm AD plant were tracked week-by-week using Excel. On-farm AD plants in Ireland may not have gas grid access – therefore, the effects of facilitating a seasonal gas demand were also tracked week-by-week, concurrently with the effects of seasonal slurry availability. The scenarios investigated either had access to slurry year-round or had seasonally available slurry, and scenarios facilitated either a constant, winter, or summer gas demand period, giving six scenarios in total. Whether these seasonal traits have an effect on the sustainability of the biomethane produced as per EU RED II guidelines was also calculated.

Chapter 5: *Logistical considerations and challenges in deploying virtual biomethane pipelines to serve on-farm biogas plants*

This chapter models the operations of a virtual biomethane pipeline serving 100 on-farm AD plants of various sizes based on local farm statistics, optimised for shortest routing distance based on the vehicle routing problem. A publicly available Excel tool was adapted to investigate the logistical considerations in the operation of the virtual pipeline. Multiple configurations were deployed – varying vehicle biomethane storage capacities, varying numbers of vehicle type availability, one or two biomethane depots, and the use of a mobile-upgrading and compression unit, giving seven scenarios. The emissions resulting from the routing of these vehicles was also calculated.

Chapter 6: *A methodology for designing biogas pipelines*

This chapter describes how best to optimise biogas pipeline layouts using GIS software. Pipelines are optimised for shortest length and follow two methodologies: pipelines may connect as the crow flies, finding the shortest path possible, using Steiner nodes where appropriate to shorten the overall length, or pipelines must follow the shortest possible path along the road network. The pipelines serve up to 10 AD plants and one biogas user. As well as connecting all the AD plants to the biogas user, two heuristics were developed to design a total of 40 biogas pipeline layouts. Commercial software was used to calculate the pipeline material costs of each layout design. A multi-criteria decision analysis (MCDA) was conducted to determine the best performing layouts when pipeline material cost and biogas flow-rate were compared.

Chapter 7: *Conclusions and recommendations*

This chapter gives conclusions to the eight research objectives outlined in section 1.2, and, based on those conclusions and with consideration of the MaREI research centre's three impact priorities of 1) informing policy, 2) supporting industry, and 3) empowering society, recommendations are made. Further recommendations are made for areas of future research.

References

CSO (2019) Livestock Survey December 2019 - CSO - Central Statistics Office. Available at: https://www.cso.ie/en/releasesandpublications/er/lsd/livestocksurveydecember2019/ (Accessed: 27 July 2020).

CSO (2020) Crops and livestock. Routledge. Available at: https://www.cso.ie/en/releasesandpublications/er/clsjf/cropsandlivestocksurveyjunefinal2019/ (Accessed: 11 August 2020).

Department of the Environment Climate and Communications (2021) Climate Action Plan 2021. Available at: https://www.gov.ie/en/publication/6223e-climate-action-plan-2021/.

Department of the Environment Climate and Communications (2022) Sectoral Emissions Ceilings. Available at: https://www.gov.ie/en/publication/76864-sectoral-emissions-ceilings/ (Accessed: 25 October 2022).

Environmental Protection Agency (2022) Agriculture. Environmental Protection Agency (EPA). Available at: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/ (Accessed: 25 October 2021).

European Commission (2022) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: REPowerEU Plan. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF (Accessed: 19 August 2022).

IEA (2022) World Energy Outlook 2022. Available at: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf.

U.S. Energy Information Administration (2021) International Energy Outlook Consumption 2021. Available at: https://www.eia.gov/outlooks/ieo/narrative/consumption/sub-topic-01.php (Accessed: 3 February 2023).

UNFCCC and UN (2021) 'The Glasgow Climate Pact', in 2021 United Nations Climate Change Conference (COP26). Glasgow: UNFCCC. Available at: https://ukcop26.org/cop26-presidency-outcomes-the-climate-pact/.

2 The logistics of on-farm anaerobic digestion: feedstock, plant type, and energy end-use considerations

2.1 Overview of Ireland's agricultural feedstock resource and the ability to meet industry natural gas demand

Previous literature has calculated that the total theoretically available biomethane resource from cattle slurry in Ireland was 9.6 PJ a^{-1}, equivalent to 4.8% of total energy used in heat (O'Shea *et al.*, 2017). The largest practicable grass silage resource available in Ireland was calculated to generate 48.21 PJ a^{-1} (Wall, O'Kiely and Murphy, 2013), equivalent to 24% of total energy in heat (SEAI, 2019). Industry in Ireland uses about 33 PJ of natural gas per year, primarily for heat. Fabricated metals products, electrical and optical equipment, and the food and beverages sectors accounting for 53.4%, 16.6% and 14% respectively of the industrial gas for heat market (SEAI, 2018).

2.1.1 Farming systems and the availability of slurry

Depending on the specific farming practice, the availability of slurry can vary. Indoor housing of cattle throughout the year allows for an uninterrupted supply of slurry. These systems of cattle farming are known as zero-grazing (ZG) and this approach is common in the USA, continental Europe, and the southern hemisphere. In pasture-based (PB) systems, cattle are typically housed indoors only in winter, limiting the time that slurry is available as an AD feedstock. This occurs, for example, in New Zealand and Ireland, and represents 10% of global milk production (O'Callaghan *et al.*, 2017). Pasture based farming is highly valued due to the benefits of improved livestock welfare, which contributes to the social acceptance of dairy farming (Smid, Weary and von Keyserlingk, 2020). However, pasture-based farming on dairy farms presents a challenge for AD operators that rely on slurry as a feedstock. In Ireland, cattle graze on the land during the summer and are brought in in winter when grass growth is limited, and pastureland is wet. Dairy cows in Ireland must be housed for a minimum of 16 to 22 weeks in the year; the exact storage period depends on the soil type in the region (Hennessy *et al.*, 2011). Year-round slurry collection generally does not occur. Ireland has approximately 6.56 million cattle, including over 1.4 million dairy cows (CSO, 2019). Wall *et al.* estimated that over 7 Mt of dairy slurry are produced in Ireland each year during the cattle housing period (Wall, O'Kiely and Murphy, 2013). Slurry collected in Ireland has been reported to have a dry solids (DS) content of between 5.7% and 9.65%, and a volatile solids (VS) content of between 4.78% and 7.5%, depending on the time of year of

slurry collection and the diet of the herd (Allen *et al.*, 2014, 2016; Wall *et al.*, 2014a). A wide range of biomethane potential (BMP) yields have been reported for such slurry, from 125 to 239 L CH_4 kg^{-1} VS (Amon *et al.*, 2006; Wall, O'Kiely and Murphy, 2013).

2.1.2 Grass silage resource and availability

The most common farmed crops used in AD in Germany and Austria is maize silage (IEA Bioenergy: Task 37, 2019), whereas in Ireland, the climate is more suited to the production of grass (Smyth, Murphy and O'Brien, 2009). Grass silage surplus to livestock requirements could be utilised in a farm-based AD industry (Wall, O'Kiely and Murphy, 2013). Over 92% of the 4.52 million hectares (ha) of land used for agriculture in Ireland is grassland, and approximately 1.1 million ha is harvested for grass silage (CSO, 2020). The total theoretical biomethane resource potential of grass silage in Ireland has been reported to be in excess of 128 PJ a^{-1} (O'Shea *et al.*, 2017).

Grass yields in Ireland are estimated to currently be between around 7 and 9 t dry matter (DM) ha^{-1} a^{-1}, and it is reported that by increasing nitrogen fertiliser input and improving grass utilisation practices that this may increase to 9-11 t DM ha^{-1} a^{-1} (McEniry *et al.*, 2013). It is worth noting that increased nitrogen fertiliser input may result in increased cultivation emissions and water eutrophication. Teagasc (the Agricultural and Food Development Authority in Ireland) launched the "Grass10" initiative (2017 – 2020), with the aim of achieving yields of 10 t DM ha^{-1} a^{-1} on Irish livestock farms (Teagasc, 2020a); 85% of Irish farms make grass silage every year (Teagasc, 2020b). Thus, Irish farmers already own or have access to expensive equipment and machinery, and have knowledge of silage production processes, making grass silage an attractive potential feedstock for AD (Smyth, Murphy and O'Brien, 2009), and a necessary crop feedstock if the AD industry in Ireland is to succeed.

Grass silage has a reported DS content of between 12% and 33%, depending on what time of year it is harvested and whether it is pit silage or baled silage (Smyth, Murphy and O'Brien, 2009; Allen *et al.*, 2016). Volatile solids content of ca. 11-30% (of wet weight) have been reported (Smyth, Murphy and O'Brien, 2009; Wall, O'Kiely and Murphy, 2013; Allen *et al.*, 2016; FitzGerald *et al.*, 2019). A wide

range of biomethane potential yields have been reported for grass silage, from 229 to 432 L CH_4 kg^{-1} VS (McEniry and O'Kiely, 2013; Allen *et al.*, 2016; Voelklein, Rusmanis and Murphy, 2016), depending on soil type, climate, and time of harvest.

2.1.3 Hay

The production of hay is another common method of grass preservation in Ireland. Hay is harvested on 0.18 million ha in Ireland (CSO, 2020). Hay yields in Ireland are estimated to be between 6-7.66 t DM ha^{-1} a^{-1}, and it is reported that by increasing nitrogen fertiliser input and improving grass utilisation practices this value may increase to 8-9.63 t DM ha^{-1} a^{-1} (McEniry *et al.*, 2013). Hay has a high DS content of ca. 87% and a VS content of ca. 82% but has a reported lower biomethane potential than grass silage (156 L CH_4 kg^{-1} VS). This is due to a reduction of sugars in the hay over its 7-day drying period (Allen *et al.*, 2016).

2.1.4 Straw

Straw, a by-product of cereal production, is considered another relevant on-farm feedstock for AD (Murphy *et al.*, 2013). Cereals harvested in Ireland include wheat, barley, and oats. Cereals are harvested on over 267,000 ha of land in Ireland (CSO, 2020). Straws are generally used for animal bedding and feed (Teagasc, 2018). Depending on the type of cereal, straw yields in Ireland have been reported in the range 3 to 4 t DM ha^{-1} a^{-1} (Teagasc, 2018). Table 2-1 shows the characteristics of wheat, barley and oats straws reported in literature.

Cereal Straw	**DS (%)**	**VS (%)**	**Methane yield (L CH_4 kg^{-1} VS)**	**Sources**
Wheat Straw	85 – 92.7	82.3 – 84.5	233 – 324	(McCartney *et al.*, 2006; Murphy *et al.*, 2011; Liang, Zhang and Mou, 2013; Ferreira *et al.*, 2014; Reilly, Dinsdale and Guwy, 2015; Jaffar *et al.*, 2016; Teagasc, 2018; Gao *et al.*, 2020)
Barley Straw	85 – 93.1	79.4 – 96.3	159.6 – 280	(McCartney *et al.*, 2006; Dubrovskis *et al.*, 2013; Shin *et al.*, 2016; Teagasc, 2018; Rocha-Meneses *et al.*, 2019)
Oats Straw	85 – 94.7	86	191.1 – 331.9	(McCartney *et al.*, 2006; Teagasc, 2018; Zhao *et al.*, 2018)

Table 2-1: Reported characteristics of cereal straws.

Winter crops (denoted by *W.*) of wheat, barley, and oats become available for harvest from July to August. The Spring sown crops (denoted by *S.*) become available in late August to the end of September. Table 2-2 shows the average straw yields by straw type and harvest period.

Type	Hectares	Yield (t DM ha^{-1})	% Winter	% Summer	Weighted tDM/ha
W. Wheat	85,400	3.6	66.9%	-	3.24
S. Wheat	42,300	2.5	-	33.1%	-
W. Barley	21,100	3.6	15.6%	-	3.09
S. Barley	114,000	3	-	84.4%	-
W. Oats.	18,024	4	81.5%	-	3.87
S. Oats	4,083	3.3	-	18.5%	-
Straw at 15% moisture.					

Table 2-2: Average straw yields (Teagasc, 2018).

2.1.5 Seasonal feedstock availability

Investment in AD plants may be deterred if feedstock availability varies throughout the year (Reynolds *et al.*, 2022). Crops may be preserved and stored over long periods of time; however, slurries may require to be immediately digested to avoid fugitive emissions. Whilst many studies on the modelling and optimisation of AD systems have previously been conducted, the literature assessed indicates that studies do not consider the implications of modelling seasonally available feedstocks (Kunatsa and Xia, 2022). Ganeshan and Rajendran (2022) developed a MATLAB model which simulated and optimised the AD process but did not analyse the effects of seasonal feedstock availability. Chodkowska-Miszczuk *et al.* (2021) discuss the implications of seasonally available crop wastes but suggested this can be alleviated by storing the feedstock. O'Connor *et al.* (2021) modelled the effects of seasonal variation in manure quantities, but did not address when feedstock is unavailable for periods of the year. Ackrill and Abdo (2020) correctly identified that the unavailability of slurry during the summer months is a potential barrier in the uptake of on-farm AD, but did not model the implications of this challenge. Styles *et al.* (2022) conducted an environmental analysis which supports the use of energy crops for AD to balance the seasonal operations of plants which are fed with slurry but did not analyse the impact this strategy would have on a facility. Furthermore, no previous literature has evaluated the combined effects of seasonal slurry availability and seasonal gas demand on the operations of an on-farm AD plant.

2.2 Profile of on-farm AD plants

2.2.1 Continuously-stirred tank reactor (CSTR)

There are many plant configurations that can be employed for on-farm AD. The type of digester required will primarily depend on the feedstocks available. When feedstocks of high solids content are used for AD, such as grass and straw, liquid

digestate may be recirculated and mixed with the feedstock prior to digestion, to lower the overall solids content and enhance hydrolysis (Nizami *et al.*, 2010). On-farm AD plants generally operate at mesophilic temperatures due to lower heating energy requirements and more operational stability (Labatut, Angenent and Scott, 2014).

The literature suggests that CSTRs are the most common type of system used in on-farm AD (Wilkinson, 2011; Fjørtoft *et al.*, 2014; Van Stappen *et al.*, 2016; Ahlberg-Eliasson *et al.*, 2017; Usack *et al.*, 2018; Rouhollahi *et al.*, 2020). This is particularly true for the digestion of slurries and co-digestion of slurries with other on-farm crops or wastes (Wilkinson, 2011; Lukehurst and Bywater, 2015). CSTRs require higher hydraulic retention times (HRTs) and operate with a solids content of less than 10% (United States Environmental Protection Agency, 2011). Typical organic loading rates (OLRs) of CSTRs range from 2 to 4 kg VS m^{-3} d^{-1}, with higher ranges sometimes resulting in inhibited biogas production (Xie, 2012; Pohl, Heeg and Mumme, 2013; Wall *et al.*, 2014a; Jürgensen *et al.*, 2018). Relatively high OLRs (4 kg VS m^{-3} d^{-1}) and HRTs in excess of 20 days have been reported for the co-digestion of grass silage and dairy slurry with high biomethane production efficiencies (Wall *et al.*, 2014a).

Good mixing systems are vital in the design of CSTRs to avoid scum and sediment layers (FNR, 2012). Efficient mixing of the reactor substrate will also aid the distribution of microorganisms and heat in the digester. Hydraulic agitation involves using pumps to mix the feedstock in the digester. The mixing components are located outside the digester and so are easily repaired and maintained (Lukehurst and Bywater, 2015; Nsair *et al.*, 2020). This mixing system is well suited to small-scale digesters (Nsair *et al.*, 2020). Pneumatic agitation involves injecting biogas back into the digester with pressure, with the rising gas mixing the contents. Pneumatic mixing systems are available from manufacturers for agricultural digesters but are not widely used (FNR, 2012).

2.2.2 Co-digestion

Prior literature suggests that grass silage may be co-digested with slurry to promote better digestion and increase the biomethane potential of the feedstocks (Wall, O'Kiely and Murphy, 2013; Wall *et al.*, 2014a, 2014b). Due to their high water

content, slurries generally have a much lower energy content as compared to crop feedstocks, however mono-digesting crops such as grass silage can lead to problems during digestion (Thamsiriroj, Nizami and Murphy, 2012). Wall *et al.* (2014b) reported that despite the higher biomethane potential yield in the mono-digestion of grass silage, the co-digestion of grass silage and dairy slurry can be more efficient and provide a more stable AD process. Micro-nutrient availability and suitable C:N ratios are some of the other benefits of using dairy slurries as a co-digestion feedstock with crops (Allen *et al.*, 2016).

2.3 Energy end-use and on-farm AD plant development

The most common use of biogas generated from on-farm AD is combustion in a combined heat and power (CHP) unit (Bywater, 2011; Ahlberg-Eliasson *et al.*, 2017). The literature shows that biogas is rarely upgraded when it is produced in an on-farm AD plant. Small upgrading plants do exist, but upgrading technologies are more often used by plants that have biogas production rates in excess of 300 m^3 $hour^{-1}$ (Lukehurst and Bywater, 2015), whilst a digester serving 100 dairy cows only produces approximately 6 m^3 $hour^{-1}$ of biogas, and upgrading facilities serving plants this size are extremely rare (IEA, 2014). However, systems which upgrade biogas in a centralised location are feasible. A "Green Gas Hub" in Wijster, a rural low-population area in the Netherlands, employs this strategy, whereby farmers deliver biogas produced on their farms to the centralised upgrading hub via pipeline (IEA Bioenergy: Task 37, 2017).

Mobile upgrading of biogas is another possibility but the literature on this technique is scarce. Mobile upgrading, an upgrading process in which a small-scale upgrading plant and storage are integrated in a mobile unit and serve as a virtual pipeline, is being considered for farms away from the grid as a means to upgrade biogas at a lower cost. A model was developed by Gil-Carrera *et al.* (2019) which determined that the use of a mobile upgrading system through farming could be essential in making biogas upgrading systems financially viable for small scale producers in an Irish context.

2.4 Renewable gas delivery methods

2.4.1 Virtual pipelines

The delivery of biogas from a producer to an end user can be achieved through different means depending on whether it is upgraded to biomethane (via the removal of CO_2) or not. If the biogas is not upgraded, it must be used either on-site or transported via a biogas pipeline, as has been demonstrated in the Netherlands (IEA Bioenergy: Task 37, 2017). Transporting biogas via compressed cylinders, whilst possible, poses problems due to the CO_2 content of the biogas (typically 40 – 50 $\%_{vol}$) (Hovland, 2017). Biomethane can be delivered via gas grid injection or the development of a virtual biomethane pipeline. A virtual pipeline is a gas delivery system that transports biomethane via haulage of gas cylinders as opposed to traditional pipeline infrastructure, and is commonly used in areas where there is no gas grid access or in countries that have limited gas grid infrastructure (Udaeta, 2012). Virtual pipelines are already in operation across China, Europe, North America, and South America. For example, Galileo Technologies, based in Argentina, operate in multiple countries in South America and also in Bulgaria (Galileo Technologies, 2020). Cost-saving virtual pipeline projects have been developed in the US, serving four dairy biogas plants (DMT Clear Gas Solutions, 2022). The majority of Sweden's biomethane industry operates off-grid through the use of virtual pipelines and local, regional gas grids (Swedish Gas Association and Klackenberg, 2019).

Despite the widespread use of virtual pipelines, there is little literature on the optimisation or "best practice implementation" of these systems when integrated with biomethane production. Hoo *et al.* (2019) created a spatial-economic model of biomethane injection from 2 to 4 biogas plants into the gas grid via virtual pipeline, but no work to date has optimised the routing of vehicles servicing a large number of biogas (AD) plants. The optimisation of a virtual pipeline servicing a large number of biogas plants and a market entry point (which may be a gas grid injection point, a compressed natural gas (CNG) fuelling station, or an individual gas user), can be solved through the application of vehicle routing problem (VRP) techniques and optimisation solutions. Rural areas that have large biomass resources, but no direct gas-grid access would benefit from the use of such optimisation solutions to

determine the most efficient strategies for the creation of virtual biomethane pipelines from a sustainability and economic viability perspective.

VRP solutions have previously been applied to a variety of logistic problems. A mathematical solution for the VRP was first proposed by Dantzig and Ramser (1959) for the distribution of petrol to a network of service stations. Due to the complexity and the practical applications of the problems arising from VRPs, much research has been undertaken on the topic (Toth and Vigo, 2002; Laporte, 2009). Heuristic approaches, akin to "short-cuts", are used to find solutions, which may or may not be optimal, for complex problems; over time, researchers have devised various problem-dependent heuristics and more flexible problem-independent metaheuristic (strategies that guide a heuristic search process) methods to provide solutions to complicated VRPs including variants such as the capacitated vehicle routing problem (CVRP) where the additional complexity of capacity constraints must be considered. Some well-known algorithms that have been devised to solve these operational research problems include the savings algorithm, the Adaptive Large Neighbourhood Search algorithm, and Unified Hybrid Genetic Search (Vidal, 2020). Application of the CVRP approach for solving routing problems is common in industries such as tourism (Erdoğan, 2017), the supply chain of agricultural goods (Lahyani *et al.*, 2015), fuel delivery (Popović, Vidović and Radivojević, 2012), and waste collection (Markov, Varone and Bierlaire, 2016). More recently, there has been a focus on the use of VRPs to solve problems presented through research in the renewable energy sector (Asghari and Mirzapour Al-e-hashem, 2021). For example, VRP based solutions have been proposed for the smart management of electric vehicle charging locations to decrease overall charging costs (Yagcitekin and Uzunoglu, 2016).

2.4.2 Biogas pipelines

AD plants could feed biogas to a market entry point, or biogas user (industry or central upgrading hub) via low-pressure biogas pipelines as is currently done in Wijster and Zeewolde in the Netherlands (IEA Bioenergy: Task 37, 2011, 2017). Furthermore, Aemetis Inc., located in California, pipe biogas generated from farm-based AD plants to a centralised upgrading facility (Aemetis Inc., 2022). A key consideration in the development of biogas pipelines is how to arrange their physical layout. One method is to build pipelines along the shortest path possible; this manner of connection may require the construction of pipelines through the property of

multiple landowners, who may or may not have a desire to facilitate such construction. Pipeline networks and layouts often face such logistical and geographic constraints, and may take alternative routes in the construction of pipelines, such as following an existing road network (Gas Networks Ireland, 2018).

Numerous pipeline design techniques have been described and analysed in different works. A study by Arya *et al.* (2022) reviewed various gas pipeline optimisation methodologies, including non-linear programming techniques, Particle Swarm Optimisation and Ant Colony Algorithms. Chu and Chen (2012) optimised the design of long-distance diesel fuel pipelines based on shortest path by utilising the Dijkstra algorithm.

Layout optimisation and analysis has also been studied previously. Hengeveld *et al.* (2016) compared the performance and costs of a fishbone biogas pipeline layout to a star layout. Li *et al.* (2023) conducted a performance analysis of a centralised biogas plant supplying biogas via pipeline to a network of rural households with no natural gas grid access, as a source of cooking and heating fuel. An and Peng (2016) used layout optimisation to synchronise the minimum risk loss and total cost of a natural gas pipeline. Layout optimisation was also used by Zhou *et al.* (2019) to reduce gas pipeline investment costs. O'Shea *et al.* (2017) designed a biogas pipeline layout and calculated pressure profiles from first principles, finding one Steiner node using MATLAB.

Marcoulaki *et al.* (2012) showed that GIS can be used for designing pipeline systems. Baufumé *et al.* (2013) used GIS to design hydrogen pipeline layouts on a national level in Germany, connecting several sources and demand points. GIS software was also used by Lumbreras *et al.* (2022) to design district heating pipeline networks in urban areas, using Kruskal's algorithm to determine the MST.

2.5 Logistics overview and theoretical framework

The optimisation of on-farm AD, from plant location, plant type, feedstocks, energy delivery methods, and energy end-use, is largely unexplored in the literature. Resource assessments in Ireland have not conducted spatial analyses with regards to either gas grid infrastructure or large energy users. Considerations such as seasonal feedstock availability may have significant ramifications for on-farm AD plant operation. Gas delivery methods will be paramount to the success of on-farm AD

developments. This thesis will seek to develop optimisation techniques concerning these research strands that have not been investigated in the literature.

Whilst some discussion will be made as to the wider, holistic impacts of biogas delivery systems, the theoretical framework of this thesis will emphasise a quantitative approach. The methodologies in each chapter are therefore based on data analysis, statistical techniques, and mathematical modelling and the results will provide valuable insights into resource quantification, location, and how future biogas delivery systems may operate in a technical manner. For example, the sustainability focus of this thesis is based on the sustainability criteria as outlined in EU RED II ($CO_{2\text{-eq}}$ emissions per MJ) – whilst other sustainability matters such as biodiversity, community engagement, and stakeholder participation are deeply intertwined with any industrial, energy, and agriculture industry, these frameworks are considered outside the scope of this thesis. This quantitative perspective will enable a more comprehensive understanding of the technical and logistical challenges faced in implementing on-farm AD systems as a viable renewable energy delivery mechanism. It is also worth noting that the parameters chosen for analysis in this work are influential in the results obtained – a change in scenario parameters may significantly influence the results obtained, and would likely vary with different feedstocks, biogas outputs, AD plant size, and different seasonality aspects of feedstocks and/or gas demand."

References

Ackrill, R. and Abdo, H. (2020) 'On-farm anaerobic digestion uptake barriers and required incentives: A case study of the UK East Midlands region', Journal of Cleaner Production, 264, p. 121727. Available at: https://doi.org/10.1016/j.jclepro.2020.121727.

Aemetis Inc. (2022) Renewable Natural Gas. Available at: https://www.aemetis.com/products/renewable-natural-gas/ (Accessed: 14 October 2022).

Ahlberg-Eliasson, K. et al. (2017) 'Production efficiency of Swedish farm-scale biogas plants', Biomass and Bioenergy, 97, pp. 27–37. Available at: https://doi.org/10.1016/j.biombioe.2016.12.002.

Allen, E. et al. (2014) 'Investigation of the optimal percentage of green seaweed that may be co-digested with dairy slurry to produce gaseous biofuel', Bioresource Technology, 170, pp. 436–444. Available at: https://doi.org/10.1016/j.biortech.2014.08.005.

Allen, E. et al. (2016) 'A detailed assessment of resource of biomethane from first, second and third generation substrates', Renewable Energy, 87, pp. 656–665. Available at: https://doi.org/10.1016/j.renene.2015.10.060.

Amon, T. et al. (2006) 'Optimising methane yield from anaerobic digestion of manure: Effects of dairy systems and of glycerine supplementation', International Congress Series, 1293, pp. 217–220. Available at: https://doi.org/10.1016/j.ics.2006.03.007.

An, J. and Peng, S. (2016) 'Layout optimization of natural gas network planning: Synchronizing minimum risk loss with total cost', Journal of Natural Gas Science and Engineering, 33, pp. 255–263. Available at: https://doi.org/10.1016/J.JNGSE.2016.05.017.

Arya, A.K. et al. (2022) 'Recent trends in gas pipeline optimization', Materials Today: Proceedings, 57, pp. 1455–1461. Available at: https://doi.org/10.1016/j.matpr.2021.11.232.

Asghari, M. and Mirzapour Al-e-hashem, S.M.J. (2021) 'Green vehicle routing problem: A state-of-the-art review', International Journal of Production Economics, 231, p. 107899. Available at: https://doi.org/10.1016/J.IJPE.2020.107899.

Baufumé, S. et al. (2013) 'GIS-based scenario calculations for a nationwide German hydrogen pipeline infrastructure', International Journal of Hydrogen Energy, 38(10), pp. 3813–3829. Available at: https://doi.org/10.1016/j.ijhydene.2012.12.147.

Bywater, A. (2011) ‘A Review of Anaerobic Digestion Plants on UK Farms - Barriers, Benefits and Case Studies’, Royal Agricultural Society of England, p. 115. Available at: http://www.fre-energy.co.uk/pdf/RASE-On-Farm-AD-Review.pdf (Accessed: 23 July 2020).

Chodkowska-Miszczuk, J., Martinát, S. and van der Horst, D. (2021) ‘Changes in feedstocks of rural anaerobic digestion plants: External drivers towards a circular bioeconomy’, Renewable and Sustainable Energy Reviews, 148, p. 111344. Available at: https://doi.org/10.1016/J.RSER.2021.111344.

Chu, F. and Chen, S. (2012) ‘Optimal Design of Pipeline Based on the Shortest Path’, Physics Procedia, 33, pp. 216–220. Available at: https://doi.org/10.1016/J.PHPRO.2012.05.054.

CSO (2019) Livestock Survey December 2019 - CSO - Central Statistics Office. Available at: https://www.cso.ie/en/releasesandpublications/er/lsd/livestocksurveydecember2019/ (Accessed: 27 July 2020).

CSO (2020) Crops and livestock. Routledge. Available at: https://www.cso.ie/en/releasesandpublications/er/clsjf/cropsandlivestocksurveyjunefinal2019/ (Accessed: 11 August 2020).

Dantzig, G.B. and Ramser, J.H. (1959) ‘The Truck Dispatching Problem’, Management Science, 6(1), pp. 80–91. Available at: http://www.jstor.org/stable/2627477.

DMT Clear Gas Solutions (2022) No Pipeline for RNG Projects? No problem. Available at: https://www.dmt-cgs.com/publications/virtual-pipeline-technology-rng/ (Accessed: 10 August 2022).

Dubrovskis, V. et al. (2013) ‘Biogas production potential from agricultural residues in Latvia’, in Engineering for Rural Development, pp. 446–450.

Erdoğan, G. (2017) ‘An open source Spreadsheet Solver for Vehicle Routing Problems’, Computers & Operations Research, 84, pp. 62–72. Available at: https://doi.org/10.1016/J.COR.2017.02.022.

Ferreira, L.C. et al. (2014) ‘Biomethane potential of wheat straw: Influence of particle size, water impregnation and thermal hydrolysis’, Chemical Engineering Journal, 242, pp. 254–259. Available at: https://doi.org/10.1016/j.cej.2013.08.041.

FitzGerald, J.A. et al. (2019) ‘Trace element supplementation is associated with increases in fermenting bacteria in biogas mono-digestion of grass silage’, Renewable Energy, 138, pp. 980–986. Available at: https://doi.org/10.1016/j.renene.2019.02.051.

Fjørtoft, K. et al. (2014) ‘Methane production and energy evaluation of a farm scaled biogas plant in cold climate area’, Bioresource Technology, 169, pp. 72–79. Available at: https://doi.org/10.1016/j.biortech.2014.06.077.

FNR (2012) Guide to Biogas: From production to use, Fachagentur Nachwachsende Rohstoffe e. V. (FNR) FNR,. Available at: https://mediathek.fnr.de/broschuren/fremdsprachige-publikationen/english-books/guide-to-biogas-from-production-to-use.html (Accessed: 18 August 2020).

Galileo Technologies (2020) Virtual Pipeline - CNG - Galileo Technologies. Available at: https://www.galileoar.com/en/virtual-pipeline/ (Accessed: 24 May 2021).

Ganeshan, P. and Rajendran, K. (2022) ‘Dynamic simulation and optimization of anaerobic digestion processes using MATLAB’, Bioresource Technology, 351, p. 126970. Available at: https://doi.org/10.1016/J.BIORTECH.2022.126970.

Gao, J. et al. (2020) ‘Mass conversion pathway during anaerobic digestion of wheat straw’, RSC Advances, 10(46), pp. 27720–27727. Available at: https://doi.org/10.1039/d0ra02441d.

Gas Networks Ireland (2018) Phase 2 Works Begins on Natural Gas Pipeline to Center Parcs, County Longford. Available at: https://www.gasnetworks.ie/corporate/news/active-news-articles/phase-2-works-begins-on-natural-gas-pipeline-to-center-parcs-county-longford/ (Accessed: 23 August 2022).

Gil-Carrera, L. et al. (2019) ‘Feasibility study of an off-grid biomethane mobile solution for agri-waste’, Applied Energy, 239(January), pp. 471–481. Available at: https://doi.org/10.1016/j.apenergy.2019.01.141.

Hengeveld, E.J. et al. (2016) ‘Biogas infrastructures from farm to regional scale, prospects of biogas transport grids’, Biomass and Bioenergy, 86, pp. 43–52. Available at: https://doi.org/10.1016/J.BIOMBIOE.2016.01.005.

Hennessy, T. et al. (2011) National Farm Survey of Manure Application and Storage Practices on Irish Farms. Available at: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf (Accessed: 1 April 2019).

Hovland, J. (2017) Compression of raw biogas: A feasibility study. Available at: https://www.biogas2020.se/wp-content/uploads/2017/06/2217020-1compressionrawbiogas.pdf (Accessed: 26 October 2021).

IEA (2014) Upgrading Plant Lists - IEA Bioenergy Task 37, IEA Bioenergy Task 37. Available at: http://task37.ieabioenergy.com/plant-list.html (Accessed: 14 August 2020).

IEA Bioenergy: Task 37 (2011) Biogas Pipeline for Local Heat and Power Production in a Residential Area, Zeewolde, Nl. A Success Story from IEA Bioenergy Task 37 'Energy from Biogas'. Available at: https://www.ieabioenergy.com/wp-content/uploads/2018/01/success_story_zeewolde2011.pdf (Accessed: 23 August 2022).

IEA Bioenergy: Task 37 (2017) GREEN GAS HUB: Provision of biogas by farmers by pipe to a Green Gas Hub with a centralised upgrading process. Available at: https://www.ieabioenergy.com/blog/publications/green-gas-hub-provision-of-biogas-by-farmers-by-pipe-to-a-green-gas-hub-with-a-centralised-upgrading-process/.

IEA Bioenergy: Task 37 (2019) Country reports. Available at: http://task37.ieabioenergy.com/country-reports.html (Accessed: 9 July 2021).

Jaffar, M. et al. (2016) 'Wheat straw pretreatment with KOH for enhancing biomethane production and fertilizer value in anaerobic digestion', Chinese Journal of Chemical Engineering, 24(3), pp. 404–409. Available at: https://doi.org/10.1016/j.cjche.2015.11.005.

Jürgensen, L. et al. (2018) 'A combination anaerobic digestion scheme for biogas production from dairy effluent—CSTR and ABR, and biogas upgrading', Biomass and Bioenergy, 111, pp. 241–247. Available at: https://doi.org/10.1016/j.biombioe.2017.04.007.

Kunatsa, T. and Xia, X. (2022) 'A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement', Bioresource Technology, 344, p. 126311. Available at: https://doi.org/10.1016/j.biortech.2021.126311.

Labatut, R.A., Angenent, L.T. and Scott, N.R. (2014) 'Conventional mesophilic vs. thermophilic anaerobic digestion: A trade-off between performance and stability?', Water Research, 53, pp. 249–258. Available at: https://doi.org/10.1016/j.watres.2014.01.035.

Lahyani, R. et al. (2015) 'A multi-compartment vehicle routing problem arising in the collection of olive oil in Tunisia', Omega, 51, pp. 1–10. Available at: https://doi.org/10.1016/J.OMEGA.2014.08.007.

Laporte, G. (2009) 'Fifty Years of Vehicle Routing', Transportation Science, 43(4), pp. 408–416. Available at: http://www.jstor.org/stable/25769465.

Li, J. et al. (2023) 'Performance analysis of biomass direct combustion heating and centralized biogas supply system for rural districts in China', Energy Conversion and Management, 278, p. 116730. Available at: https://doi.org/10.1016/j.enconman.2023.116730.

Liang, Y., Zhang, H. and Mou, G. (2013) 'Experimental study on biogas production through anaerobic digestion of wheat straw and urban fallen leaves', in 2013 International Conference on Materials for Renewable Energy and Environment, pp. 265–269. Available at: https://doi.org/10.1109/ICMREE.2013.6893662.

Lukehurst, C. and Bywater, A. (2015) Exploring the viability of small scale anaerobic digesters in livestock farming, IEA Bioenergy. Available at: http://www.iea-biogas.net/files/daten-redaktion/download/Technical Brochures/Small_Scale_RZ_web1.pdf.

Lumbreras, M. et al. (2022) 'Design of district heating networks in built environments using GIS: A case study in Vitoria-Gasteiz, Spain', Journal of Cleaner Production, 349, p. 131491. Available at: https://doi.org/10.1016/J.JCLEPRO.2022.131491.

Marcoulaki, E.C., Papazoglou, I.A. and Pixopoulou, N. (2012) 'Integrated framework for the design of pipeline systems using stochastic optimisation and GIS tools', Chemical Engineering Research and Design, 90(12), pp. 2209–2222. Available at: https://doi.org/10.1016/j.cherd.2012.05.012.

Markov, I., Varone, S. and Bierlaire, M. (2016) 'Integrating a heterogeneous fixed fleet and a flexible assignment of destination depots in the waste collection VRP with intermediate facilities', Transportation Research Part B: Methodological, 84, pp. 256–273. Available at: https://doi.org/10.1016/J.TRB.2015.12.004.

McCartney, D.H. et al. (2006) 'Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in Western Canada', Canadian Journal of Animal Science, 86. Available at: https://doi.org/10.4141/A05-092.

McEniry, J. et al. (2013) 'How much grassland biomass is available in Ireland in excess of livestock requirements?', Irish Journal of Agricultural and Food Research, 52(1), pp. 67–80. Available at: http://www.jstor.org/stable/23631018.

McEniry, J. and O'Kiely, P. (2013) 'Anaerobic methane production from five common grassland species at sequential stages of maturity', Bioresource Technology, 127, pp. 143–150. Available at: https://doi.org/10.1016/j.biortech.2012.09.084.

Murphy, J. et al. (2011) 'Biogas from Energy Crop Digestion', IEA Bioenergy - Task 37, Task 37 Br, p. 24. Available at: http://www.iea-biogas.net/files/daten-redaktion/download/publi-task37/Update_Energy_crop_2011.pdf (Accessed: 10 August 2020).

Murphy, J.D. et al. (2013) 'The resource of biomethane, produced via biological, thermal and electrical routes, as a transport biofuel', Renewable Energy, 55, pp. 474–479. Available at: https://doi.org/10.1016/j.renene.2013.01.012.

Nizami, A.S. et al. (2010) ‘Role of leaching and hydrolysis in a two-phase grass digestion system’, Energy and Fuels, 24(8), pp. 4549–4559. Available at: https://doi.org/10.1021/ef100677s.

Nsair, A. et al. (2020) ‘Operational Parameters of Biogas Plants: A Review and Evaluation Study’, Energies, 13(15), p. 3761. Available at: https://doi.org/10.3390/en13153761.

O’Callaghan, T. et al. (2017) Dairy products from grass are simply better. Available at: https://www.teagasc.ie/media/website/publications/2017/Segment-006-of-Todays-Farm-July-Aug2017.pdf (Accessed: 11 October 2021).

O’Connor, S. et al. (2021) ‘Decision support tool for the construction and seasonal operation of farm-scale anaerobic digestion plants’, in Environmental Science.

O’Shea, R. et al. (2017) ‘Assessing the total theoretical, and financially viable, resource of biomethane for injection to a natural gas network in a region’, Applied Energy, 188, pp. 237–256. Available at: https://doi.org/10.1016/j.apenergy.2016.11.121.

O’Shea, R., Wall, D.M. and Murphy, J.D. (2017) ‘An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network’, Applied Energy, 208, pp. 108–122. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2017.10.045.

Pohl, M., Heeg, K. and Mumme, J. (2013) ‘Anaerobic digestion of wheat straw - Performance of continuous solid-state digestion’, Bioresource Technology, 146, pp. 408–415. Available at: https://doi.org/10.1016/j.biortech.2013.07.101.

Popović, D., Vidović, M. and Radivojević, G. (2012) ‘Variable Neighborhood Search heuristic for the Inventory Routing Problem in fuel delivery’, Expert Systems with Applications, 39(18), pp. 13390–13398. Available at: https://doi.org/10.1016/J.ESWA.2012.05.064.

Reilly, M., Dinsdale, R. and Guwy, A. (2015) ‘Enhanced biomethane potential from wheat straw by low temperature alkaline calcium hydroxide pre-treatment’, Bioresource Technology, 189, pp. 258–265. Available at: https://doi.org/10.1016/j.biortech.2015.03.150.

Reynolds, J. et al. (2022) ‘An evaluation of feedstocks for sustainable energy and circular economy practices in a small island community’, Renewable and Sustainable Energy Reviews, 161, p. 112360. Available at: https://doi.org/10.1016/J.RSER.2022.112360.

Rocha-Meneses, L. et al. (2019) ‘Enhancing bioenergy yields from sequential bioethanol and biomethane production by means of solid-liquid separation of the substrates’, Energies, 12(19). Available at: https://doi.org/10.3390/en12193683.

Rouhollahi, Z. et al. (2020) ‘Farm biogas plants, a sustainable waste to energy and bio-fertilizer opportunity for Iran’, Journal of Cleaner Production, 253, p. 119876. Available at: https://doi.org/10.1016/j.jclepro.2019.119876.

SEAI (2018) 2018 National Energy Balance. Available at: https://www.seai.ie/data-and-insights/seai-statistics/key-publications/national-energy-balance/ (Accessed: 15 September 2020).

SEAI (2019) Energy in Ireland 2019 Report. Available at: https://www.seai.ie/publications/Energy-in-Ireland-2019-.pdf (Accessed: 8 September 2020).

Shin, J. et al. (2016) ‘Predicting Methane Production on Anaerobic Digestion to Crop Residues and Biomass Loading Rates’, Journal of the Korea Organic Resource Recycling Association, 24(3), pp. 75–82. Available at: https://doi.org/10.17137/korrae.2016.24.3.75.

Smid, A.-M.C., Weary, D.M. and von Keyserlingk, M.A.G. (2020) ‘The Influence of Different Types of Outdoor Access on Dairy Cattle Behavior’, Frontiers in veterinary science, 7, p. 257. Available at: https://doi.org/10.3389/fvets.2020.00257.

Smyth, B.M., Murphy, J.D. and O’Brien, C.M. (2009) ‘What is the energy balance of grass biomethane in Ireland and other temperate northern European climates?’, Renewable and Sustainable Energy Reviews, 13(9), pp. 2349–2360. Available at: https://doi.org/10.1016/j.rser.2009.04.003.

Van Stappen, F. et al. (2016) ‘Consequential environmental life cycle assessment of a farm-scale biogas plant’, Journal of Environmental Management, 175, pp. 20–32. Available at: https://doi.org/10.1016/j.jenvman.2016.03.020.

Styles, D. et al. (2022) ‘Climate mitigation efficacy of anaerobic digestion in a decarbonising economy’, Journal of Cleaner Production, 338, p. 130441. Available at: https://doi.org/10.1016/J.JCLEPRO.2022.130441.

Swedish Gas Association and Klackenberg, L. (2019) Biomethane in Sweden-market overview & policies. Available at: https://www.energigas.se/library/2907/biomethane-in-sweden-191107-cw.pdf (Accessed: 7 July 2021).

Teagasc (2018) Straw for Energy. Available at: https://www.teagasc.ie/media/website/publications/2018/Teagasc-A4-Energy-Fact-Sheet-No.-12-Straw-for-Energy_2pp.pdf (Accessed: 28 August 2020).

Teagasc (2020a) Grass10. Available at: https://www.teagasc.ie/crops/grassland/grass10/ (Accessed: 27 August 2020).

Teagasc (2020b) Quality Grass Silage. Available at: https://www.teagasc.ie/crops/grassland/quality-grass-silage/ (Accessed: 11 January 2019).

Thamsiriroj, T., Nizami, A.S. and Murphy, J.D. (2012) 'Why does mono-digestion of grass silage fail in long term operation?', Applied Energy, 95, pp. 64–76. Available at: https://doi.org/10.1016/j.apenergy.2012.02.008.

Toth, P. and Vigo, D. (2002) The Vehicle Routing Problem. Edited by P. Toth and D. Vigo. Philadelphia: Society for Industrial and Applied Mathematics. Available at: https://doi.org/10.1137/1.9780898718515.

Udaeta, M.E.M. (2012) 'Natural Gas Virtual-Pipeline for Alternative Energy Distribution', in J.L. de O. Bernal (ed.). Rijeka: IntechOpen, p. Ch. 6. Available at: https://doi.org/10.5772/48711.

United States Environmental Protection Agency (2011) Recovering Value from Waste: Anaerobic Digester System Basics. Available at: https://www.epa.gov/agstar/recovering-value-waste-anaerobic-digester-system-basics (Accessed: 10 August 2020).

Usack, J.G. et al. (2018) 'An evaluation of anaerobic co-digestion implementation on New York State dairy farms using an environmental and economic life-cycle framework', Applied Energy, 211, pp. 28–40. Available at: https://doi.org/10.1016/j.apenergy.2017.11.032.

Vidal, T. (2020) 'Hybrid Genetic Search for the CVRP: Open-Source Implementation and SWAP* Neighborhood', Computers and Operations Research, 140. Available at: https://doi.org/10.48550/arxiv.2012.10384.

Voelklein, M.A., Rusmanis, D. and Murphy, J.D. (2016) 'Increased loading rates and specific methane yields facilitated by digesting grass silage at thermophilic rather than mesophilic temperatures', Bioresource Technology, 216, pp. 486–493. Available at: https://doi.org/10.1016/j.biortech.2016.05.109.

Wall, D.M. et al. (2014a) 'Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry', Bioresource Technology, 173, pp. 422–428. Available at: https://doi.org/10.1016/j.biortech.2014.09.126.

Wall, D.M. et al. (2014b) 'The effect of trace element addition to mono-digestion of grass silage at high organic loading rates', Bioresource Technology, 172, pp. 349–355. Available at: https://doi.org/10.1016/j.biortech.2014.09.066.

Wall, D.M., O'Kiely, P. and Murphy, J.D. (2013) 'The potential for biomethane from grass and slurry to satisfy renewable energy targets', Bioresource

Technology, 149, pp. 425–431. Available at: https://doi.org/https://doi.org/10.1016/j.biortech.2013.09.094.

Wilkinson, K. (2011) ‘Development of on-farm anaerobic digestion’, BioCycle, 52(1), pp. 49–50. Available at: https://doi.org/10.5772/17243.

Xie, S. (2012) Evaluation Of Biogas Production From Anaerobic Digestion Of Pig Manure And Grass Silage, PhD Thesis. Available at: http://hdl.handle.net/10379/3023 (Accessed: 16 January 2019).

Yagcitekin, B. and Uzunoglu, M. (2016) ‘A double-layer smart charging strategy of electric vehicles taking routing and charge scheduling into account’, Applied Energy, 167, pp. 407–419. Available at: https://doi.org/10.1016/J.APENERGY.2015.09.040.

Zhao, Y. et al. (2018) ‘Co-digestion of oat straw and cow manure during anaerobic digestion: Stimulative and inhibitory effects on fermentation’, Bioresource Technology, 269, pp. 143–152. Available at: https://doi.org/10.1016/j.biortech.2018.08.040.

Zhou, J. et al. (2019) ‘Layout optimization of tree-tree gas pipeline network’, Journal of Petroleum Science and Engineering, 173, pp. 666–680. Available at: https://doi.org/10.1016/j.petrol.2018.10.067.

3 Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane

Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane

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Abstract:

A methodology was developed to determine the location and biomethane potential of on-farm biomass feedstocks and furthermore, the quantity of this biomass situated away from an existing gas grid network. The development of decentralised systems which can be integrated with large industry in such locations offers a potential alternative deployment opportunity to centralised gas grid injection. The total biomethane resource from all on-farm feedstocks in a chosen case country (Ireland) was estimated at 67 PJ. Thematic maps were developed to show the quantity of each on-farm feedstock in different regions of Ireland and their distance from the existing gas network. Approximately 17% of the on-farm biomethane resource in Ireland, though in excess of 15 km from the grid, was within a 15 km radius of a large energy user. Two large energy users were presented as case studies, of which their entire heating demand could be met by the on-farm biomethane resource within a 2.5 km radius of each site. Coupling decentralised biomass with large industry users can potentially offer an alternative energy management strategy.

Keywords: Biomethane, on-farm, decentralised, grass silage, slurry, large energy user

3.1 Introduction

3.1.1 Energy demand and emissions

It is projected that global energy consumption will increase by almost 50% from 2018 to 2050; natural gas consumption is also projected to increase by more than 40% in the same period, reaching nearly 58,600 TWh by 2050 (U.S. Energy Information Administration, 2020). Natural gas is considered an important transition fuel toward a decarbonised energy system. Much effort is being made to displace carbon-intensive fossil fuels such as coal with natural gas to reduce carbon dioxide (CO_2) emissions (U.S. Energy Information Administration, 2016). Switching from coal to gas reduces CO_2 emissions by around 40% for each unit of energy output and emits less air pollutants such as $PM_{2.5}$, SO_2 and NO_X (IEA, 2019a). Furthermore, in the US and the EU natural gas currently delivers between 50 to 100% more energy to end-users than the electricity grid, and up to 20% of natural gas demand globally could be provided in a sustainable manner (IEA, 2019b). The Paris Agreement has committed countries to regulate greenhouse gas (GHG) emissions to limit the increase in global average temperature to below 2 °C above pre-industrial levels, and to invest in pathways towards low GHG emissions (UN and UNFCCC, 2015). Bioenergy accounted for 15% (65.73 EJ) of the global final energy demand in 2019, and it has been proposed that at least 125 EJ of bioenergy will be required by 2070 in the Sustainable Development Scenario (IEA, 2020b); an increase of 92%.

Ireland, as an EU Member State, has committed to achieving a 34% share of renewable energy in its final energy consumption by 2030 (Department of Communications Climate Action and Environment, 2020). This obligation is made up of sub-targets: 70% renewable electricity (RES-E), 13.4% renewable energy in transport (RES-T) and 24% renewable heating and cooling (RES-H&C). As of 2018, Ireland had reached 33.2% in RES-E, 7.2% in RES-T and 6.5% in RES-H&C (Department of Communications Climate Action and Environment, 2020). Ireland imports 53% of its natural gas via the UK, with the remainder supplied by domestic gas fields and reserves (Ervia, 2017). Biomethane has been identified as a resource of significant potential in Ireland, however as of yet the industry is very limited (IEA, 2020a). In contrast, 108 biogas plants in the UK produce biomethane and inject to the gas network, and it is projected that the overall biomethane industry could amount to ca. 300 PJ by 2030 (ADBA, 2020). This success is due in part to the

Renewable Heat Incentive (RHI) introduced in the UK. Similar incentives for the Irish biomethane industry are required for the industry to succeed in Ireland (Rajendran, Gallachóir and Murphy, 2019).

The agricultural sector in Ireland accounted for 33.9% of the total annual GHG emissions in 2018, with 9.6% of that coming from manure management (EPA, 2020a). Anaerobic digestion (AD) is a sustainable technology (Lin, Chen, *et al.*, 2011; Lin, Liao, *et al.*, 2011; Lin *et al.*, 2013; Wang *et al.*, 2014), which can not only degrade organic matters, but also reduce GHG emissions from manure management processes and agriculture (Giuntoli *et al.*, 2015), help farms comply with the Nitrates Directive, replace fossil-fuel sourced natural gas in energy systems, and improve Ireland's energy security (Joint Committee on Communication Energy and Natural Resources, 2011; Rajendran, Gallachóir and Murphy, 2019). Ireland's abundance of agricultural resources can be utilised in AD systems to lower GHG emissions in agriculture and contribute to EU renewable energy and emissions targets (Smyth, Murphy and O'Brien, 2009; Wall, O'Kiely and Murphy, 2013; O'Shea, Kilgallon, *et al.*, 2016).

3.1.2 Renewable gas from decentralised biomass

Green renewable gas can have a significant impact on decarbonising future energy systems, particularly in the heat and transport sectors (Wall, Dumont and Murphy, 2018). In 2015, seven European gas transmission system operators signed a joint declaration to providing a carbon-neutral gas supply by 2050 (Green Gas Initiative, 2017). Pathways towards decarbonising natural gas systems include biomass derived biomethane produced thermochemically via gasification, or via the biological process of AD (Speirs *et al.*, 2018). Biomethane has a composition very similar to natural gas, and therefore is well suited to currently existing natural gas infrastructure. However, it is difficult to enter the biomethane market in rural regions with plentiful biomass resources but limited access to the existing gas grid infrastructure. This presents a challenge in delivering the energy to the potential end-users (Smyth, Smyth and Murphy, 2011). In the Irish context, rural resources of biomass can be considered 'decentralised', that is, out of range of gas grid infrastructure to the point where it is logistically challenging and/or uneconomical to utilise. Whilst large amounts of biomethane are planned to be utilised in gas grids across Europe (Green Gas Initiative, 2017), maximising the potential of biomethane

internationally will require the development of ‘decentralised clusters’ away from a gas grid, where biomethane is delivered directly to an end-user. Other European countries which do not rely on gas grid infrastructure, such as Sweden, may have alternative definitions of what biomass may be considered decentralised.

Large energy users (LEUs) that are situated away from the gas grid may benefit from biomethane generated from decentralised biomass within their locality. Such LEUs that are situated away from the gas grid may decarbonise through biomethane generated from decentralised, on-farm biomass in their locality. The potential symbiosis of this coupling and the logistics involved have not been analysed in prior literature and is of interest on a global scale to facilitate the maximum utilisation of a decentralised biomethane resource.

3.1.3 Objectives

The aim of this paper is to assess the decentralised resource of farm-based feedstocks (biomass) suitable for use in AD systems, and furthermore, determine the merit of utilising such biomass for biomethane production through integration with large industrial natural gas users. The innovation in this paper is that it provides a methodology to determine the quantity of wet organic biomass suitable for the production of biomethane located at varying distances from existing gas grid infrastructure that is also within a set distance of a large industry energy user. Previous studies have performed spatial analyses of feedstock (O’Shea, Kilgallon, *et al.*, 2016) and analyses on rural biomass resources (Harahap *et al.*, 2020), but the coupling of decentralised biomethane resources with decentralised LEUs on a national scale, accounting for the distance from existing gas grid infrastructure, has not been reported in scientific literature before to the author’s knowledge. Such a methodology enables the quantification and utilisation of biomass that is considered decentralised, but in proximity to LEUs which are also decentralised.

Bioenergy systems tend to be very geographic specific (IEA Bioenergy: Task 37, 2020). As such, Ireland will be used to exemplify the analysis in this paper. The analysis of Ireland as a region is applicable to temperate oceanic climates with a national gas grid serving the major areas of population. However, the utility of the methodology can be applied to any region in locating decentralised biomass and providing a strategy for the utilisation of such distributed biomass. Ireland has a

limited biomethane industry, and although significant gas grid infrastructure exists, coverage may not be available in more rural regions. Ireland, as a member state of the EU, has also committed to reducing its GHG emissions. Slurry from dairy cows, grass silage, hay and straw were chosen as feedstocks for this assessment owing to their large resource in Ireland, but any biomass feedstock can be applied to the methodology when applied to other regions. The specific objectives of the paper are as follows:

i. Calculate the gross decentralised on-farm biomass resource suitable for use in AD systems in Ireland and its proximity to the national gas grid.
ii. Provide an overview of the logistics of on-farm anaerobic digestion systems.
iii. Locate large energy users (LEUs) in Ireland and calculate how much on-farm biomass resource is located within a range of distances from them.
iv. Present a case study for the integration of decentralised farm biomass with respect to large industry heat users.

3.2 Methodology

3.2.1 Ireland's agricultural feedstocks

3.2.1.1 Dairy slurry

In this work it is assumed that a dairy cow produces 5.84 t_{wwt} of slurry over a 20-week collection period (O'Shea, Kilgallon, *et al.*, 2016). The average dairy farm in Ireland has a herd of 79 cows (Dillon *et al.*, 2019); therefore, the average dairy farm will collect ca. 461.36 t_{wwt} of slurry per annum.

The total dairy slurry resource in terms of wet tonnes (t_{wwt}) was calculated at each electoral division (ED), the smallest region for which such data was available, according to Eq. (3.1). The most recent data on dairy livestock were sourced from the Central Statistics Office (CSO) (CSO, 2020b).

Eq. (3.1); dairy slurry resource per electoral division ($m^{dairy\ slurry}$):

$$m^{dairy\ slurry} = N_{dairy\ cows} S_{dairy\ cows} \tag{3.1}$$

In Eq. (3.1), $m^{dairy\ slurry}$ is the mass of dairy slurry in t_{wwt}, $N_{dairy\ cows}$ is the number of dairy cows in an ED, and $S_{dairy\ cows}$ is the annual slurry production per dairy cow in t_{wwt}.

3.2.1.2 Grass silage

As per the Teagasc "Grass10" initiative, a silage yield of 10 t DM ha^{-1} a^{-1} was assumed for this work. The area of land in each ED under grass silage was sourced from the Central Statistics Office (CSO, 2020b). This study also takes into consideration that grass silage is primarily grown for livestock consumption, and only silage surplus to feeding requirements is considered available for AD, as not to disturb agricultural feeding systems. The total consumption of grass silage per ED was calculated using figures for livestock grass silage consumption per head (McEniry *et al.*, 2013) as per Table 3-1. The total grass silage requirement per ED was then subtracted from the theoretical grass silage yields (as per the Teagasc Grass10 initiative, (Teagasc, 2020)) per hectare.

The CSO data available did not break down the categories of livestock "Other Cattle" and "Other Sheep" into further detail at ED level. However, McEniry *et al.* (2013) provided a table of national figures for all livestock types, and their silage requirements. This table was adapted to show the national ratios of each kind of

livestock in the relevant categories (Table 3-1). These ratios were then applied to the relevant categories at ED level.

CSO Category	Animal category	% Total (of category)	Silage Consumption (t DM head^{-1})
-	Dairy Cows	100%	1.495
-	Other Cows	100%	1.738
-	Bulls (Breeding Only)	100%	1.738
Other Cattle	Cattle male: 2 years and over	8%	0.141
	Cattle female: 2 years and over	9%	0.785
	Cattle male: 1-2 years	16%	1.274
	Cattle female: 1-2 years	21%	0.785
	Cattle male: under 1 year	22%	0.678
	Cattle female: under 1 year	24%	0.653
-	Ewes: lowland and upland	100%	0.089
-	Rams	100%	0.08
Other Sheep	Other sheep > 1 year	25%	0.08
	Other Sheep (mainly lambs)	75%	0.032

Table 3-1: Livestock numbers and silage requirements.

An example calculation using this table to determine the livestock types per ED is presented in Appendix A.1.

After subtracting the silage requirement from the theoretical grass silage yields (as per the Grass10 initiative) per hectare, the remaining grass silage is considered 'surplus' and represents the available source of feedstock in this work, as shown in Eq. (3.2). If a "negative" surplus silage is generated in a particular ED, it was assumed that there was no surplus silage in that ED.

Eq. (3.2); surplus grass silage resource per ED ($m^{surplus\ silage}$):

$$m^{surplus\ silage} = A_{silage} * Y_{silage}^{Grass10} - \left(\sum (N_\theta * M_\theta^{silage,req.})\right) \qquad (3.2)$$

In Eq. (3.2), $m^{surplus\ silage}$ is the mass of surplus silage in t DM, A_{silage} is the area in hectares per ED that is under grass silage, $Y_{silage}^{Grass10}$ is the silage yield in t DM ha^{-1}, N_θ is the number of livestock of each type and $M_\theta^{silage,req.}$ is the silage requirement in t DM for the different livestock (θ represents the different livestock types as outlined in Table 3-1). As the grass silage mass is calculated on a t DM basis, the t_{wwt} mass may be found by dividing the t DM mass by the DS % of the silage (see Table 3-3).

3.2.1.3 Hay

The area of land in each ED used to harvest hay was sourced from the CSO (CSO, 2020b). As per McEniry *et al.* (2013), the hay yield used in this work is 8 t DM ha^{-1} a^{-1}, and for each ED, the number of hectares under hay was multiplied by this yield to give the theoretical hay production.

Eq. (3.3) summarises the hay production per ED (m^{hay});

$$m^{hay} = A_{hay} * Y_{hay} \tag{3.3}$$

where m^{hay} is the mass of hay in t DM, A_{hay} is the total area under hay in hectares in the ED and Y_{hay} is the hay yield in t DM ha^{-1}. The hay mass is calculated on a t DM basis, the t_{wwt} mass may be found by dividing the t DM mass by the DS % of the hay (see Table 3-3).

3.2.1.4 Straw

See Table 2-1 for the characteristics of wheat, barley, and oat straws as reported in the literature. Winter crops (denoted by *W.*) of wheat, barley, and oats become available for harvest from July to August. The Spring sown crops (denoted by *S.*) become available in late August to the end of September. Further details can be found in Table 2-1 and Table 2-2. The CSO data only provides the area in hectares under cereal crops in each ED and does not provide information at an ED level as to how many hectares are of a certain type of cereal. However, information on the different cereals planted in each region of the country is considered (CSO, 2020a). This data was used to create Table 3-2, showing the ratio of each cereal in each region, and applied at an ED level to give an approximation of how much of each cereal was being harvested.

	Northern and Western		**Southern**			**Eastern and Midland**	
Cereal Ratios by Region	**Border**	**West**	**Mid-West**	**South-East**	**South-West**	**Mid-East & Dublin**	**Midland**
W. Wheat	12.50%	5.13%	17.62%	12.84%	12.26%	38.45%	14.53%
S. Wheat	2.08%	2.56%	0.95%	1.17%	1.91%	1.58%	1.04%
W. Barley	33.33%	25.64%	40.95%	24.38%	34.60%	32.67%	31.14%
S. Barley	41.67%	46.15%	29.52%	50.97%	43.60%	18.91%	45.67%
W. Oats.	4.17%	5.13%	7.62%	7.26%	3.81%	6.62%	4.50%
S. Oats	6.25%	15.38%	2.86%	2.98%	3.81%	1.37%	2.42%
Other Cereals	0.00%	0.00%	0.48%	0.39%	0.00%	0.42%	0.69%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 3-2: Ratio of cereals harvested per region.

An example calculation using this table to determine the cereal crops harvested in an ED is presented in Appendix A.2.

Eq. (3.4) summarises the cereal straw production of each cereal type per ED (m_{straw}^{ω});

$$m_{straw}^{\omega} = A_{total\ cereals} * Y_{straw}^{\omega} * R_{\%}^{\omega} \quad (3.4)$$

where m_{straw}^{ω} is the mass of each cereal straw type in t DM, $A_{total\ cereals}$ is the total area in hectares under all cereal crops in the ED, $Y_{straw}^{\omega}$is the straw yield of each cereal type in t DM ha^{-1}, and $R_{\%}^{\omega}$ is the percentage of the ED that is under each cereal type (where ω represents each cereal type as per Table 2-2 and Table 3-2). As the cereal straw mass is calculated on a t DM basis, the t_{wwt} mass may be found by dividing the t DM mass by the DS % of the cereal straw (see Table 3-3).

3.2.2 Profile of on-farm AD plants

3.2.2.1 Parasitic energy demand

Often in on-farm AD systems, the biogas produced from the plant is used to provide the heat and/or electricity necessary for the plant to operate, unless the electricity is sourced from the grid. Thermal energy is required to bring the feedstocks and plant itself from ambient temperature to the desired temperature inside the digester. In this work, it is assumed that only the feedstock needs to be brought to the desired digester temperature and not the plant, as each AD plant is different and at this level of analysis the individual heating demands would be unknown.

Eq. (3.5), is used to calculate the parasitic thermal demand (Q_{AD}) in kJ to bring feedstocks to the desired digester temperature (t_{Hi});

$$Q_{AD} = (m_{wwt} * MC_{\%}) * C_pH_20 * (t_{Hi} - t_{Low}) \quad (3.5)$$

where m_{wwt} is the total mass of the feedstock in t_{wwt}, $MC_{\%}$ the water content of the feedstock, C_pH_20 is the specific heat capacity of water and t_{Low} the ambient ground temperature. The water content percentage of the feedstock may be determined by subtracting the DS % of the feedstock (see Table 3-3) from 100%.

3.2.3 Energy end-use and on-farm AD plant development

Most often, on-farm use of biogas is hampered by the lack of thermal demand on Irish farms and the low tariffs available for electricity production. Biogas could also

be transported for direct use at a LEU. This could be achieved through biogas pipelines to the LEU offering a method of industry decarbonisation. Another promising option is that the biogas will be upgraded to produce biomethane; the upgrading method applied can either be centralised, decentralised, or mobile (Gil-Carrera *et al.*, 2019). As Irish farms generally lack thermal demand, this work considers exporting either the biogas or biomethane from the farm to LEUs. Wind energy provides a lot of renewable electricity to Ireland, whereas there is very limited penetration of renewable energy in the transport and industry heating sectors. Biomethane for the purpose of transport would most likely be serviced around the gas grid, therefore in this paper, off-grid industry heating is considered a valuable target for decentralised biogas and biomethane. The biomass could also be transferred to a LEU and used as feedstock in an on-site AD plant (O'Shea, Wall and Murphy, 2017), or from decentralised areas to AD plants near the gas grid – however, this would incur significant transport costs in the transportation of the feedstocks over large distances, especially feedstocks of high water content such as slurry. This work then suggests, to negate such transport costs, that on-farm AD be employed and the resultant biogas/biomethane brought to the LEUs. However, it is important that the large energy user has a sufficient heat demand and is also willing to use biogas/biomethane.

Figure 3-1 presents a flow-diagram that includes for all stages of consideration in developing an on-farm AD plant. In Figure 3-1, the path towards biogas/biomethane use by a LEU (green box) accounts for the different aspects of on-farm AD that will be analysed in detail in this paper. Furthermore, GIS analysis will be conducted on the location of the feedstocks and large energy users. The components of Figure 3-1 in the red box identify areas of potential future research, whereby the actual logistics of getting biomethane to the end user (by truck or pipeline) and the cost of undertaking this would be considered. Nonetheless, the local production and use of renewable gas in decentralised areas can potentially allow for greater utilisation of suitable biomass located away from the gas grid.

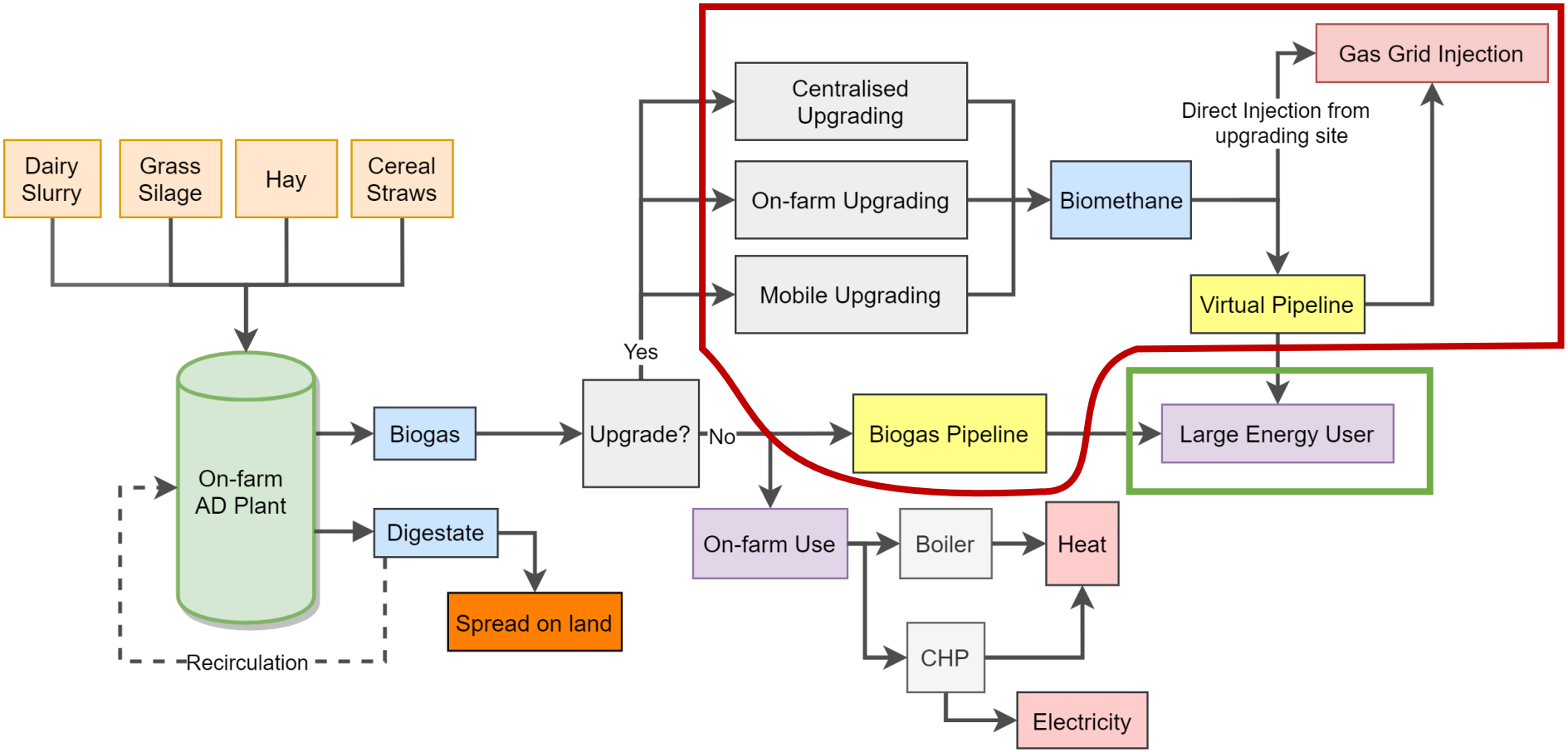


Figure 3-1: Flow diagram of on-farm AD logistical considerations.

3.2.4 GIS mapping

3.2.4.1 Development of bioresource maps

A GIS was developed to show the biomethane resource of the above-mentioned feedstocks per ED in Ireland. Data for each of the 3409 EDs in Ireland were collected from shapefiles provided by the Central Statistics Office (CSO, 2016) and input into QGIS, a free GIS mapping software. The co-ordinate reference system used was IRENET95 / Irish Transverse Mercator.

The latest agricultural census in Ireland was conducted in 2010. Agricultural data were acquired from the CSO on the 30th of June 2020 for 2828 out of 3409 electoral divisions (ED) in the country. Some EDs have no farms, and data were not provided for EDs with less than 10 farms to preserve privacy. The data have figures detailing the hectares of land under grass silage, hay, and cereals, and also has livestock figures for dairy cows, bulls, other cattle, and other livestock. Equations (3.1) - (3.4), in conjunction with the information in Table 3-3, were used to calculate the biomethane resource from dairy slurry, surplus grass silage, hay and cereals straws per ED, in a method similar to O'Shea *et al.* (2016).

The location of the gas grid in Ireland was mapped by superimposing an image of the existing gas grid (Gas Networks Ireland, 2020) onto the ED shapefile in QGIS (

Figure 3-2). A shapefile of EPA (Environmental Protection Agency, Ireland) IPC (Integrated Pollution Control) licenced facilities in Ireland was acquired from the EPA (Figure 3-3) (EPA, 2020b). The aim of IPC licences is to ensure that facilities prevent or reduce air, water and land emissions, reduce waste and use energy and resources efficiently (EPA, 2020c). Facilities provided in the shapefile that were not in a licensing category or that are no longer operating were excluded from the study. The IPC licensed facilities were identified as potential LEUs which could use biogas or biomethane produced from the feedstocks assessed in this work.

3.2.4.2 Feedstock data for resource mapping

Table 3-3 shows the feedstock characteristics used for the GIS mapping analysis. The DS, VS and biomethane potential yields for wheat, barley and oat straw used in this study were taken as the median values of that reported in the literature. The methane yield of the winter (*W.)* and summer (*S.)* straws were assumed to be identical. For the "other cereals" dataset included in the CSO files, a DS content of

85%, VS content of 80%, and a methane potential yield of 200 L CH_4 kg^{-1} VS was assumed.

Feedstock	DS ($\%_{wwt}$)	VS ($\%_{wwt}$)	Biomethane potential (L CH_4 kg^{-1} VS)	Methane Yield (m^3 CH_4 t_{wwt}^{-1})	Sources
Dairy Slurry	8.4	6.2	143	8.9	(Wall *et al.*, 2014; O'Shea *et al.*, 2016)
Grass Silage	29.3	26.8	400	107.4	(Wall, O'Kiely and Murphy, 2013)
Hay	87	82	156	127.9	(Allen *et al.*, 2016)
W. Wheat Straw	88.9	83.4	278.5	232.3	
S. Wheat Straw	88.9	83.4	278.5	232.3	
W. Barley Straw	89	87.8	220	193.2	Median value of ranges (see Table 2-1)
S. Barley Straw	89	87.8	220	193.2	
W. Oats Straw	89.9	86	261.5	224.9	
S. Oats Straw	89.9	86	261.5	224.9	
Other Cereals	85	80	200	160	Assumed for this study

Table 3-3: Feedstock characteristics.

3.2.4.3 Identification of decentralised regions

To identify locations with decentralised biomass, buffer zones were created around the gas grid and the potential LEUs, in steps of 2.5 km radii, up to 25 km. The biomass resource in the EDs outside the gas grid buffer zones were calculated, to determine the amount of resource located away from the gas grid at a set distance (km). Using the LEU buffer zones, the biomass resource within the EDs in the buffer zones was calculated, to determine the amount of resource within a given distance of the LEUs. Figure 3-4 and Figure 3-5 show the buffer zones created around the gas grid and the LEUs. Ten radii increasing from 2.5 km to 25 km in 2.5 km steps were created – for clarity, only three radii are displayed in the figures. The GIS software allows for the exportation of .csv files containing only the EDs that are either within or outside the buffer zones. By varying the size (km radii) of the buffer zones around the gas grid and LEUs through the GIS software, it was possible to export multiple .csv files of differing buffer zone combinations and containing different EDs, and therefore determine the biomethane resource beyond a given distance from the gas grid, but within a given distance of a LEU. An origin destination matrix was developed through Excel based on the .csv files to identify which combination of distances from the gas grid and LEUs maximised the use of biomass resources, and therefore would indicate the resource to be considered decentralised. See Appendix A.3 for a summarised step-by-step methodology process.

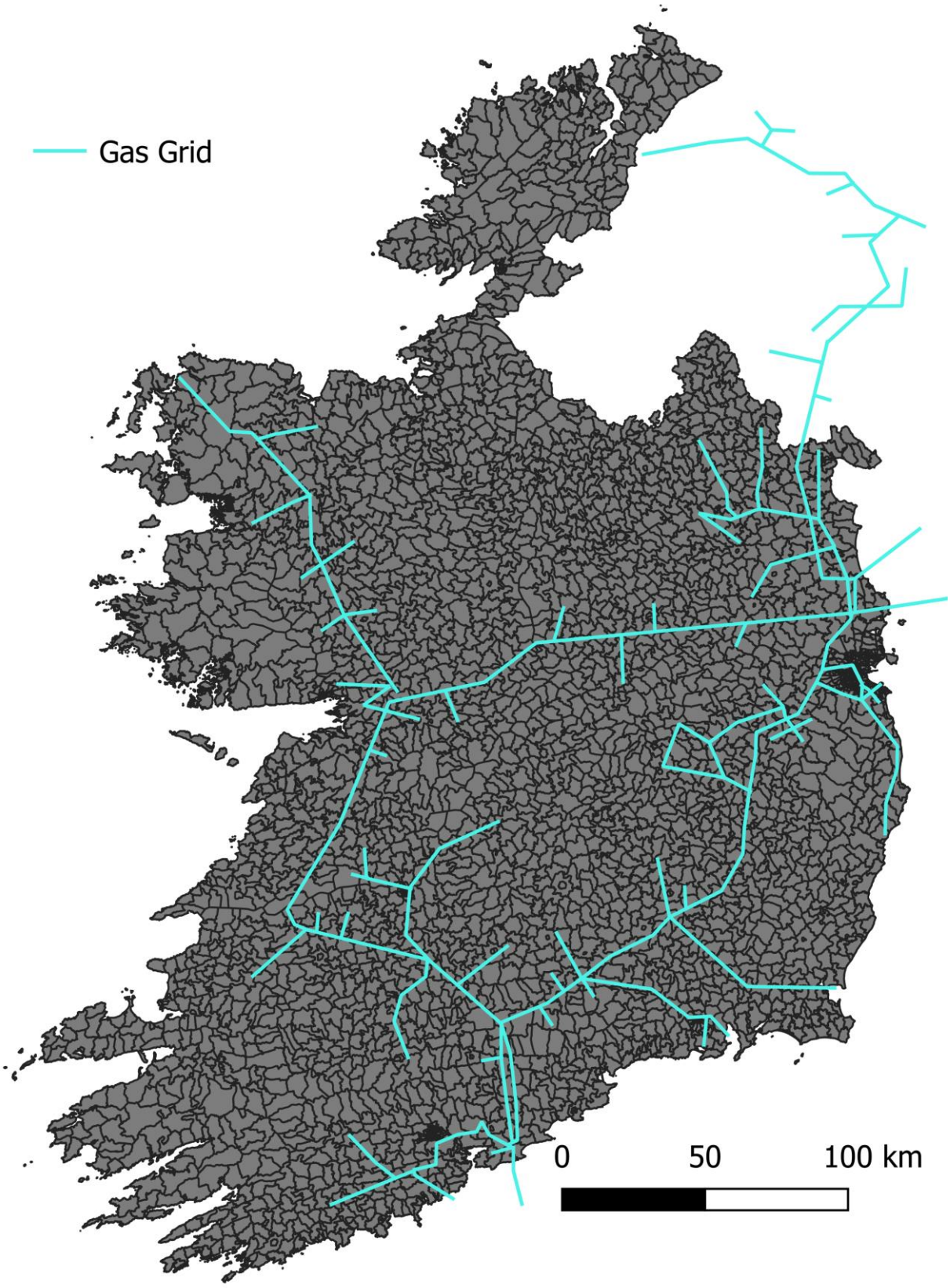


Figure 3-2: Existing gas grid network.

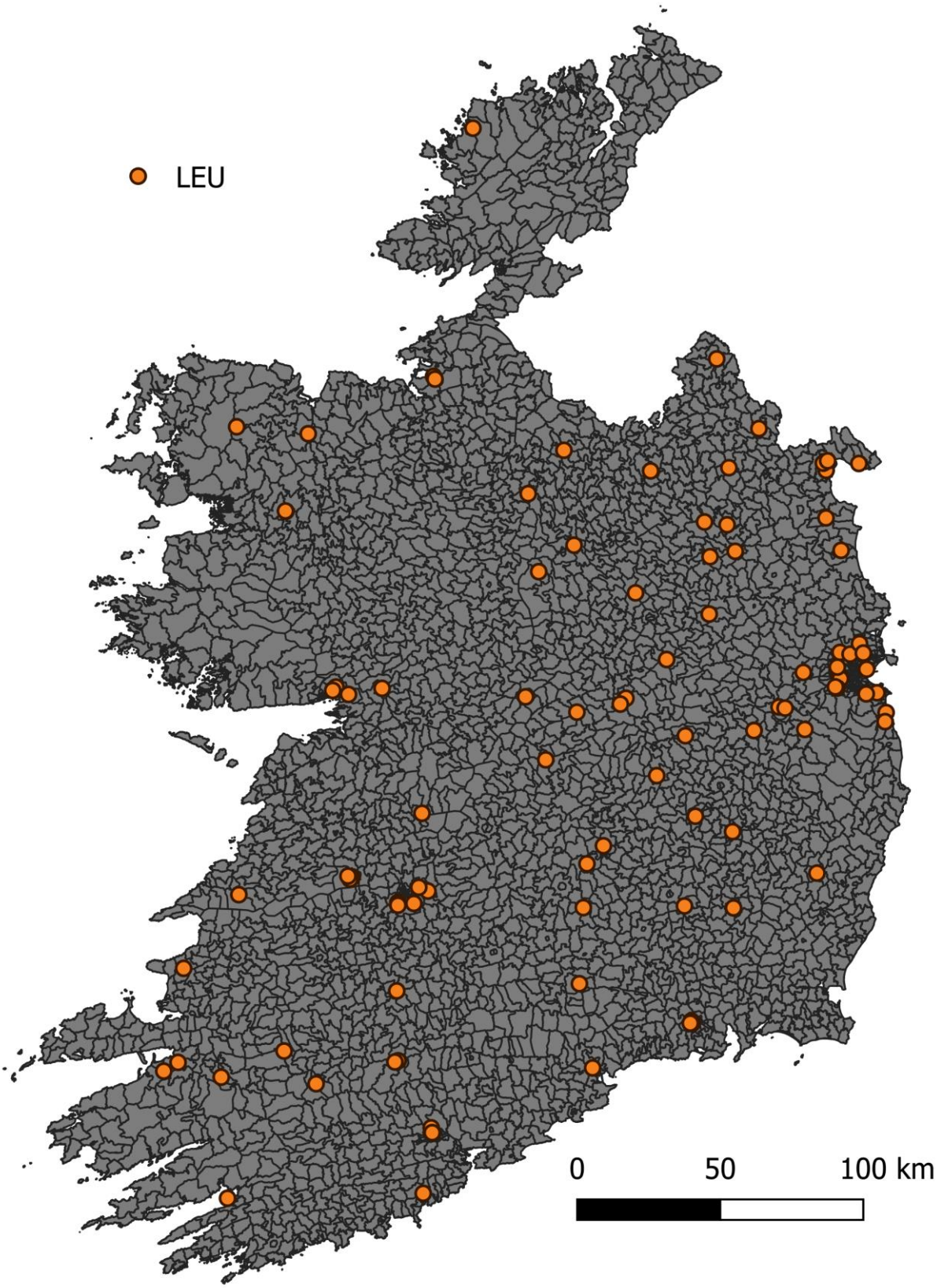


Figure 3-3: Location of LEUs.

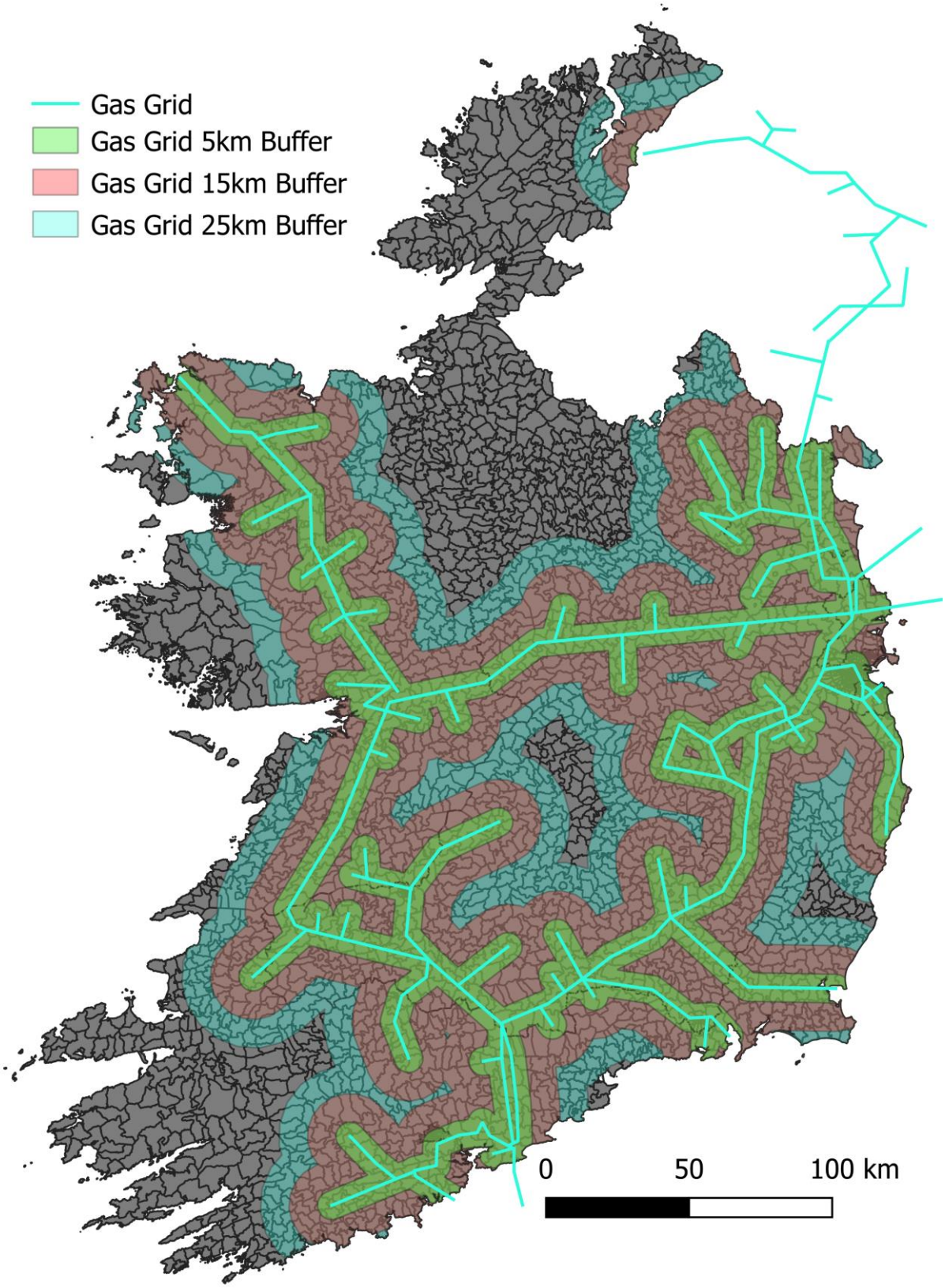


Figure 3-4: Buffer zones created around gas grid.

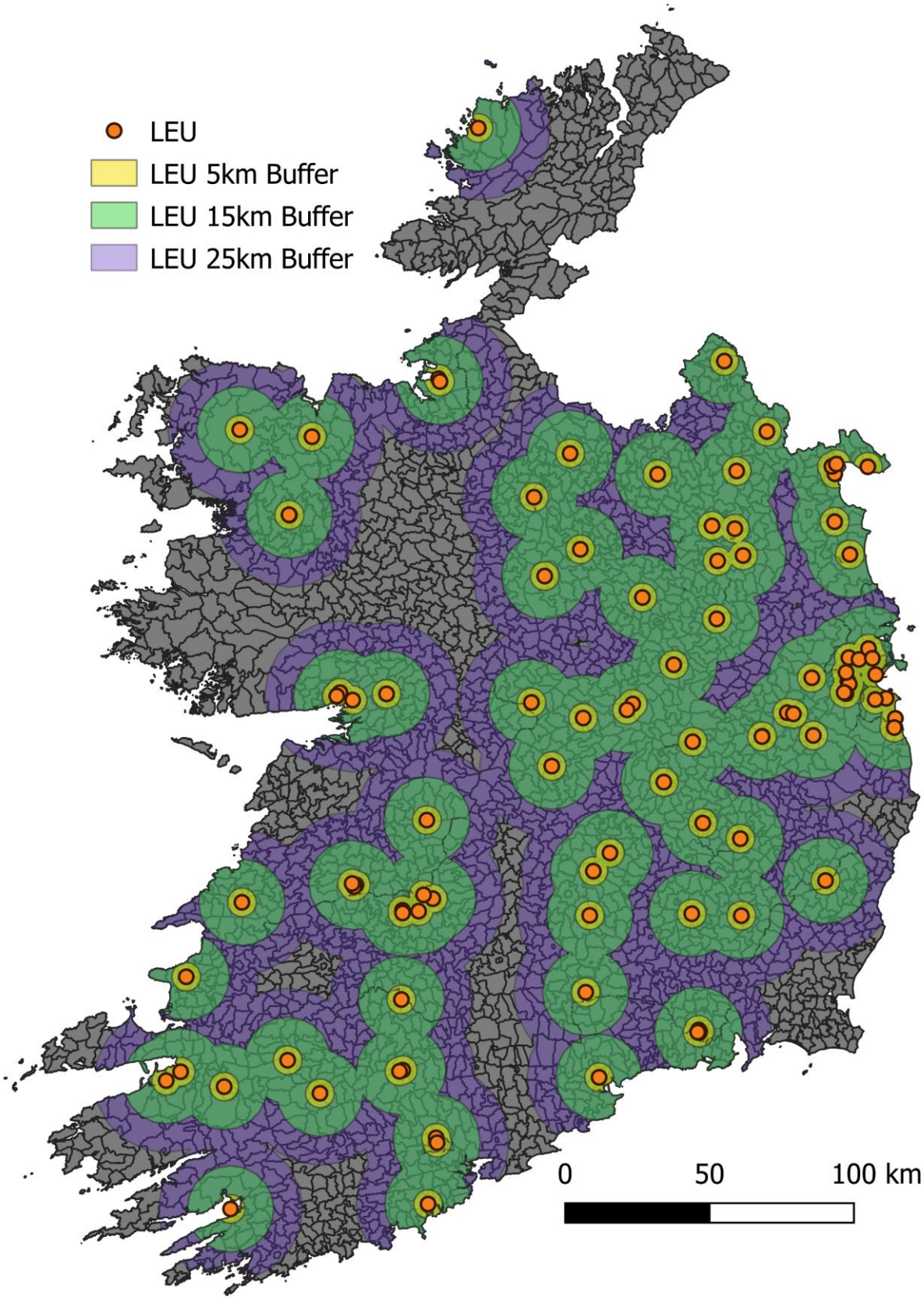


Figure 3-5: Buffer zones created around LEUs.

3.3 Results

3.3.1 Energy resource and location of on-farm feedstocks

Table 3-4 shows the gross theoretical biomethane resource available from dairy slurry, surplus grass silage, hay, and cereal straws in the study region. The largest gross resource of biomethane by far is from grass silage, representing 72.1% of the available resource. Hay, cereal straws, and slurry account for much lower proportions of the total biomethane resource at 12.8%, 11.9% and 3.1% respectively. Figure 3-6 shows four GIS maps of the gross biomethane resource with respect to each on-farm feedstock in each ED in in the study region (Ireland). Figure 3-7 shows the combined gross theoretical biomethane resource that considers a culmination of all on-farm feedstock in Ireland. A Sankey diagram illustrating the feedstock and produced gas flows can be found in Appendix A.4.

Feedstock	**Tonnes Dry Matter (t DM a^{-1})**	**Gross Biomethane Resource (Mm^3 CH_4 a^{-1})**	**Gross Biomethane Resource (PJ a^{-1})**	**% of resource (%)**
Dairy Slurry	520,699	55.6	2.1	3.1%
Silage	10,737,120	1,277.7	48.3	72.1%
Hay	1,544,776	227.1	8.6	12.8%
W. Wheat Straw	211,080	211	2.1	3.1%
S. Wheat Straw	9,717	2.5	0.1	0.1%
W. Barley Straw	303,025	65.7	2.5	3.7%
S. Barley Straw	299,210	64.9	2.5	3.7%
W. Oats Straw	66,773	16.7	0.6	0.9%
S. Oats Straw	25,081	6.3	0.2	0.4%
Other Cereal Straws	2,950	0.6	0.02	0.03%
Total	**13,720,430**	**1,772.4**	**67.0**	**100.0%**

Table 3-4: Total theoretical biomethane resource from selected feedstock.

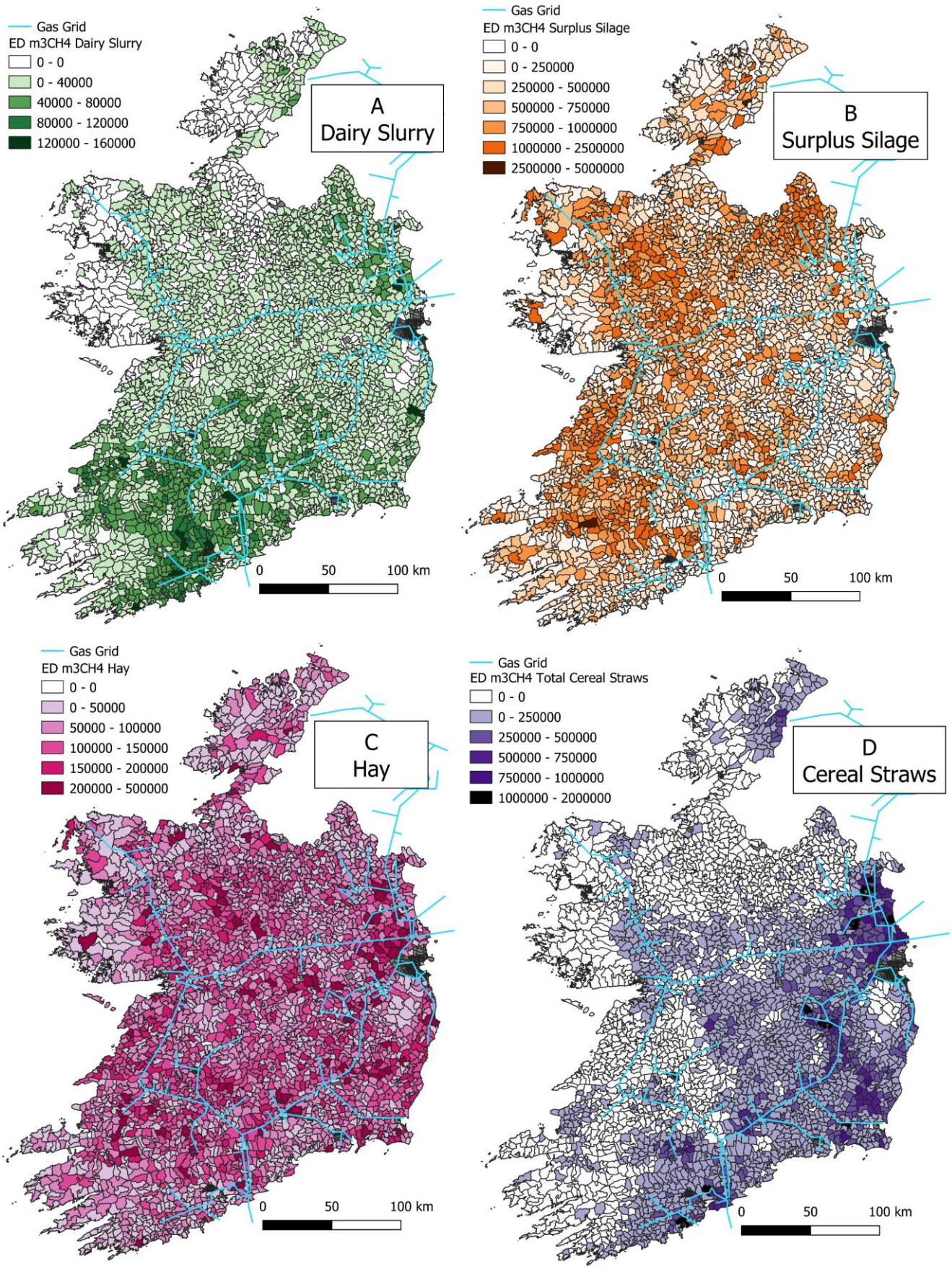


Figure 3-6: Gross biomethane resource from A) dairy slurry, B) surplus grass silage, C) hay, D) cereal straw, per ED.

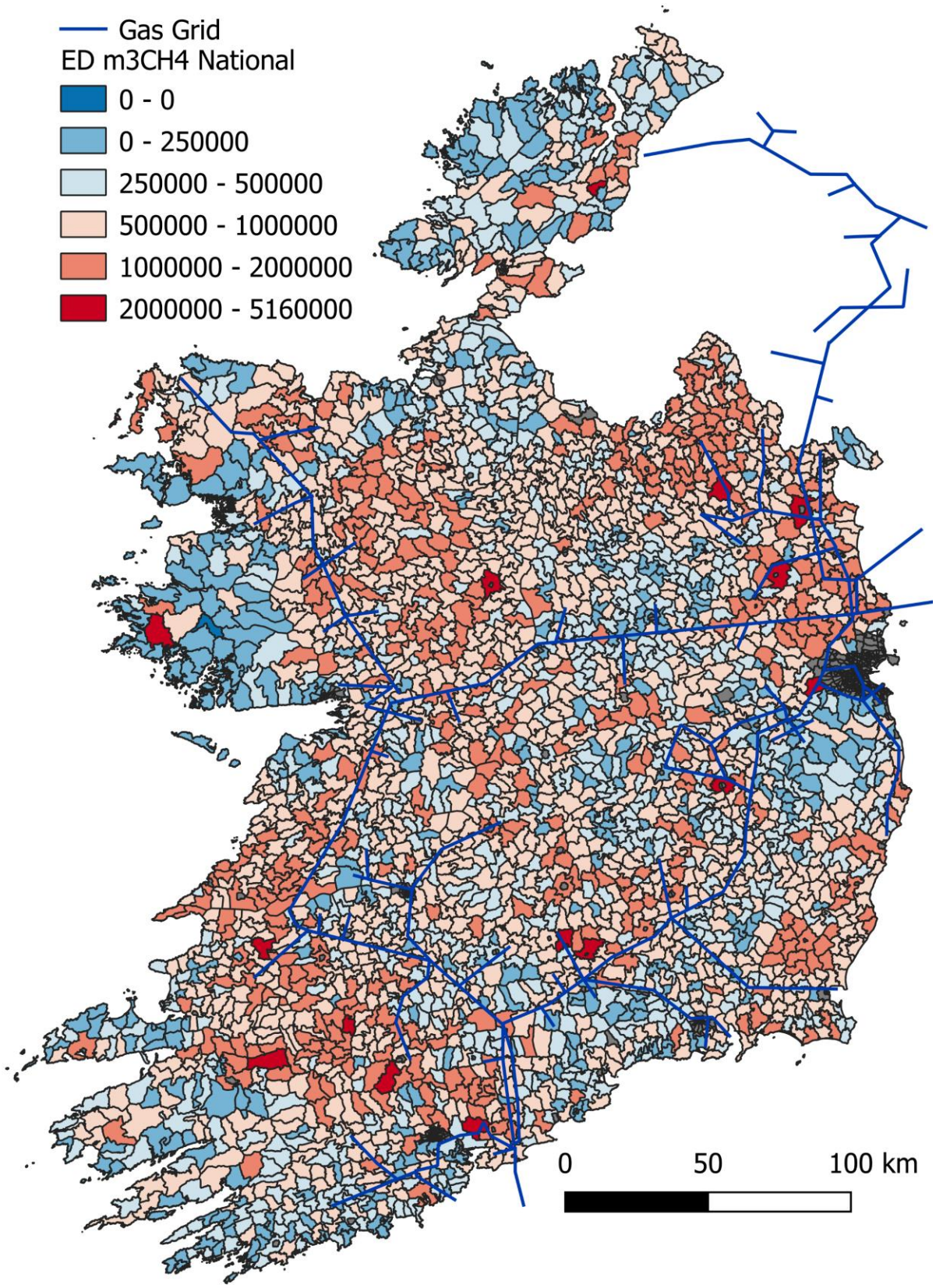


Figure 3-7: Gross on-farm biomethane resource from all on-farm feedstocks.

3.3.2 Identification of decentralised zones

Figure 3-8 shows the gross biomethane resource located outside 2.5 km intervals of the gas grid. Over 56% of the national biomethane resources associated with these feedstocks is more than 5 km away from the national gas grid, and over 29% is more than 15 km away from the grid.

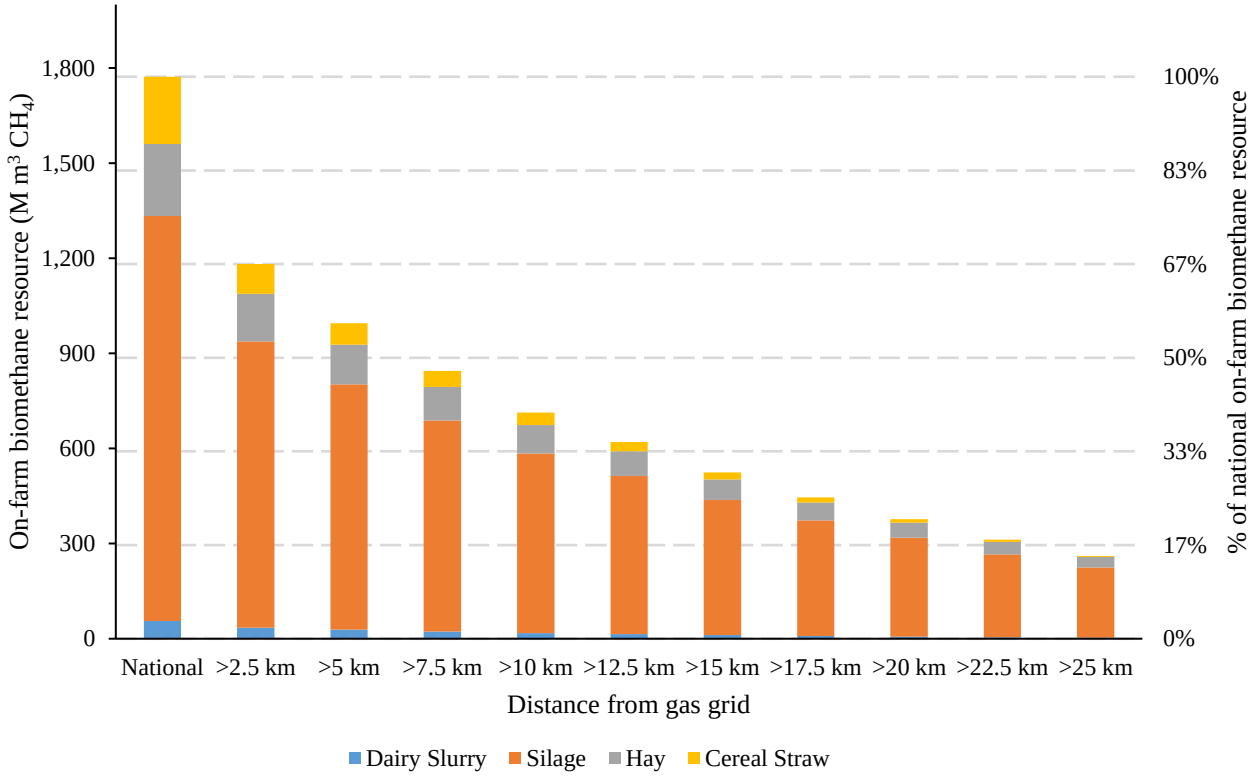


Figure 3-8: Gross theoretical on-farm biomethane resource vs. distance from natural gas grid.

Using the various buffer zones generated (as stated in section 2.4.3 and shown in Figure 3-4 and Figure 3-5), an origin destination matrix was developed as per Table 3-5, which indicates the percentage of the theoretical on-farm biomethane resource that could be captured at various distances away from the gas grid and within a specific distance of a LEU. Furthermore, the origin destination matrix allows for the assessment of on-farm biomass that is closer to a LEU than the existing gas grid and which could be potentially used for energy at the LEU.

Distance within LEU	2.5 km	5 km	7.5 km	10 km	12.5 km	15 km	17.5 km	20 km	22.5 km	25 km
25 km										11.19%
22.5 km									12.75%	10.36%
20 km								14.40%	11.82%	9.56%
17.5 km							16.31%	13.49%	10.99%	8.78%
15 km						17.31%	14.75%	12.28%	10.05%	7.87%
12.5 km					17.31%	14.62%	12.49%	10.27%	8.42%	6.44%
10 km				16.06%	14.24%	12.25%	10.52%	8.61%	7.03%	5.16%
7.5 km			12.69%	11.15%	10.01%	8.69%	7.38%	6.13%	4.85%	3.63%
5 km		9.72%	8.20%	7.42%	6.60%	5.69%	4.66%	3.91%	3.06%	2.42%
2.5 km	5.66%	4.50%	3.83%	3.54%	3.20%	2.82%	2.36%	1.90%	1.68%	1.39%

Distance from gas grid

Table 3-5: Origin destination matrix of percentage of national gross biomethane resource at distances from gas grid and within distances of LEUs.

An equivalent percentage of the national on-farm biomethane resource can be found at the following combination of distances: EDs within 12.5 km of LEUs and greater than 12.5 km away from the gas grid, and also EDs within 15 km of LEUs and greater than 15 km away from the gas grid. The biomethane resource that is within 15 km of LEUs and greater than 15 km away from the gas grid was chosen for analysis in this work as the resource is further away from the grid. This resource represents 17.31% (equivalent to 11.6 PJ a^{-1}) of the national gross on-farm biomethane resource. This combination of distances is an effective determination of what biomethane resource can be considered decentralised. A GIS map was subsequently developed to illustrates this decentralised biomethane resource (Figure 3-9). Furthermore, Table 3-6 shows the theoretical biomethane resource in the EDs which fit this specific distance criteria.

Feedstock	**Decentralised Biomethane Resource**		
	(M m^3CH_4 a^{-1})	**(TJ a^{-1})**	**(%)**
Dairy Slurry	8.5	321.5	2.8%
Surplus Silage	243.8	9,212.4	79.5%
Hay	37.8	1,427.2	12.3%
Cereal Straws	16.7	630.9	5.4%
Total	**306.8**	**11,592**	**100%**

Table 3-6: Gross biomethane resource more than 15 km from the gas grid and also within 15 km of a LEU

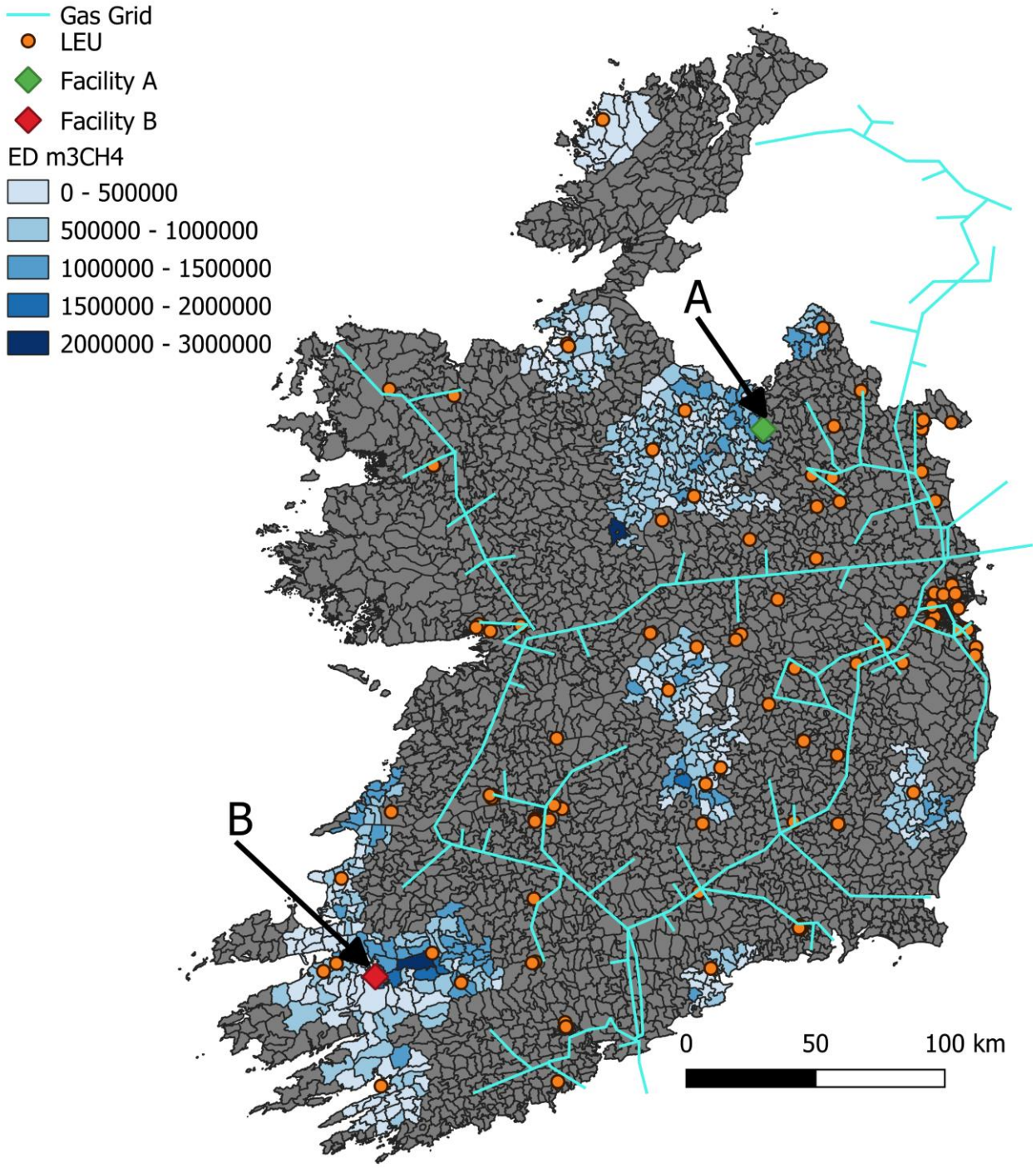


Figure 3-9: Gross biomethane resource in EDs more than 15 km from the gas grid and within 15 km of a LEU.

3.3.3 Selection of LEU case studies

Two LEUs were identified for further analysis based on their decentralised biomass availability – Facility A in Co. Cavan, and Facility B in Co. Kerry (Figure 3-9). Facility A falls under EPA IPC Licence category 3.9.*: "Boiler making and the manufacture of reservoirs, tanks and other sheet metal containers where the production area exceeds 500 square metres"* and Facility B falls under category 12.2.2.: *"The manufacture or use of coating materials in processes with a capacity to make or use at least 10 tonnes per year of organic solvents, and powder coating manufacture with a capacity to produce at least 50 tonnes per year"*. IPC licenced facilities are required to submit Annual Environmental Reports (AERs) to the EPA. These reports have data on the resources consumed by the facility each year. Further details on the AERs of facilities A and B can be found in Appendix A.5. It was evident that both facilities consumed substantial amounts of LPG (liquid petroleum gas) and/or kerosene annually. Table 3-7 shows the fuel consumed by the two facilities in 2019. It is proposed that biomethane may be a beneficial vector to decarbonise the processes in both facilities. However, Facility A and Facility B sites are situated 19 km and 36 km away from the existing gas grid, respectively. Thus, the fuel consumption in Table 3-7 was compared to the biomethane resource from on-farm feedstock in the surrounding EDs. A parasitic electrical demand of 10 $kw_e h\ t_{wwt}^{-1}$ of feedstock was assumed, to calculate the net biomethane resource available. Parasitic thermal demands were calculated as per Eq. (3.5), assuming that the feedstocks must be brought from 10 °C (ambient ground temperature) to 35 °C (mesophilic). The energy content of biomethane was assumed to be 37.78 MJ Nm^{-3}.

Fuel Consumption in 2019

Facility A	**(GJ)**
LPG*	26,906.67
Facility B	**(GJ)**
LPG*	9,431.87
Kerosene	7,762.61
Facility B Total	***17,194.48***

*LPG is assumed to be propane, butane, or a mix of the two.

Table 3-7: Resources consumed by Facility A and Facility B in 2019.

Figure 3-10 shows Facility A and the surrounding EDs within 15 km. As per the criteria in Table 3-5, no EDs within 15 km of the gas grid were included. Table 3-8 shows the net biomethane resource available within 2.5 km increments of Facility A. From the analysis, it is projected that Facility A could replace its entire thermal

energy consumption (26,906.67 GJ) with the biomethane resource available in a 2.5 km radius from the site.

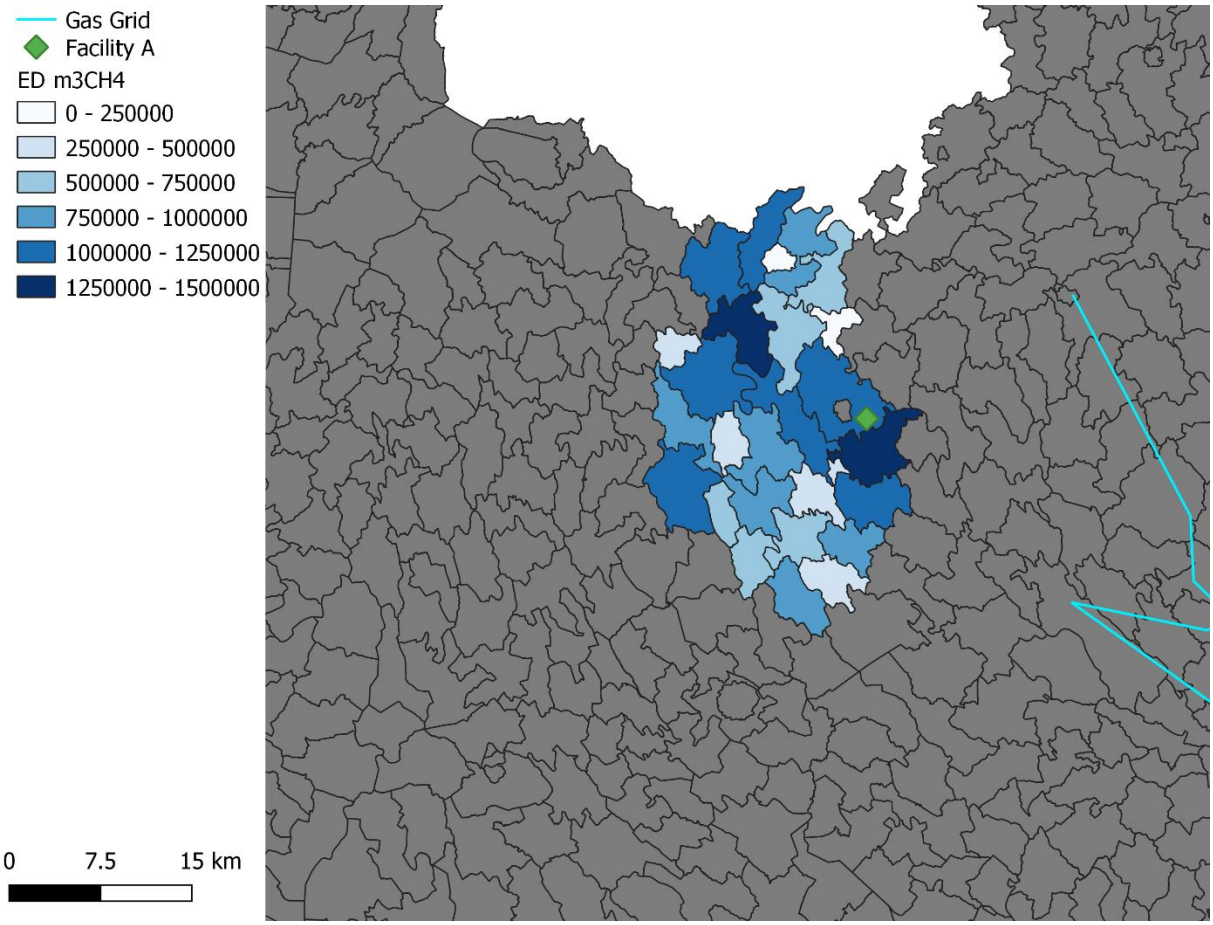


Figure 3-10: Facility A and gross biomethane resource in surrounding decentralised EDs.

Distance from Facility A	Dairy Slurry (GJ)	Surplus Silage (GJ)	Hay (GJ)	Cereal Straws (GJ)	Total (GJ)
<2.5 km	1,337.79	79,557.84	6,465.59	0.00	87,361.22
<5 km	3,914.13	159,675.77	16,185.98	0.00	179,775.88
<7.5 km	4,755.78	215,760.73	23,663.19	113.57	244,293.27
<10 km	6,978.25	397,384.66	40,245.02	141.96	444,749.89
<12.5 km	7,489.93	459,272.34	47,150.45	141.96	514,054.68
<15 km	9,695.67	651,184.34	75,431.92	141.96	736,453.89

Table 3-8: Net biomethane resource from feedstock in EDs within certain distances of Facility A.

Figure 3-11 shows Facility B and the surrounding EDs within a 15 km radius. As per the criteria in Table 3-5, no EDs within 15 km of the gas grid were considered in this resource. Table 3-9 shows the net biomethane resource available within 2.5 km increments of Facility B. Once again, it is found that the biomass available in the surrounding EDs within 2.5 km of Facility B could replace its entire annual heating energy consumption (17,194.48 GJ) with the generated biomethane.

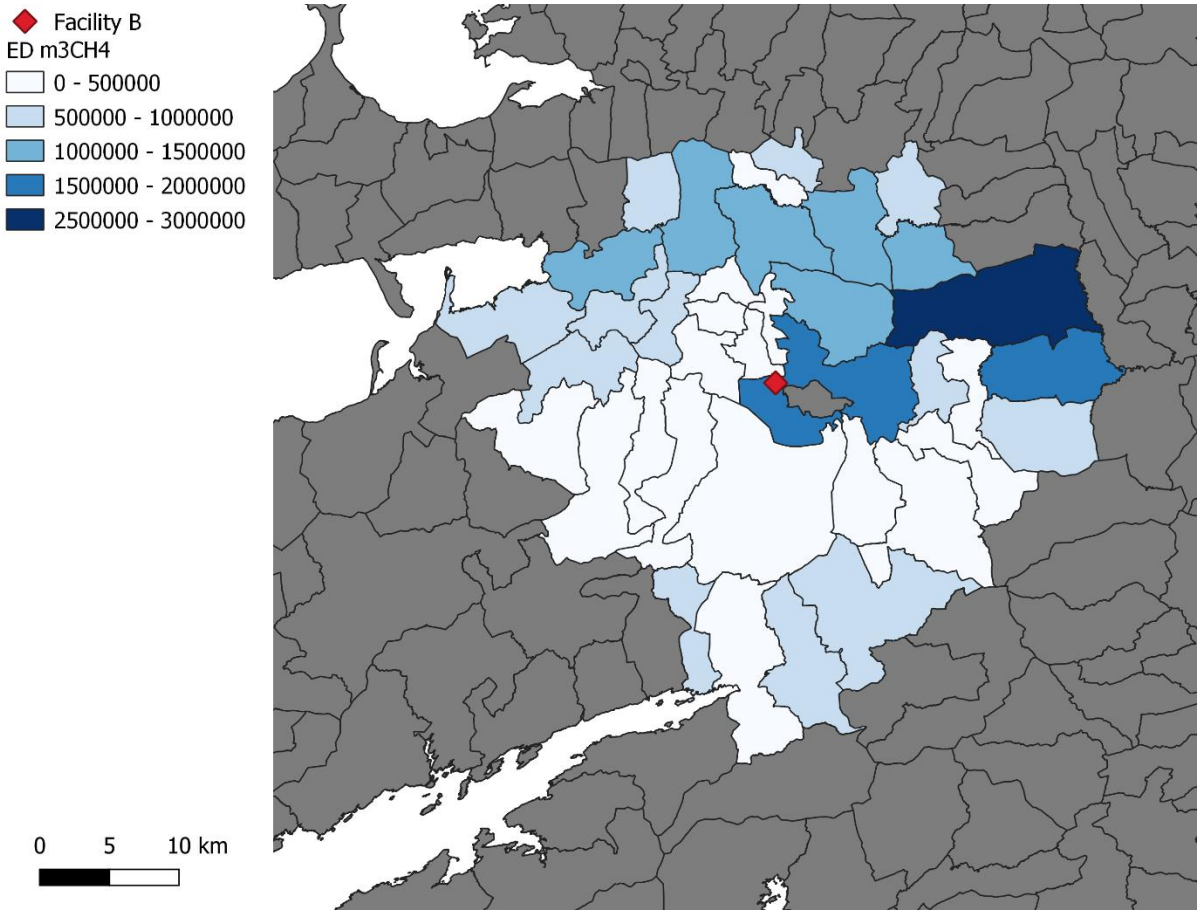


Figure 3-11: Facility B and gross biomethane resource in surrounding decentralised EDs.

Distance from Facility B	Dairy Slurry (GJ)	Surplus Silage (GJ)	Hay (GJ)	Cereal Straws (GJ)	Total (GJ)
<2.5 km	2,809.47	66,893.78	13,546.96	310.43	83,560.64
<5 km	4,183.13	126,181.19	22,563.60	310.43	153,238.34
<7.5 km	7,945.43	207,466.44	31,932.11	1,015.95	248,359.94
<10 km	14,364.17	449,919.09	64,831.87	1,693.26	530,808.39
<12.5 km	18,584.36	583,785.46	80,270.12	1,806.14	684,446.08
<15 km	25,041.36	826,734.74	113,345.81	1,862.58	966,984.49

Table 3-9: Net biomethane resource from feedstock in EDs within certain distances of Facility B.

The results above suggest a local, secure energy supply that promotes the decarbonisation of large industry and offers a strategy for maximising the utilisation of renewable gas nationally. In terms of end-of-pipe emissions savings, it is estimated that Facility A could reduce its carbon footprint by as much as ca. 322 t CO_2 a^{-1} by switching fuel to biomethane sourced from local on-farm biomass. Similarly, Facility B could reduce their emissions by ca. 268 t CO_2 a^{-1}. Further details on this calculation, and emissions intensity figures for LPG, kerosene and biomethane, can be found in Appendix A.6.

3.4 Discussion

3.4.1 On-farm feedstocks

Grass silage is the feedstock which provides the highest biomethane potential in the country, well in excess of other on-farm feedstocks. Surplus grass silage accounts for 48.3 PJ or 72.1% of the gross biomethane resource available. This grass is considered surplus to livestock requirements so should not affect the provision of feed to livestock in the region. Using slurry as a co-substrate with grass in AD would be a potential win-win for farmers, lowering emissions from slurry management, assisting in compliance with the Nitrates Directive, and improving the digestion process by introducing essential micronutrients. The resultant digestate can be considered another benefit to the farmer replacing the need for chemical fertiliser and reducing carbon footprint.

The gross theoretical biomethane resource associated with the feedstock in this study equates to 67 PJ a^{-1}, equivalent to over 200% of industrial gas use (33 PJ a^{-1}), or 82.1% of total natural gas final energy consumption (SEAI, 2018). The gross national biomethane resource was calculated as opposed to the net national resource as ideally, gas would be exported as a valuable commodity with a high exergy. To satisfy the required parasitic demands of the AD process, other sources of heat with lower exergy than biomethane such as wood chips would be used. Furthermore, the electricity requirement for biogas production may be supplied from wind farms, to minimise the carbon footprint and cost of the AD plant.

Over 56% of the identified biomethane resource was identified as being more than 5 km away from the gas grid network; over 14% of it is located over 25 km away from the grid which may be a significant barrier to the renewable gas industry based on gas grid injection going forward. Previous literature has discussed the potential for biomethane industries in Ireland based on numerous feedstocks, however the distance of the resource from the gas grid is a logistical challenge that must also be considered. Similar difficulties are faced in other regions with distributed biomass supplies globally.

The analysis presented in this study highlights that the majority of the national dairy slurry resource is in the south of Ireland (Figure 3-6A). Dairy slurry accounts for 2.1 PJ, or just over 3% of the gross on-farm biomethane resource available, equivalent to

just over 6% of natural gas usage per annum in Irish industry. Half of this dairy slurry resource is more than 5 km away from the gas grid, and only 6.2%, or 130.8 TJ, is available over 25 km away from the grid. Given the low DS content, and therefore energy density, of dairy slurry, this decentralised resource would prove logistically challenging to transport to a digester located at or near the gas grid, due to the associated costs. This logistical challenge would be abated if the slurry and AD plant were co-located. Then, the challenge lies in getting the gas to the grid or to an energy user, with longer distances increasing the cost. Evident in Figure 3-6B is that the majority of surplus silage is available in the west and southwest of Ireland. Areas that have a high resource of dairy slurry (thus more dairy cows) and are less likely to have a surplus of grass silage once livestock fodder requirements are met – whether surplus grass silage is available along with a farm's dairy slurry is a factor that must be considered in the planning of on-farm AD systems. Approximately 60.5% of the grass silage resource available nationally is more than 5 km away from the gas grid, and 17.5% (8.2 PJ) is available over 25 km away from the grid. This amount is not insignificant, and is equal to 24.8% of the natural gas demand in industry (SEAI, 2018).

As per Figure 3-6C, hay is harvested in all regions of Ireland. Hay accounts for 8.6 PJ of the gross biomethane resource available. As per Figure 3-8, 55.4% of the hay resource available nationally is more than 5 km away from the gas grid, and 14.8%, or over 1.3 PJ, is available over 25 km away from the grid. Hay is primarily used as livestock feed – whether farmers have the potential to harvest consistent supplies of surplus hay to use for AD is an issue which should be considered. Hay is generally not considered for AD due to its other uses and its low biomethane potential compared to other grass feedstocks, such as grass silage. However, it is considered in this work to evaluate all options of common on-farm feedstock.

As evident in Figure 3-6D, cereal straw resources are generally found in the south-east of Ireland. Cereal straws account for 8 PJ of the gross biomethane resource available. As seen in Figure 3-8, 32% of cereal straw resources available nationally are more than 5 km away from the gas grid, and only 1.25%, or 100.4 TJ, are available over 25 km away from the grid. Generally, cereal straws are used for livestock bedding and fodder (sometimes known as chaff). It has been proposed that at least 80,000 t DM a^{-1} of cereal straws (8.7% of the total cereal straws resource)

could be utilised for energy production (Teagasc, 2018). However, most of the biomethane resource from cereal straws is located near the gas grid (Figure 3-6D and Figure 3-8), suggesting that perhaps the use of straw as an AD feedstock is best suited to centralised AD plants situated near the grid.

Although hay and cereal straws theoretically represent more of the gross on-farm biomethane resource than dairy slurry, there are other benefits to dairy slurry digestion (emissions savings in agriculture, digestate utilisation, and adhering to nitrates limitations) that make it a more valuable AD feedstock. Cereal straws and hay also have many practical uses outside of AD, making their availability as an AD feedstock more challenging. Hay and cereal straws are woody crops with high DS % (see Table 3-3), which may be more suited to gasification than AD.

In terms of the total potential resource from all combined feedstocks assessed in the study region, ca. 60% of the resource is located within 10 km of the natural gas network. The remaining 40% of the potential resource which is located beyond 10 km from the gas grid could be more difficult from an economic perspective to use in AD plants located near the gas network. Additionally, the increased number of vehicle movements required for the transportation of remote feedstock to AD plants near the gas grid can reduce the environmental sustainability of AD plants and increase objections by members of the public. Identification of novel methods for using this decentralised resource is therefore required.

3.4.2 Origin destination matrix

The origin destination matrix (Table 3-5) reveals the extent of gross biomethane resource that is decentralised but also within the vicinity of a potential LEU. For EDs more than 2.5 km away from the gas grid, 5.66% (3.79 PJ a^{-1}) of the national gross biomethane resource is within 2.5 km of a LEU. For EDs more than 25 km away from the gas grid, 11.19% (7.5 PJ a^{-1}) of the national gross biomethane resource is within 25 km of a LEU, and 1.39% (0.93 PJ a^{-1}) is within 2.5 km of a LEU. This origin destination matrix may be used to assess a specific combination of resources and distances applicable to specific decentralised LEUs and thus can be considered a very useful tool.

The combination of distances focused on in this work were 15 km away from the grid and within 15 km of a LEU. This decentralised resource, 17.31% of the national

on-farm gross biomethane resource (equivalent to 11.6 PJ a^{-1}), is equivalent to 35% of industrial natural gas use, or 14.22% of the national total final natural gas consumption. This decentralised resource can allow for AD industries to become established away from the gas grid, with LEUs as potential consumers of biomethane.

This use of biomethane in LEUs provides a means for industry decarbonisation whilst also providing a demand for decentralised biogas systems. A similar utilisation strategy can be applied in any region globally where there is a decentralised resource of biomass suitable for use in AD. If Ireland is to meet its RES-H&C targets for 2030, the onus will be on industries to decarbonise. This origin destination matrix shows that there is a significant resource of on-farm biomass, located away from the gas grid, which if utilised could prove beneficial in the national effort to decarbonise and fulfil regional EU emissions obligations. The introduction of incentives and policy instruments (such as subsidies, carbon tax increases, renewable gas certificates, or renewable heat incentives) to replace fossil fuels with biomethane, should enable the biomethane industry to aid in this endeavour (Khatiwada *et al.*, 2016; Rajendran, Gallachóir and Murphy, 2019). The work presented herein can inform policy makers on the potential for decentralised biomethane deployment.

3.4.3 Case studies

Both case studies present an analysis which can be applied to any LEU in the study region to assess the quantity of on-farm feedstocks in range of the facility. Depending on the LEU and/or the required feedstocks in its vicinity, a smaller or larger distance may be required to fulfil the energy demand of the LEU. Closer distances would also generally result in less complex logistics and lower transportation costs.

Facility A could fulfil its entire thermal demand with biomethane resources in the EDs within 2.5 km. However, 98.5% of the resource in a 2.5 km radius of the facility is from either surplus grass silage or hay. Dairy slurry alone in a 15 km radius of the facility could supply 36% of the facility's thermal demand. Facility B could also fulfil its entire thermal demand with biomethane resources in the EDs within 2.5 km. However, 96.3% of the resource in a 2.5 km radius of the facility is from either

surplus grass silage or hay. Dairy slurry alone in a 12.5 km radius of the facility could supply over 108% of the facility's thermal demand. Whilst the parasitic heating demand in this work calculates only the heat demand needed to heat the feedstock and not the plant itself, the results in this work shows that there is an abundance of resource available near the LEUs, indicating that there is more than enough energy available to also account for the heating of the plant.

Using dairy slurry alone would be the easiest logistically for the farmers near both facilities – slurry is already being collected by farmers and can easily be mono-digested. However, as detailed in section 2.2.2, there are multiple benefits to co-digestion, aside from the fact that grass silage has a much higher biomethane yield per tonne of wet feedstock (Table 3-3). The temporal availability of slurry must also be considered since it is only collected in Ireland over a 16 to 20-week period. Thus, there may be periods of the year where a digester would have limited slurry availability and the composition of the feedstock would change (higher quantities of grass for example). Using grass silage alone, whilst possible, would prove operationally difficult (Thamsiriroj, Nizami and Murphy, 2012). The high-solids content of grass silage would also prove a logistical challenge. Hay presents a significant source of biomethane for both facilities – however, this hay is generally used as livestock feed and is unknown how much of it would be in surplus. There is relatively little biomethane available from cereal straws for both facilities – the use of this cereal straw in other sectors (such as mushroom compost) may also mean that it is unavailable as an AD feedstock.

Delivering this energy from on-farm anaerobic digesters to the LEUs could be undertaken in a number of ways. If the desired end goal was to deliver biogas to these two facilities without upgrading, this could be done via biogas pipeline from farms in the locality directly to the facilities. However, this could be challenging due to the cost and would only potentially be feasible at very short distances. Alternatively, if these facilities required biomethane, a biogas grid could provide biogas from the surrounding farms to one centralised upgrading facility, such as is done in Wijster in the Netherlands (IEA Bioenergy: Task 37, 2017). Another option would be to construct an AD plant near each facility and bring the local on-farm biomass to the site (O'Shea, Wall and Murphy, 2017).

A mobile biogas and upgrading technology as proposed by Gil-Carrera *et al.* (2019) could also provide these facilities with biomethane via a truck complete with upgrading and compression mechanisms travelling from farm to farm and to end user in a calculated schedule to minimise storage at each site and optimise the system. This would avoid the costs and disruption incurred by pipeline installation. Alternatively, if the end-users do not require biomethane in the long term or phase out their use of natural gas over time, this mobile-upgrading facility could transport the biomethane to another end-user or to a gas grid injection facility, serving as a potential insurance policy against a business change by the end-user for the farmers that invest in AD plants. Potential further research could be conducted into the specific logistics in bringing biomethane resources to LEUs in Ireland, be it pipeline or via truck transport.

Both Facility A and Facility B could make substantial end-of-pipe CO_2 emissions savings by switching their fuel use to biomethane (see Appendix A.6). This serves as an example of how industries and communities located away from the gas grid network may contribute to decarbonisation and RES targets. Other LEUs that use fuels with higher specific CO_2 emissions per GJ than LPG and kerosene, such as gasoline or heavy fuel oil (71 and 75 kg CO_2 GJ^{-1}, respectively), could potentially make even more significant CO_2 savings by utilising local on-farm biomass for energy production. The savings calculated in this study only account for that made by burning the different fuels, the wider externalities of renewable gas and specifically AD must also be considered. Such benefits include improved manure management, less pollution of waterways, pathogen reduction, odour reduction and a method of sustainable waste treatment. However, it must also be considered that a switch of heat source at these facilities may involve a change in infrastructure and thus account for an additional capital cost initially. A full techno-economic analysis would be required to assess the exact financial implications for each facility and relay the potential economic benefits for both sectors (industrial and agricultural).

There are also considerations to be made with regards to using on-farm crop feedstocks for renewable heat. Current EU emissions savings targets in the RED recast (European Parliament and European Commission, 2018) state that the criteria for biomethane for heat are more stringent than that for transport fuels. When biomethane is used as a transport fuel, end-of-pipe emissions are considered to be

zero. These criteria may encourage the use of biomethane for transport as oppose to heat, particularly when the biomethane is sourced from mono-digested grass silage or other crops (Long and Murphy, 2019). However, emissions credits are applicable to slurry, therefore co-digesting slurry with crops becomes important in making biomethane for heat a sustainable option (Guintoli *et al.*, 2017). Further considerations must also be made with regards to the sustainable supply of biomass for biomethane production; overutilisation of crops as a source of biomethane may lead to practices detrimental to the environment (Beausang, McDonnell and Murphy, 2021).

3.4.4 Application of methodology to other regions

In this paper, Ireland is presented as an example region with a decentralised biomethane resource, however the methodology presented is universal and may be applied to any region. The data necessary to conduct such analyses is the spatially explicit feedstock data, the sites of potential large energy users, and, if desired, the location of the gas grid infrastructure for a region. In the absence of any gas grid infrastructure, the proximity of biomass resources to large industry energy can still be determined. The heat demands of the industry sites are necessary to calculate the potential for offset onsite fossil fuel consumption (as per section 3.3). In essence, the methodology is universal and should be used to identify and develop integrated renewable gas clusters for decentralised areas. The application of this method will allow for the development of integrated strategies which can maximise the use of decentralised feedstocks suitable for biogas production via AD. This can aid in the decarbonisation of LEUs and can maximise the positive externalities such as sustainable waste treatment and improve manure management practices within the region being assessed.

3.4.5 Limitations of work

What constitutes as decentralised is ambiguous and may differ from country to country. In Ireland's example, the national gas grid network correlates well with developed urban areas, and so in this case it makes sense to classify areas away from the gas grid as decentralised. A limitation of this work then would be the applicability of classifying decentralised areas based on gas grid infrastructure, as other countries may have a more widespread gas grid coverage, or not use gas grid networks at all. However, the methodology in this work applies irrespective of

whichever infrastructural metric is used to measure decentralisation against. Whilst this work identifies areas of decentralised biomass resource that is suitable for AD, the logistics and economics of the utilisation of such biomass is not considered. This is a significant research gap which should be addressed by future work, and indeed the authors of this work intend to do so. The techno-economic viability of the utilisation of decentralised biomass for AD will be paramount to the industry's success. The methodology chosen in this work may lead to significant variation in results if different silage yields, slurry production, and/or biomethane yields from the feedstocks are used. Other analyses which focus simply on livestock numbers and land availability may provide more specific and less variable results.

3.5 Conclusion

Decentralised biomass can include for on-farm resources such as grass and slurries. This paper illustrates that significant portions of such biomass (and the associated biomethane resource) can be situated away from existing gas grid infrastructure, as evidenced by the study region (Ireland). If such resources are to be used for energy decarbonisation purposes, alternative end uses to gas grid injection must be considered. Large industry energy users could decarbonise their thermal energy use by switching from fossil fuels to biomethane sourced from decentralised biomass using an integrated cluster approach. The origin destination matrix developed in this analysis shows that the largest biomethane resource (17.31% of the national resource) can be captured at 15 km away from the grid but within 15 km of a large energy user. Such a methodology can be applied to any region globally to maximise the use of the resource of decentralised renewable gas and to aid industrial decarbonisation. Two case studies are presented in the paper demonstrating that the thermal energy demands of large energy users' may be easily met by biomethane produced via localised biomass conversion. Quantifying the available resource only answers whether there is enough biomass or not to potentially support an AD industry in a given area. The key considerations in establishing decentralised biomethane industries will involve meeting the logistical and operational challenges. The specifics of how biogas could be brought from the farms to the large energy users, either via pipeline or truck transport, or whether the wet organic feedstock could be brought to a digester constructed near the LEU, must be analysed. Future research is necessary to analyse these logistical and operational challenges, such as upgrading pathways and biomethane delivery options.

References

ADBA (2020) Biomethane: The Pathway to 2030. Available at: https://adbioresources.org/newsroom/report-biomethane-the-pathway-to-2030/ (Accessed: 29 July 2021).

Allen, E. et al. (2016) 'A detailed assessment of resource of biomethane from first, second and third generation substrates', Renewable Energy, 87, pp. 656–665. Available at: https://doi.org/10.1016/j.renene.2015.10.060.

Beausang, C., McDonnell, K. and Murphy, F. (2021) 'Assessing the environmental sustainability of grass silage and cattle slurry for biogas production', Journal of Cleaner Production, 298, p. 126838. Available at: https://doi.org/10.1016/j.jclepro.2021.126838.

CSO (2016) Census 2016 Small Area Population Statistics. Available at: https://www.cso.ie/en/census/census2016reports/census2016smallareapopulationstatistics/ (Accessed: 1 July 2020).

CSO (2020a) Crops and livestock. Routledge. Available at: https://www.cso.ie/en/releasesandpublications/er/clsjf/cropsandlivestocksurveyjunefinal2019/ (Accessed: 11 August 2020).

CSO (2020b) Databases - CSO - Central Statistics Office. Available at: https://www.cso.ie/en/databases/ (Accessed: 13 October 2020).

Department of Communications Climate Action and Environment (2020) National Energy & Climate Plan. Available at: https://www.gov.ie/en/publication/0015c-irelands-national-energy-climate-plan-2021-2030/# (Accessed: 7 September 2020).

Dillon, E. et al. (2019) Teagasc National Farm Survey 2018 Results. Available at: https://www.teagasc.ie/publications/2019/teagasc-national-farm-survey-2018-results.php (Accessed: 2 December 2020).

EPA (2020a) Agriculture - Environmental Protection Agency. Environmental Protection Agency (EPA). Available at: http://www.epa.ie/ghg/agriculture/ (Accessed: 22 July 2020).

EPA (2020b) Geo Portal. Available at: http://gis.epa.ie/GetData/Download (Accessed: 26 August 2020).

EPA (2020c) Integrated Pollution Control (IPC) Licensing, Environmental Protection Agency (EPA). Environmental Protection Agency (EPA). Available at: https://www.epa.ie/licensing/ipc/ (Accessed: 8 September 2020).

Ervia (2017) A look at the Irish Gas Market. Available at: https://www.gasnetworks.ie/corporate/company/our-network/irish-gas-market-overview/A-Look-at-the-Irish-Gas-Market.pdf (Accessed: 17 July 2020).

European Parliament and European Commission (2018) ‘Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)’, Official Journal of the European Union, 61, pp. 82–209.

Gas Networks Ireland (2020) Pipeline map. Available at: https://www.gasnetworks.ie/corporate/company/our-network/pipeline-map/ (Accessed: 16 January 2019).

Gil-Carrera, L. et al. (2019) ‘Feasibility study of an off-grid biomethane mobile solution for agri-waste’, Applied Energy, 239(January), pp. 471–481. Available at: https://doi.org/10.1016/j.apenergy.2019.01.141.

Giuntoli, J. et al. (2015) Solid and gaseous bioenergy pathways: input values and GHG emissions. Available at: https://doi.org/10.2790/299090.

Green Gas Initiative (2017) Biomethane - Naturally Green Gas. Available at: https://www.greengasinitiative.eu/upload/contenu/ggi-biomethane_report_062017_1.pdf (Accessed: 17 July 2020).

Guintoli, J. et al. (2017) Solid and gaseous bioenergy pathways : input values and GHG emissions. Calculated according to the methodology set in COM(2016) 767 (EUR 27215). Available at: https://doi.org/10.2790/27486.All.

Harahap, F. et al. (2020) ‘Meeting the bioenergy targets from palm oil based biorefineries: An optimal configuration in Indonesia’, in Applied Energy. Elsevier Ltd, p. 115749. Available at: https://doi.org/10.1016/j.apenergy.2020.115749.

IEA (2019a) The Role of Gas in Today’s Energy Transitions, The Role of Gas in Today’s Energy Transitions. Available at: https://doi.org/10.1787/ba7ee64f-en.

IEA (2019b) World Energy Outlook 2019, World Energy Outlook 2019. Paris: OECD. Available at: https://doi.org/https://doi.org/https://doi.org/10.1787/caf32f3b-en.

IEA (2020a) Energy Policies of IEA Countries: Ireland 2019 Review. Paris. Available at: https://www.iea.org/reports/energy-policies-of-iea-countries-ireland-2019-review (Accessed: 7 September 2020).

IEA (2020b) Energy Technology Perspectives 2020, Energy Technology Perspectives 2020. Available at: https://doi.org/10.1787/ab43a9a5-en.

IEA Bioenergy: Task 37 (2017) GREEN GAS HUB: Provision of biogas by farmers by pipe to a Green Gas Hub with a centralised upgrading process. Available at: https://www.ieabioenergy.com/blog/publications/green-gas-hub-provision-of-biogas-by-farmers-by-pipe-to-a-green-gas-hub-with-a-centralised-upgrading-process/.

IEA Bioenergy: Task 37 (2020) Integration of Anaerobic Digestion into Farming Systems. Available at: https://doi.org/10.1002/bbb.2134.

Joint Committee on Communication Energy and Natural Resources (2011) The Development of Anaerobic Digestion in Ireland. Available at: https://www.ifa.ie/wp-content/uploads/2013/10/Development-of-AD-in-Ireland-Oireachtas-Report-2011.pdf (Accessed: 16 January 2019).

Khatiwada, D. et al. (2016) 'Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil', Renewable Energy, 85, pp. 371–386. Available at: https://doi.org/10.1016/j.renene.2015.06.009.

Lin, H., Chen, J., et al. (2011) 'Feasibility evaluation of submerged anaerobic membrane bioreactor for municipal secondary wastewater treatment', Desalination, 280(1–3), pp. 120–126. Available at: https://doi.org/10.1016/j.desal.2011.06.058.

Lin, H., Liao, B.Q., et al. (2011) 'New insights into membrane fouling in a submerged anaerobic membrane bioreactor based on characterization of cake sludge and bulk sludge', Bioresource Technology, 102(3), pp. 2373–2379. Available at: https://doi.org/10.1016/j.biortech.2010.10.103.

Lin, H. et al. (2013) 'A review on anaerobic membrane bioreactors: Applications, membrane fouling and future perspectives', Desalination. Elsevier B.V., pp. 169–188. Available at: https://doi.org/10.1016/j.desal.2013.01.019.

Long, A. and Murphy, J.D. (2019) 'Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range of sources for renewable heat and or transport?', Renewable and Sustainable Energy Reviews, 115, p. 109347. Available at: https://doi.org/10.1016/j.rser.2019.109347.

McEniry, J. et al. (2013) 'How much grassland biomass is available in Ireland in excess of livestock requirements?', Irish Journal of Agricultural and Food Research, 52(1), pp. 67–80. Available at: http://www.jstor.org/stable/23631018.

O'Shea, R. et al. (2016) 'Quantification and location of a renewable gas industry based on digestion of wastes in Ireland', Applied Energy, 175, pp. 229–239. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2016.05.011.

O'Shea, R., Wall, D.M. and Murphy, J.D. (2017) 'An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network', Applied Energy, 208, pp. 108–122. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2017.10.045.

Rajendran, K., Gallachóir, B.Ó. and Murphy, J.D. (2019) The Role of Incentivising Biomethane in Ireland Using Anaerobic Digestion. Available at: https://www.epa.ie/publications/research/waste/research-279-the-role-of-incentivising-biomethane-in-ireland-using-anaerobic-digestion.php.

SEAI (2018) 2018 National Energy Balance. Available at: https://www.seai.ie/data-and-insights/seai-statistics/key-publications/national-energy-balance/ (Accessed: 15 September 2020).

Smyth, B.M., Murphy, J.D. and O'Brien, C.M. (2009) 'What is the energy balance of grass biomethane in Ireland and other temperate northern European climates?', Renewable and Sustainable Energy Reviews, 13(9), pp. 2349–2360. Available at: https://doi.org/10.1016/j.rser.2009.04.003.

Smyth, B.M., Smyth, H. and Murphy, J.D. (2011) 'Determining the regional potential for a grass biomethane industry', Applied Energy, 88(6), pp. 2037–2049. Available at: https://doi.org/10.1016/j.apenergy.2010.12.069.

Speirs, J. et al. (2018) 'A greener gas grid: What are the options', Energy Policy, 118, pp. 291–297. Available at: https://doi.org/10.1016/j.enpol.2018.03.069.

Teagasc (2018) Straw for Energy. Available at: https://www.teagasc.ie/media/website/publications/2018/Teagasc-A4-Energy-Fact-Sheet-No.-12-Straw-for-Energy_2pp.pdf (Accessed: 28 August 2020).

Teagasc (2020) Grass10. Available at: https://www.teagasc.ie/crops/grassland/grass10/ (Accessed: 27 August 2020).

Thamsiriroj, T., Nizami, A.S. and Murphy, J.D. (2012) 'Why does mono-digestion of grass silage fail in long term operation?', Applied Energy, 95, pp. 64–76. Available at: https://doi.org/10.1016/j.apenergy.2012.02.008.

U.S. Energy Information Administration (2016) 'International Energy Outlook 2016', DOE/EIA-0484, pp. 202–586. Available at: www.eia.gov (Accessed: 17 July 2020).

U.S. Energy Information Administration (2020) International Energy Outlook 2019.

UN and UNFCCC (2015) Paris Agreement, 21st Conference of the Parties of the UNFCCC. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (Accessed: 31 July 2019).

Wall, D.M. et al. (2014) 'Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry', Bioresource Technology, 173, pp. 422–428. Available at: https://doi.org/10.1016/j.biortech.2014.09.126.

Wall, D.M., Dumont, M. and Murphy, J.D. (Ed. . (2018) Green gas - Facilitating a future green gas grid through the production of renewable gas, IEA Bioenergy Task 37. Edited by J.D. Murphy. IEA Bioenergy. Available at: http://www.attero.nl/klanten-leveranciers/locaties/wijster (Accessed: 17 July 2020).

Wall, D.M., O'Kiely, P. and Murphy, J.D. (2013) 'The potential for biomethane from grass and slurry to satisfy renewable energy targets', Bioresource Technology, 149, pp. 425–431. Available at: https://doi.org/https://doi.org/10.1016/j.biortech.2013.09.094.

Wang, F. et al. (2014) 'Pollutant removal and membrane fouling in an anaerobic submerged membrane bioreactor for real sewage treatment', Water Science and Technology, 69(8), pp. 1712–1719. Available at: https://doi.org/10.2166/wst.2014.080.

4 The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant

The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant

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Abstract:

Globally, 10% of milk production occurs in countries whereby dairy livestock have pasture access for the majority of the year, leading to the seasonal collection and availability of dairy slurry. This can pose challenges if dairy slurry is used as a feedstock in on-farm biogas plants. On-farm biogas plants may also have no grid access and have to facilitate seasonal gas demands of consumers in their locality. The effects of seasonal gas demand coupled with seasonal slurry availability has yet to be addressed in literature. This work aims to analyse the effects of such seasonal factors, and whether optimised digestate recirculation may alleviate some of these challenges. Countries which employ pasture-based dairy farming require such evidence to successfully develop on-farm biogas plants, reduce fugitive emissions resultant from current manure management practices, and furthermore, produce alternatives to fossil fuels. Ireland is used as a case study in this work and the effects of seasonal or constant slurry availability and seasonal or constant gas demand is investigated. The sustainability of such systems is also evaluated in terms of emissions reductions as per EU regulations. For a farm with slurry production from 100 dairy cows and 10 ha of grass dedicated for anaerobic digestion, the seasonal availability of slurry leads to a 21% reduction in total biomethane production; over 12 times the required digestate recirculation; smaller digester sizes; and increased variation in the organic loading rate throughout the year. Facilitating a seasonal gas demand leads to larger digester sizes due to periods of increased mass flow-rates, and large peaks and troughs in biogas flow-rates. Seasonal slurry availability increases greenhouse gas emissions by ca. 11 grams of CO_2 per megajoule of biomethane produced. Pasture-based AD systems may successfully manage the

seasonal availability of slurry by optimising digestate recirculation to lower the solids content of the plant.

Keywords: Biomethane, on-farm, seasonality, sustainability, renewable energy, bioenergy

4.1 Introduction

4.1.1 The energy transition and reducing emissions

The 197 participating countries at the 2021 United Nations Climate Change Conference (COP26) agreed to work towards limiting the increase in global average temperatures to 1.5 °C above pre-industrial levels by mitigating greenhouse gas (GHG) emissions and by financing low emissions pathways (UNFCCC and UN, 2021). EU member states are currently obliged to regulate their GHG emissions and increase the share of renewable energy in their energy systems. The production of biomethane through on-farm anaerobic digestion (AD) systems is a potential method to provide a renewable and sustainable substitute to fossil-based natural gas. Utilising feedstocks such as grass silage and livestock manure (hereafter referred to as slurry) could provide for a potential pathway to mitigate agricultural emissions through the generation of renewable biomethane which can be used in the hard to abate sectors of transport and heat. AD plants also produce digestate, a nutrient-rich biofertiliser which, by replacing chemical fertilisers, can lower a farmer's land management costs and reduce their carbon footprint.

4.1.2 On-farm feedstock availability

On-farm AD may be an important strategy towards decarbonisation of industry and localities through the provision of renewable heat (Ó Céileachair *et al.*, 2021). Continuously stirred tank reactors (CSTR) (most commonly used farm-based AD plant) typically require the solids content of the feedstock to be below a certain threshold (usually 12%) for optimal mixing and operation (Murphy and Thamsiriroj, 2013). However, in many countries, it is common for livestock to spend many weeks of the year outdoors (O'Callaghan *et al.*, 2017). Without access to dairy slurry whilst the livestock are outdoors, on-farm AD plants may struggle to reduce the solids content of crop feedstocks to a sufficient level. Recirculation of the liquid portion of the digestate may be considered to lower the solids content of the digester (Thamsiriroj and Murphy, 2011).

4.1.3 Gas demand

The end-use of biomethane from on-farm AD can also dictate the operations of the plant. If gas grid access is available, gas demand may be treated as constant year-round. If an AD plant does not have grid access, it may need to alter its feeding strategy based on when the end user requires gas throughout the year. For example, it

may be assumed that gas demand could peak during the winter months for residential or industrial heating, or in summer months for milk processing. In essence, on-farm AD plants may operate based on three gas demand profiles: constant demand, winter demand, or summer demand.

4.1.4 Sustainability of on-farm biomethane

The preferred route for biomethane utilisation in the EU as per the recast REDII directive (European Parliament and European Commission, 2018), is transport as per the recast REDII directive, in which required GHG emissions savings criteria to be deemed sustainable for biomethane are lower as compared to heat and electricity (Table 4-1). In applying the process to calculate sustainability of biomethane, conversion efficiencies are not required for transport fuels while they are required for heat and electricity end use. In terms of sustainability, slurry is awarded a credit as it saves fugitive methane emissions from open slurry tanks (-54 kg $CO_{2\text{-eq}}$ tonnes wet weight^{-1} (t_{wwt}) of slurry, as per REDII). This impacts on the assessment for biogas systems as the sustainability criteria will be influenced by the annual volatile solids (VS) ratio between the different feedstocks digested; thus, a challenge for on-farm AD will be ensuring that the seasonality of slurry (correlating to a specific VS ratio of grass to slurry (G:S)) has a minimal negative impact on the sustainability of the biomethane produced.

End use	Fossil fuel comparator (FFC) (g $CO_{2\text{-eq}}$ MJ^{-1})	Conversion efficiency (%)	Minimum emissions saving in 2026 (%)	Maximum emissions (g $CO_{2\text{-eq}}$ MJ^{-1})
Heating	80	90	80%	14.4
Electricity	183	50	80%	18.3
Transport	94	N/A	65%	32.9

Table 4-1: Maximum emissions per end use for biomethane (Long and Murphy, 2019).

Emissions from biomethane plants can arise from a number of sources, such as the feedstock transportation to the digester, the harvesting of feedstock, and the transportation and distribution of the resultant biomethane. Methane losses may also occur in the system, which typically range from 1% for gas-tight storage AD plants, to 3.55% for open-air digestate storage AD plants (Scott and Blanchard, 2021). AD plants can also include for emissions savings from improved manure management systems.

4.1.5 Objectives

This work investigates the effects of dairy slurry availability from specific farming practices (zero-grazing and pasture-based systems), on the operation and sustainability of an on-farm AD plant under three gas demand scenarios (constant, winter, and summer demand profiles). This work also evaluates the effects of dairy slurry availability on digestate storage requirements and biofertiliser spreading regimes. Table 4-2 shows the six scenarios investigated in this work. Scenarios in which livestock do not have pasture access or are indoors year-round are denoted zero-grazing (ZG) scenarios, and scenarios in which livestock do have pasture access are denoted pasture-based (PB) scenarios. Further details on these scenarios can be found in sections 4.2.2 and 4.2.3.

		Constant gas demand	**Winter Gas Demand**	**Summer Gas Demand**
	Code	***C***	***W***	***S***
Zero-grazing	***ZG***	ZG-C	ZG-W	ZG-S
Pasture based	***PB***	PB-C	PB-W	PB-S

Table 4-2: Scenario matrix.

The innovation in this work is that, to the best of the authors' knowledge, it is the first paper to illustrate the effect of seasonal on-farm feedstock availability (specifically, the complete absence of slurry as feedstock for periods of the year) on the operation of an AD plant with specific gas demand profiles. Much literature assumes that feedstocks are available year-round, and that gas demand is constant, which is not accurate to real-life biogas operation. This work advances beyond the state of the art in determining how such AD plants can be analysed from an operational and sustainability perspective with respect to varying feedstock and gas demand characteristics. The hypothesis of this work is that pasture-based farming AD systems can adapt to function at times when there is limited feedstock availability and seasonal gas demand, despite the effects on the operation of the system. The objectives of this work are to determine:

i. The effect of slurry availability on the operational characteristics of an on-farm AD plant for two specific farming practices (ZG and PB);
ii. The effect of gas demand seasonality on the operational characteristics of an on-farm AD plant;
iii. Whether the seasonal availability of slurry or seasonal gas demand affects the sustainability of an on-farm AD plant.

4.2 Methodology

4.2.1 Case study

Ireland is chosen as a case study in this work due to its PB dairy farming practices, available crop feedstock for AD, its committed obligations to reducing GHG emissions, and that the pertinent data is available to the authors. This work is applicable to any region which employs PB farming systems.

4.2.2 Analysis assumptions

4.2.2.1 Feedstocks

For all six scenarios in Table 4-2, a hypothetical dairy farm was modelled with 100 dairy cows and 100 ha of grassland. This would be considered to be within the largest 10% of dairy farms in Ireland (Teagasc *et al.*, 2021). For the PB scenarios, a total of 18 weeks is assumed where the livestock are housed indoors in winter from early November to late March (weeks 46 to 52 and week 1 to the end of week 11 of the calendar year), as per Hennessy *et al.* (2011). It was assumed that a single dairy cow produces 0.33 m^3, or 0.33 t_{wwt}, of slurry per week when housed indoors using a wet slurry management system (Hennessy *et al.*, 2011). Therefore, if the farm was to house all livestock (100 cows) indoors year-round (ZG farming system), 1,716 t_{wwt} a^{-1} of dairy slurry would be collected. Conversely, if the farm was to house all livestock indoors for 18 weeks of the year (PB farming system), 594 t_{wwt} a^{-1} of dairy slurry would be collected, requiring the same volume of slurry storage (594 m^3).

A dairy cow in an Irish PB farming practice requires 4,895 kg total solids (TS) a^{-1} of grazed grass and 1,495 kg TS a^{-1} of grass silage (McEniry *et al.*, 2013). Assuming grazed grass yields of 6.94 t TS ha^{-1} (McEniry *et al.*, 2013), and grass silage yields of 10 t TS ha^{-1}, a farm would have to dedicate 70.53 ha and 14.95 ha towards grazed grass and grass silage respectively; thus a total of 85.48 ha is required for the livestock. As the farm considered in the scenarios assessed has 100 ha, 14.52 ha remains as a surplus. It was conservatively assumed that 10 ha of land would be available for grass silage production to be used directly for AD. If it is assumed that 10 t TS ha^{-1} a^{-1} of grass silage is available for harvesting (Teagasc, 2020), and given the TS content of grass silage of 29.27% (see Table 4-3), the farm investigated in the scenarios will harvest 100 t TS a^{-1}, or 341.65 t_{wwt} a^{-1}, of grass silage for AD.

Table 4-3 shows the characteristics of the feedstock considered in this work, including for TS and volatile solids (VS) (Wall, O'Kiely and Murphy, 2013). The feedstock's respective mono- and co-digestion specific methane yields (SMY) at an organic loading rate (OLR) of 2.5 kg VS m^{-3} d^{-1} were used to calculate the gross biomethane output from the AD plant (Wall *et al.*, 2014). VS ratios of grass and slurry between those listed in the table (for example a VS ratio of 50:50), were interpolated linearly from literature values to obtain corresponding SMY values and the methane composition of the biogas.

Grass : Slurry (VS Ratio)	Dry Solids (%)	Volatile Solids (%)	Energy Yield (MJ kg_{wwt}^{-1})	Specific Methane Yield (m^3 CH_4 t^{-1} VS)	CH_4 % in biogas (v/v)
0:100	8.75	6.69	0.36	143	54.2%
20:80	-	-	-	198	54.7%
40:60	-	-	-	239	54.9%
60:40	-	-	-	316	54.2%
80:20	-	-	-	343	53.3%
100:0	29.27	26.84	4.04	398	51.2%

Table 4-3: Feedstock characteristics and co-digestion yields.

4.2.2.2 Emissions

No transport emissions were assumed to be associated with the collection of dairy slurry in agreement with the RED II methodology for waste materials used in AD (European Parliament and European Commission, 2018). Emissions of 1,900 and 525 kg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1} were assumed from the cultivation of grass silage and field application of fertilisers, respectively. Soil carbon sequestration of 0.6 t C ha^{-1} yr^{-1}, or 2.2 t CO_2 ha^{-1} yr^{-1}, was assumed (McGeever *et al.*, 2019). Fugitive methane losses of 1%, 2% and 3.55% were investigated for the AD system. It was also assumed that the biogas would be upgraded to biomethane to allow for injection to the gas grid. A full list of the assumptions and the calculations used to determine the emissions from AD can be found in Appendix B.1.

4.2.2.3 AD plant characteristics

A desired solids content of 12% was chosen for the CSTR (SEAI, 2020). A VS destruction of 100% was assumed. A minimum hydraulic retention time (HRT) of 40 days was selected, but this may increase depending on the OLR of the digester. The electricity demand for grass maceration was assumed to be 2 kWh t_{wwt}^{-1} of grass (Smyth, Murphy and O'Brien, 2009) and 10 kWh t_{wwt}^{-1} (Murphy, McKeogh and Kiely, 2004) for digester mixing. In Ireland, it is advised that fertiliser be spread on land three times per year; the first spreading in January or February, the second

spreading in March, and the third and final spreading in August or September (Wall, Plunkett and Teagasc, 2020). In this work, digestate is assumed to be spread on land on weeks 5, 11 and 37. The digestate produced is separated into liquid and solid fractions using a screw press separator (see Table 4-4) and then added to their respective digestate tanks for storage (digestate storage hereby referred to as digestate banks). Table 4-4 also shows an example calculation of this separation with 100 t_{wwt} of digestate. Approximately 33% of the total annual production of liquid and solid digestates are spread during the three spreading weeks (weeks 5, 11 and 37). The solid digestate bank may be fully emptied after spreading, however a portion of liquid digestate is always retained so as to be available for recirculation to reduce the digester TS content.

		Percentage of total digestate fresh weight (%)		**Percentage of digestate TS (%)**
Solid fraction		10		48.1
Liquid fraction		90		51.9
Example Separation	**Digestate**	***Separation***	**Liquid Digestate**	**Solid Digestate**
Total Mass (t_{wwt})	100	⇒	90	10
Solids (t TS)	10	⇒	5.19	4.81
TS (%)	10%	⇒	5.8%	48.1%

Table 4-4: Digestate separation performance and example separation (Drosg *et al.*, 2015). *TS: Total Solids*

4.2.3 Gas demand periods

4.2.3.1 Constant gas demand

In scenario ZG-C, where annual gas demand is constant and the livestock are housed year-round, both slurry and grass silage inputs to the digester are constant for 52 weeks of the year. However, in scenario PB-C, in which gas demand is constant but the livestock are pasture based, there is no slurry resource available from weeks 12-45. The proportion of silage used for digestion during these weeks is increased relative to the rest of the year to ensure the biomethane output remains constant. Details of this calculation are outlined in Appendix B.2.

4.2.3.2 Winter demand period

The winter gas demand scenario is linked to the heating demand of residential buildings, based on heating degree days (HDDs). HDDs quantify the demand for heating energy in a building, derived from outdoor air temperature. The winter peak demand period was modelled on the HDDs at Cork Airport, Ireland, and was calculated by taking the average monthly HDDs from a base temperature of 15.5 ° C from May 2018 to April 2021. Full details can be found in Appendix B.2.

4.2.3.3 *Summer demand period*

The summer demand scenario period was modelled on Ireland's domestic milk intake from milk processors using data from the Central Statistics Office (CSO) from 2017 to 2020 (CSO, 2021). The energy and gas demand of milk processors is strongly correlated with milk production (Geraghty, 2011; Shine *et al.*, 2020). Full details can be found in Appendix B.2. Table 4-5 shows a summary of the specific scenario timelines investigated in this paper and their assumptions.

Scenario	**Constant gas demand**		**Winter gas demand**		**Summer gas demand**	
Scenario code	**ZG-C**	**PB-C**	**ZG-W**	**PB-W**	**ZG-S**	**PB-S**
Peak demand weeks	1-52	1-52	1-15, 41-52	1-15, 41-52	10-39	10-39
Dairy cow housing weeks	1-52	1-11, 46-52	1-52	1-11, 46-52	1-52	1-11, 46-52
Annual slurry digested (t_{wwt})	1,716	594	1,716	594	1,716	594
Annual silage digested (t_{wwt})	341.65	341.65	341.65	341.65	341.65	341.65
Silage share used for peak demand period[1]	N/A	75.1% reserved for weeks 12-45[2]	83%	83%	78%	78%

1 Silage share is divided on a % of the total annual harvest weight (t_{wwt})

2 Some silage is reserved for when livestock are outdoors to keep gas output constant through all 52 weeks (see section 4.2.3.1 and Appendix B.2)

Table 4-5: Scenario parameters.

4.2.4 Formulae

A model was developed to track the key characteristics (feedstock input, biogas output, biogas CH_4 %, digestate output, digestate solids content, liquid digestate recirculation requirements, digester size, and digester OLR) of the AD plant weekly, depending on the inputs and user-set characteristics as outlined in sections 4.2.2 and 4.2.3. The following formulae were used to calculate each scenarios' weekly characteristics (full calculation results can be found in Appendix B.3).

Eq. (4.1); the amount of silage from the total annual harvest that should be used for the peak demand periods, in t_{wwt} (m_{silage}^{peak}):

$$m_{silage}^{peak} = m_{silage} * PR\% \quad (4.1)$$

In Eq. (4.1), m_{silage} is the total annual mass of silage harvested for the purpose of AD in t_{wwt}, and $PR\%$ is the percentage in decimals of silage that is used during the peak demand period (see section 4.2.3 and Appendix B.2). To calculate how much of the feedstock should be input during each week of the peak period, the result of Eq. (4.1) was divided by the number of weeks in the peak period.

Eq. (4.2); the volume of CO_2 in the biogas output from the digester from either grass or slurry, in m^3 ($V_{CO_2}^{\theta}$):

$$V_{CO_2}^{\theta} = \frac{V_{CH_4}^{\theta}}{\%_{CH_4}^{\theta}} - V_{CH_4}^{\theta} \tag{4.2}$$

In Eq. (4.2), $V_{CH_4}^{\theta}$ is the volume of CH_4 output from the digestion or co-digestion of grass or slurry in m^3 (see Table 4-3 and Appendix B.3), and $\%_{CH_4}^{\theta}$ is the methane content percentage in decimals of the biogas from the respective feedstocks or co-digestion mix (as per Table 4-3). θ represents the slurry or grass silage feedstock, or their co-digestion.

Eq. (4.3); the mass of the biogas output from the digester in t_{wwt} (m_{Biogas}):

$$m_{Biogas} = \sum \left(m_{CH_4}^{\theta} + m_{CO_2}^{\theta}\right) \tag{4.3}$$

In Eq. (4.3), $m_{CH_4}^{\theta}$ and $m_{CO_2}^{\theta}$ are the mass of biomethane and carbon dioxide from the digestion of the feedstock in t_{wwt} (θ represents the slurry or grass silage feedstock, or their co-digestion). The mass of the respective gases was found by multiplying their output volume by their gaseous density, assumed to be 0.7177 kg m^{-3} and 1.9778 kg m^{-3}, at 0 °C and atmospheric pressure, for CH_4 and CO_2, respectively.

Eq. (4.4); the mass of digestate output from the digester per week, in t_{wwt} (m_D):

$$m_D = m_F - m_{Biogas} \tag{4.4}$$

In Eq. (4.4), m_F is the total mass of feedstock input, in t_{wwt}, into the digester in one week, and m_{Biogas} is the mass of the biogas output, in t_{wwt}, from the digester in one week. The total digestate produced is split into liquid and solid digestate, as per Table 4-4.

Eq. (4.5); the TS percentage of the digestate output per week (X_{TS_D}):

$$X_{TS_D} = 1 - \frac{m_{W_F}}{m_D} \tag{4.5}$$

In Eq. (4.5), m_{W_F} is the weekly mass of water in the feedstocks input to the digester in t_{wwt}, and m_D is the weekly mass of the digestate in t_{wwt}, as per Eq. (4.4). This formula applies to both the liquid and solid digestate, post-separation.

Eq. (4.6); the required weekly mass of recirculated liquid digestate in t_{wwt} ($m_{D_{recirc}}$):

$$m_{D_{recirc}} = \frac{(m_F * X_{TS_F}) + (X_{TS_{Desired}} * m_F)}{X_{TS_{Desired}} - X_{TS_D}} \quad (4.6)$$

In Eq. (4.6), m_F is the total mass of feedstock input, in t_{wwt}, into the digester in one week, X_{TS_F} the TS percentage of that feedstock, $X_{TS_{Desired}}$ is the desired solids percentage of the digester, and X_{TS_D} is the TS percentage of the liquid digestate, as per Eq. (4.5). When the farm spreads digestate (see section 0), ca. 33% of the projected total annual digestate produced is spread, however some liquid digestate is kept, ensuring that enough remains to satisfy recirculation requirements to keep the digester solids at 12% or less. Every week, digestate that is not required for recirculation is added to the farm's liquid or solid 'digestate bank' which is akin to slurry storage. This digestate bank is stored on the farm and digestate is added to it cumulatively, until ca. 33% of the total annual production is spread on weeks 5, 11 and 37.

Eq. (4.7); the required digester size in m^3 (V_{dig}):

$$V_{dig} = HRT * \dot{V} \quad (4.7)$$

In Eq. (4.7), HRT is the digester's hydraulic retention time in days, and $\dot{V}$ the flow-rate of the inputs into the digester in m^3 day^{-1} (grass silage, dairy cow slurry, and digestate recirculation). The digester size is calculated for the period with the highest mass input flow-rate.

Eq. (4.8); the organic loading rate (OLR) of the digester in kg VS m^{-3} day^{-1}:

$$OLR = S_0 * \frac{Q}{V_{dig}} \quad (4.8)$$

In Eq. (4.8), S_0 is the influent substrate concentration in kg VS m^{-3}, Q is the total flowrate into the digester in m^3 day^{-1}, and V_{dig} the digester size in m^3.

4.2.5 EU RED II sustainability

A sustainability analysis of the six scenarios was carried out based on the criteria in the EU RED II recast (Annex VI) (European Parliament and European Commission, 2018), and also on the methodology and assumptions developed by Long *et al.* (2021). It is assumed that the biogas in all scenarios is brought to a central upgrading hub via biogas pipeline as part of a network of individual farms, in a way similar to what is done in Wijster in the Netherlands (Wall, Dumont and Murphy, 2018), and then injected into the natural gas grid, to be used as heating or transport fuel. Emissions calculations in this work are evaluated based on the net biomethane output of the scenarios (biogas produced on the farms satisfies the parasitic upgrading demands). Each scenario's sustainability is evaluated. The energy required for upgrading the biogas and compressing the biomethane was assumed to be 0.58 kWh_{th} Nm^{-3}_{biogas} and 0.11 kWh_e $Nm^{-3}_{biomethane}$, respectively (Beil and Beyrich, 2013).

Sustainability criteria are based on, among other factors listed below, the annual average CH_4 output per tonne of total mixed feedstock per year. Eq. (4.9) was used to conduct the sustainability analysis which accounts for the total emissions (E) from the production of biomethane before energy conversion from co-digestion of n substrates:

$$E = \sum_{1}^{n} S_n * \left(e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n}\right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr} \quad (4.9)$$

In Eq. (4.9), S_n is the share of each feedstock n in fraction of input to the digester, $e_{ec,n}$ the emissions from the extraction or cultivation of feedstock n, $e_{td,feedstock,n}$ the emissions from transport of feedstock n to the digester, $e_{l,n}$ the annualised emissions from carbon stock changes caused by land-use change for feedstock n, $e_{sca,n}$ emissions savings from improved agricultural management of feedstock n, e_p the emissions from processing, $e_{td,product}$ the emissions from transport and distribution of the biomethane, e_u emissions from the fuel in use, e_{ccs} the emissions savings from CO_2 capture, and geological storage and e_{ccr} the emissions savings from CO_2 capture and replacement. All emissions units in Eq. (4.9) are in g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$.

The share of each feedstock (as a fraction of input) into the digester was determined from the following two equations:

Eq. (4.10), the weighting factor (W_n) of each feedstock n:

$$W_n = \frac{I_n}{\sum_1^n I_n} \tag{4.10}$$

In Eq. (4.10), I_n is the annual input in t_{wwt} to the digester of each feedstock n (see section 4.2.2.1).

And Eq. (4.11), the share of feedstock n in energy content (S_n):

$$S_n = \frac{P_n * W_n}{\sum_1^n P_n * W_n} \tag{4.11}$$

In Eq. (4.11), P_n is the biogas energy yield in MJ per kg of wet input of each feedstock n (see Table 4-3), W_n the weighting factor of each substrate n.

The emissions from each scenario were calculated and subsequently evaluated against the permissible EU regulatory emissions as outlined in Table 4-1 to determine whether the scenarios were sustainable as per the existing EU regulations. See Appendix B for full details on sustainability calculations.

4.2.6 Limitations of work

The analysis herein is an academic exercise to model the impact of seasonal slurry availability and energy demand profile on the feeding regime of an on-farm AD plant providing biomethane as an end product. Other variables and concerns have been simplified and/or held constant to allow this interrogation such as:

i. In reality, the VS destruction of the feedstocks would vary depending on their quality and the digester design. The AD plants' biomethane output, digestate solids content, required digestate recirculation, digester size, biogas flowrate, and the overall sustainability would be affected by variations in VS destruction rates. Such elements were considered outside the scope of this analysis.
ii. The system as described is very small for biogas upgrading, and the variability in biogas output is not ideal for biogas upgrading systems. The analysis uses a farm with 100 cows and 100 ha of land, which can be

scaled up or down for the purposes of interpretation. The model could readily be modified whereby a series of biogas facilities such as the one modelled could be served by a mobile-upgrading system (Gil-Carrera *et al.*, 2019) or connected by biogas pipeline to a central biogas upgrading hub such as is in operation in Wijster as described by IEA Bioenergy Task 37 (Wall, Dumont and Murphy, 2018).

iii. The plants in this work operate on a weekly discrete time basis. In reality, the composition of the digestate will vary continuously with time as opposed to on a weekly basis. Also, when the digesters enter their peak demand periods it is more likely that there would be an incremental change in the feeding regimes as opposed to an instantaneous switch to maximum input levels. This change could take place during a single week or may need to take place over a longer time period depending on the stability of the AD process.

iv. The nitrogen concentration of the digestate produced in the scenarios would vary depending on slurry availability, grass silage use, feedstock input regimes and gas demand periods, and future research should investigate how this would affect the digestate spreading strategies employed by the farmers.

v. Changes in the farm size assessed would have an impact on the results obtained. For example, it can be predicted that farms with higher ratios of grass silage to slurry, and therefore more dry matter, would require more liquid digestate recirculation than farms with a higher ratio of slurry. It is also likely that farms with higher slurry to grass ratio would produce biomethane with more favourable sustainability results as per EU RED II.

4.3 Results

4.3.1 Constant gas demand

4.3.1.1 Scenario ZG-C

Figure 4-1 shows the operational profile of the AD plant in the ZG-C scenario (zero-grazing, with constant gas demand). The TS content of the digester inputs pre-recirculation is 12.16%; 0.76 t_{wwt} of liquid digestate must be recirculated weekly to bring the TS content down further to 12%.

The weekly gross biomethane output of scenario ZG-C is 1,010 m^3 CH_4. A total of 1,742 t_{wwt} of liquid digestate and 194 t_{wwt} of solid digestate are produced annually, of which ca. 33% of the total annual production are spread on each of the weeks 5, 11 and 37 – however, the liquid digestate bank is not fully emptied to ensure that enough remains for digestate recirculation (this is true for all scenarios).

Full details on the digestate banks for all scenarios can be found in Appendix B.3. Details on the solids content of the digestate banks in all scenarios can be found in Appendix B.4. Details on the HRT and OLR of the digesters in all scenarios can be found in Table 4-6 (full details in Appendix B.5).

4.3.1.2 Scenario PB-C

Figure 4-2 shows the operational profile of the AD plant in the PB-C scenario (pasture based, with constant gas demand).

The TS content of the digester inputs pre-recirculation ranges from 11.3% whilst the livestock are indoors, to 29.3% when they are pasture based; 12.2 - 15.5 t_{wwt} of liquid digestate must be recirculated weekly whilst the animals are pasture based to reduce the solids content to 12%. There is a dip in week 38 in the amount of liquid digestate recirculated, due to the changing composition of the digestate bank after spreading liquid digestate (see Appendix B.4, Figure B-2). Whilst livestock have access to pasture, silage input to the digester increases from 4.8 t_{wwt} $week^{-1}$ to 7.5 t_{wwt} $week^{-1}$ to ensure that the biomethane output from the digester remains constant throughout the year. CO_2 production increases at times when grass is mono-digested (see Table 4-3).

The weekly gross biomethane output of scenario PB-C is 804.3 m^3 CH_4. A total of 748 t_{wwt} of liquid digestate and 83 t_{wwt} of solid digestate are produced annually.

Much less liquid and solid digestate is produced in the PB-C scenario compared to the ZG-C scenarios, due to the lower quantity of slurry digested annually (this is true for all PB scenarios).

4.3.2 Winter gas demand

4.3.2.1 Scenario ZG-W

Figure 4-3 shows the operational profile of the plant in the ZG-W scenario (zero-grazing, with winter gas demand). The TS content of the digester inputs pre-recirculation ranges from 10.1% during the off-peak demand period to 13.7% during the peak demand period; ca. 8.8 t_{wwt} of liquid digestate must be recirculated weekly during the peak demand period to reduce the solids content to 12%.

The weekly gross biomethane output of scenario ZG-W during the peak demand period is 1,511 m^3 CH_4, and 572 m^3 CH_4 during the off-peak demand period. A total of 1,735 t_{wwt} of liquid digestate and 193 t_{wwt} of solid digestate are produced annually.

4.3.2.2 Scenario PB-W

Figure 4-4 shows the operational profile of the AD plant in the PB-W scenario (pasture based, with winter gas demand).

During the peak demand period in winter, the TS content of the digester inputs pre-recirculation ranges from 13.7% (whilst livestock are indoors), to 29.3% when livestock have access to pasture (weeks 12-15 and 41-45). During the peak demand period, ca. 6.1 t_{wwt} of liquid digestate must be recirculated weekly to the digester whilst livestock are indoors, and 20.7 – 25.4 t_{wwt} of liquid digestate per week must be recirculated whilst the livestock have pasture access, to maintain the solids content at 12%.

In the off-peak demand period, the TS content of the digester input is 29.27% and ca. 4.4 t_{wwt} of liquid digestate must be recirculated weekly to reduce the TS content to 12%.

In the peak demand period, the weekly gross biomethane output of scenario PB-W is 1,365 m^3 CH_4. During the off-peak demand period, the weekly gross biomethane output is 248 m^3 CH_4. A total of 747 t_{wwt} of liquid digestate and 83 t_{wwt} of solid digestate are produced annually.

4.3.3 Summer gas demand

4.3.3.1 Scenario ZG-S

Figure 4-5 shows the operational profile of the AD plant in the ZG-S scenario (zero-grazing, with summer gas demand). The TS content of the digester inputs pre-recirculation ranges from 10.7% during the off-peak demand period to 13.1% during the peak demand period; ca. 5.5 t_{wwt} of liquid digestate must be recirculated weekly during the peak demand period to bring the TS content down to 12%.

The weekly gross biomethane output of scenario ZG-S during the peak demand period is 1,291 m^3 CH_4, and 676 m^3 CH_4 during the off-peak demand period. A total of 1,739 t_{wwt} of liquid digestate and 193 t_{wwt} of solid digestate are produced annually.

4.3.3.2 Scenario PB-S

Figure 4-6 shows the operational profile of the plant in the PB-S scenario (pasture based, with summer gas demand).

In the peak demand period, the TS content of the digester inputs pre-recirculation ranges from 12% (weeks 10 and 11), to 29.3% whilst livestock have pasture access; 14.7 – 18.5 t_{wwt} of liquid digestate must be recirculated weekly between weeks 12 and 39 whilst livestock have pasture access, to reduce the solids content to 12%. During the off-peak demand period, the TS content of the digester input ranges from 10.3%, to 29.3% (weeks 40 to 45); ca. 9 t_{wwt} of liquid digestate must be recirculated weekly between weeks 40 to 45 during the off-peak demand period to reduce the TS content down to 12%.

The weekly gross biomethane output of scenario PB-S is ca. 969 m^3 CH_4 during the peak demand period, and ca. 599 m^3 during the off-peak demand period. A total of 746 t_{wwt} of liquid digestate and 83 t_{wwt} of solid digestate are produced annually, each of which ca. 33% are spread on weeks 5, 11 and 37.

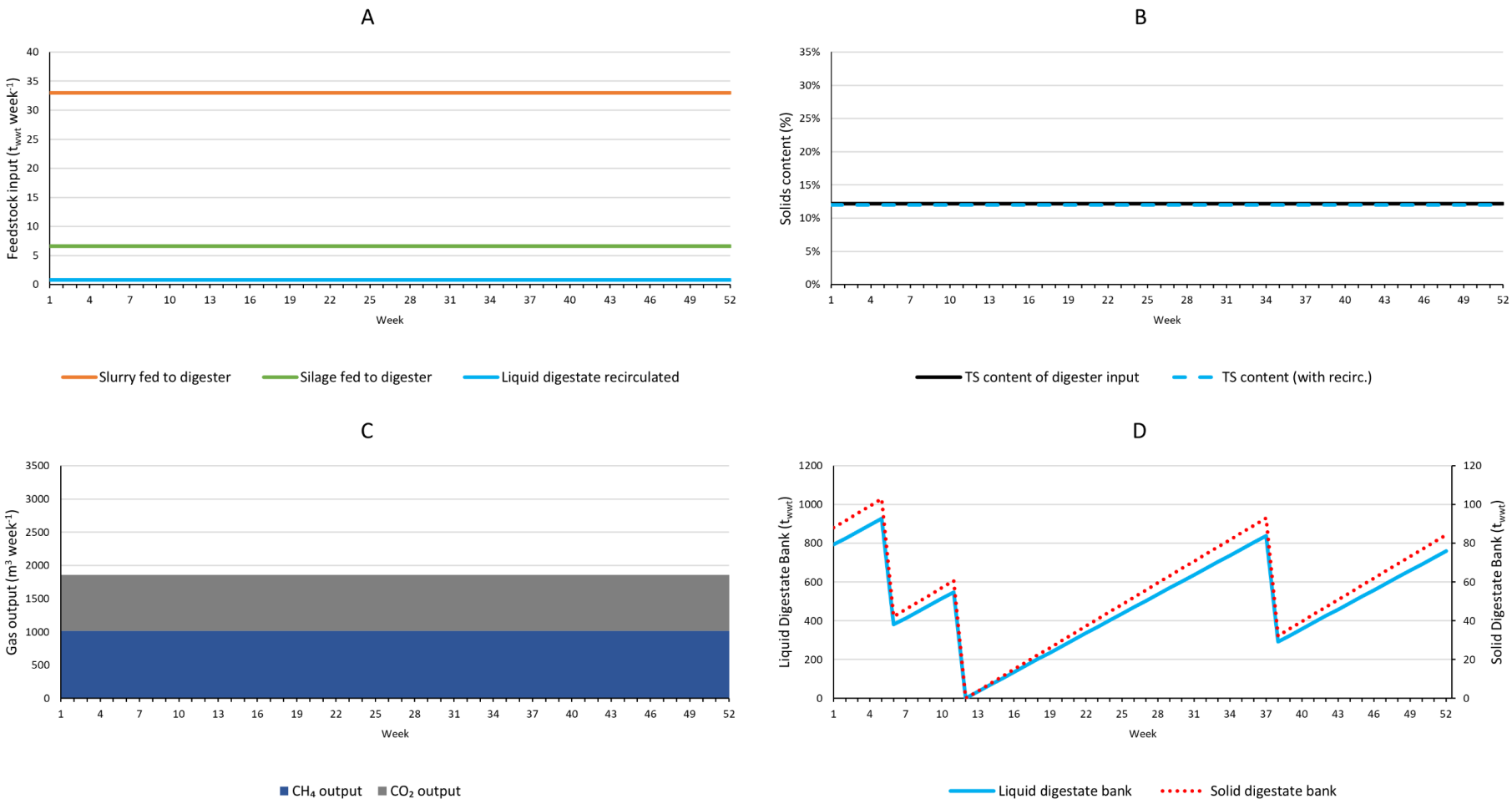


Figure 4-1: Scenario ZG-C, A) Weekly digester inputs, B) Digester solids content, C) Weekly digester gas output, D) Cumulative digestate bank.

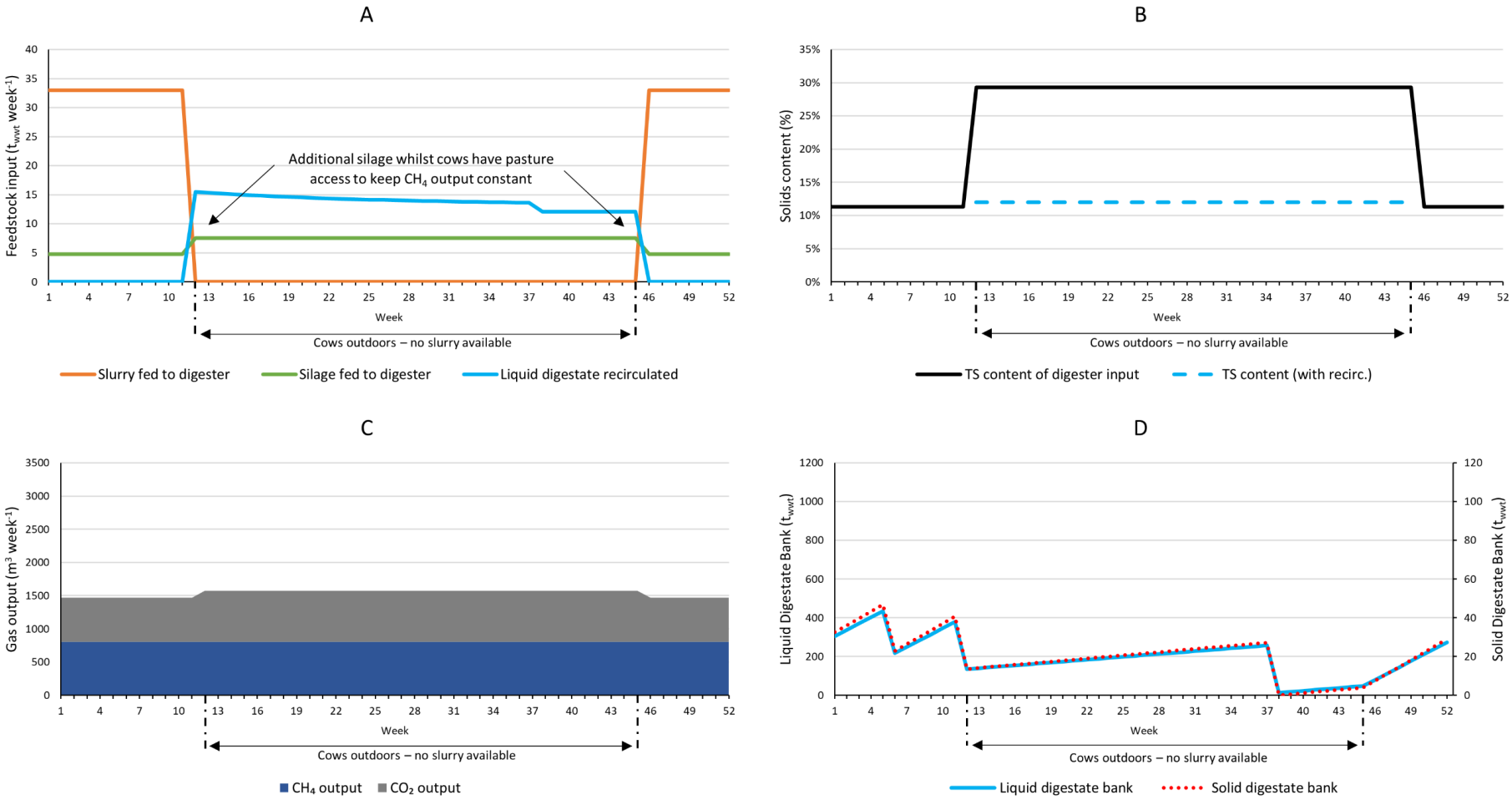


Figure 4-2: Scenario PB-C, A) Weekly digester inputs, B) Digester solids content, C) Weekly digester gas output, D) Cumulative digestate bank.

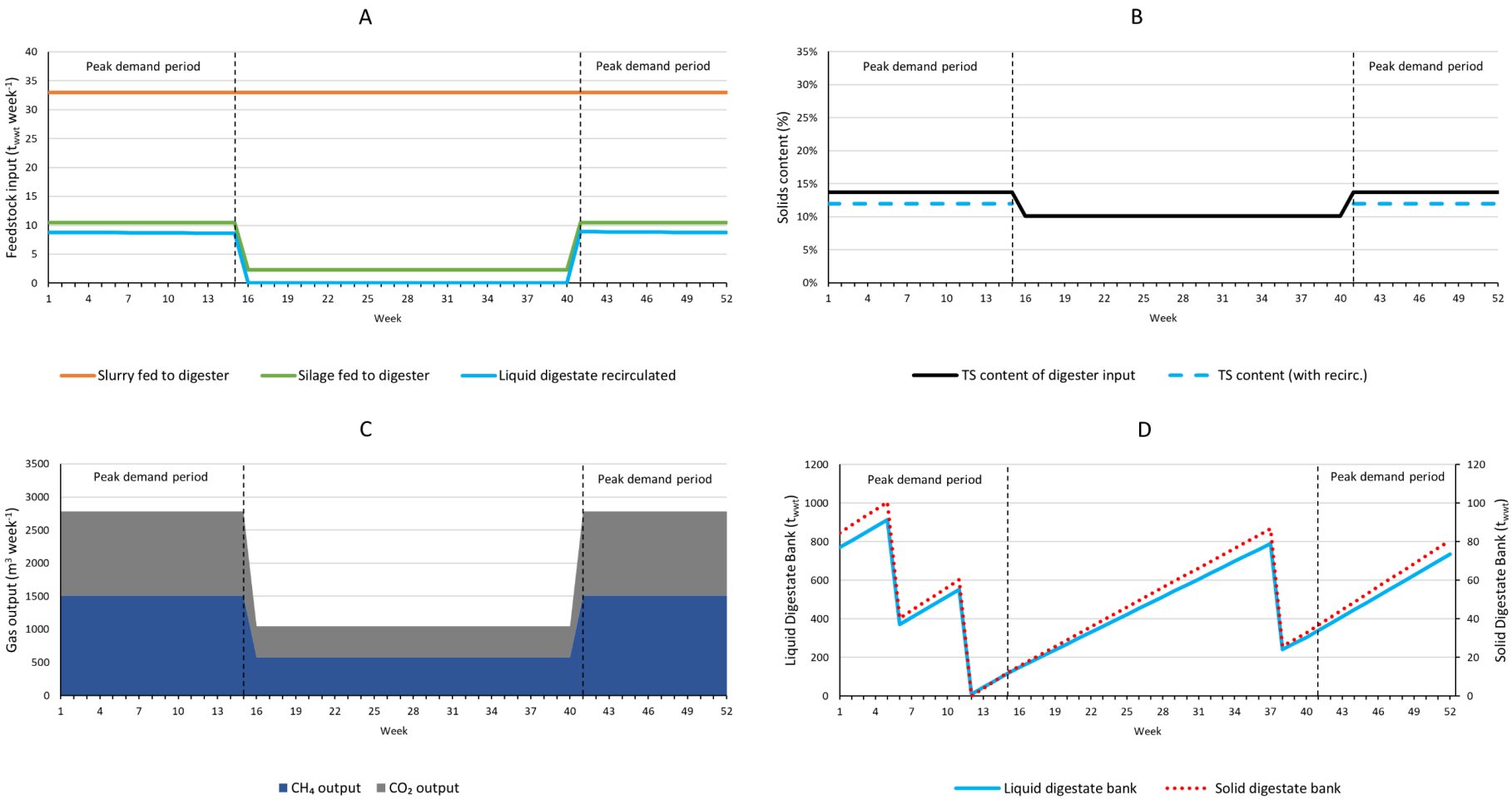


Figure 4-3: Scenario ZG-W, A) Weekly digester inputs, B) Digester solids content, C) Weekly digester gas output, D) Cumulative digestate bank.

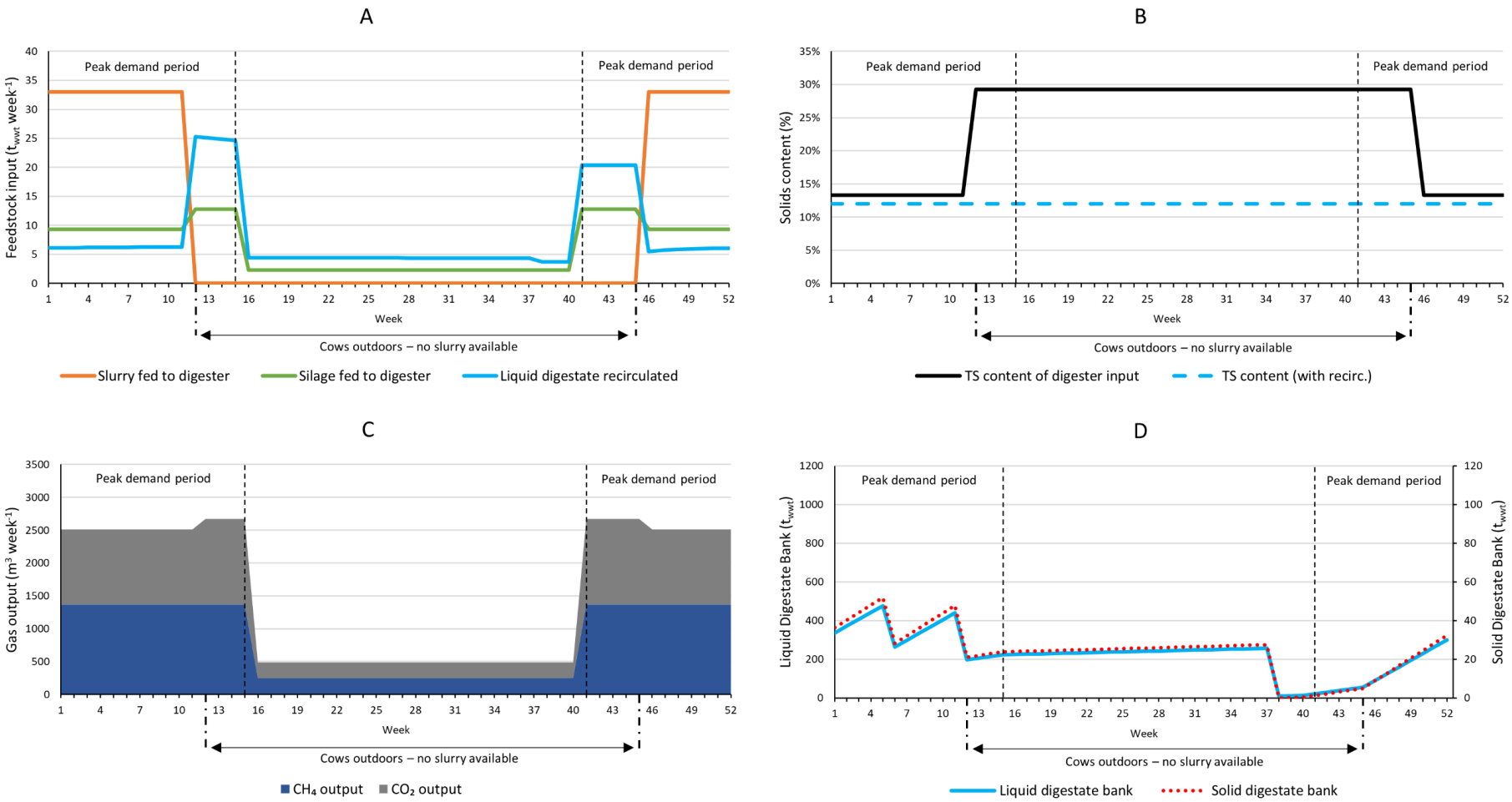


Figure 4-4: Scenario PB-W, A) Weekly digester inputs, B) Digester solids content, C) Weekly digester gas output, D) Cumulative digestate bank.

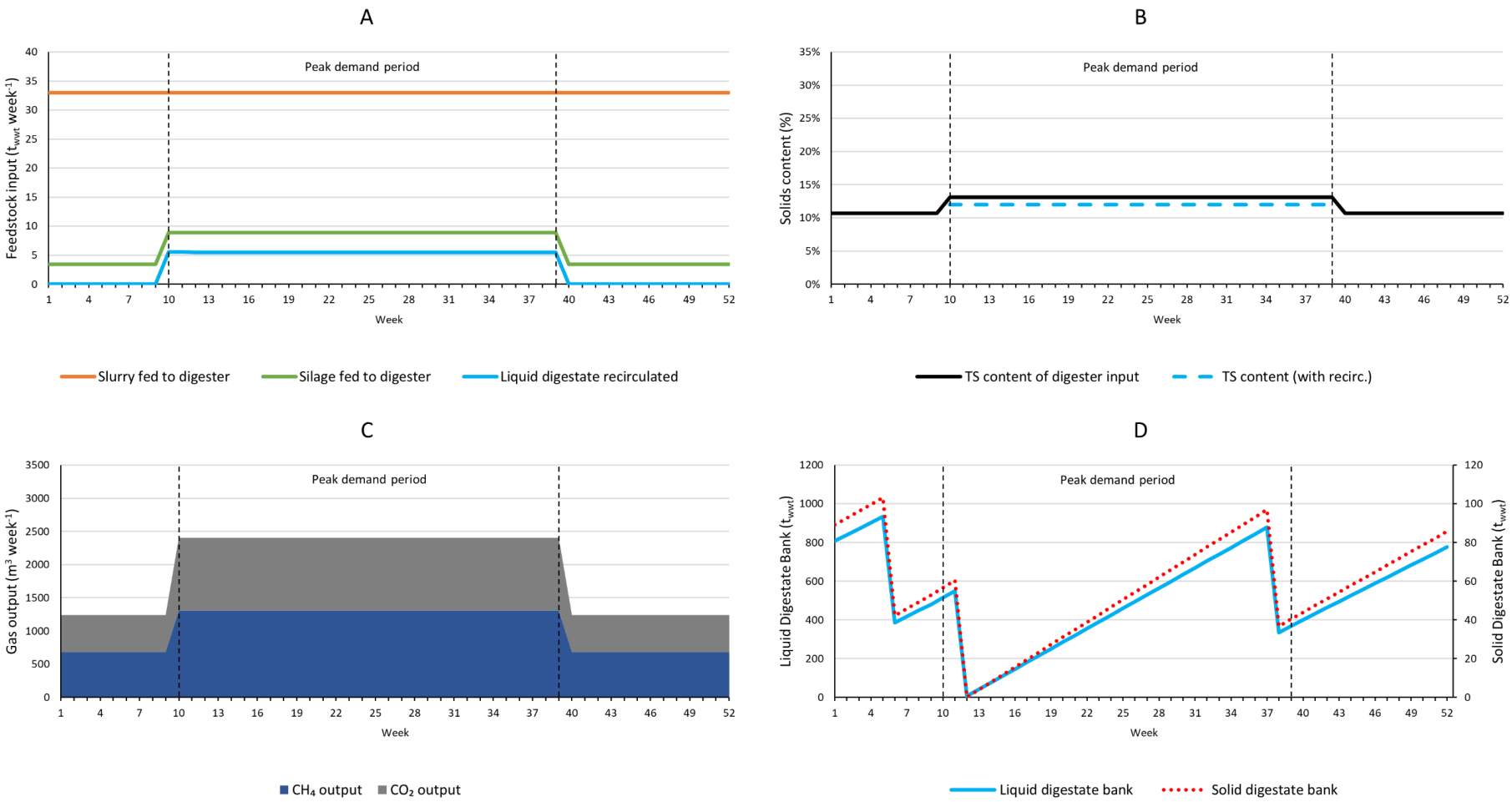


Figure 4-5: Scenario ZG-S, A) Weekly digester inputs, B) Digester solids content, C) Weekly digester gas output, D) Cumulative digestate bank.

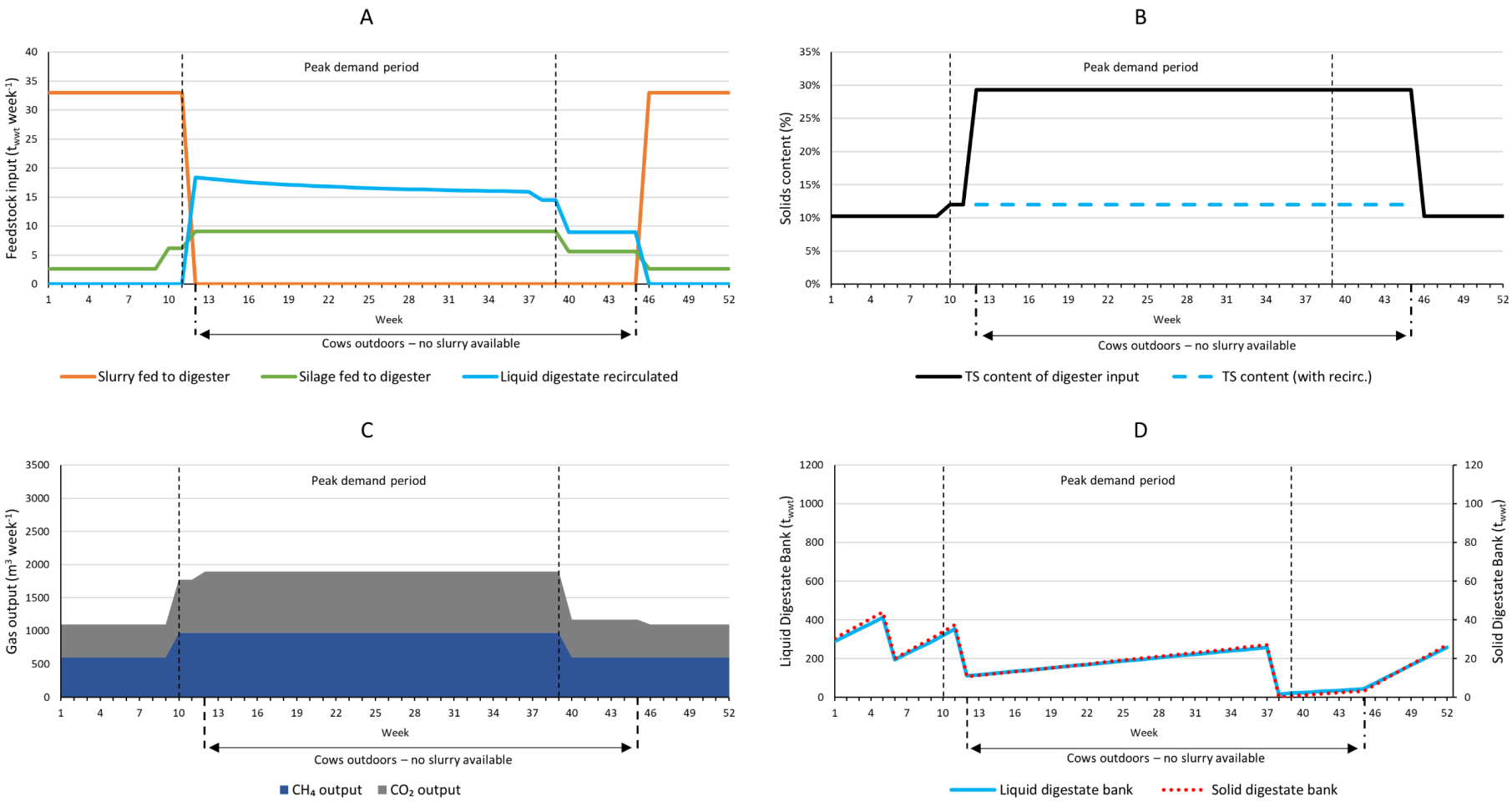


Figure 4-6: Scenario PB-S, A) Weekly digester inputs, B) Digester solids content, C) Weekly digester gas output, D) Cumulative digestate bank.

4.3.4 Comparison of operational characteristics

Table 4-6 shows the impact that the seasonal availability of slurry has on the operational characteristics of an on-farm AD plant producing biomethane. A lower heating value of 50 MJ kg^{-1} CH_4 was assumed, yielding an energy content of 35.88 MJ m^{-3} CH_4. Full weekly analysis of the scenarios can be found in Appendix B.3. The average CH_4 output per t_{wwt} of feedstock is higher in the PB scenarios than the ZG scenarios, as whilst less slurry is available in the PB scenarios, the majority of the biomethane comes from the grass silage digested, resulting in higher average biomethane outputs per tonne of total feedstock. The HRT increases dramatically in scenario PB-W due to there being very little feedstock input during the summer weeks when cows have pasture access, whilst the AD plant is sized for the period of maximum feedstock input during the peak demand period in winter (see Appendix B.3 and Appendix B.5 for full details).

Scenario	ZG-C	PB-C	ZG-W	PB-W	ZG-S	PB-S
Total Slurry Input (t_{wwt} a^{-1})	1,716	594	1,716	594	1,716	594
Total Silage Input (t_{wwt} a^{-1})	341.65	341.65	341.65	341.65	341.65	341.65
Max. Slurry Input (t_{wwt} $week^{-1}$)	33	33	33	33	33	33
Min. Slurry Input (t_{wwt} $week^{-1}$)	33	0	33	0	33	0
Max. Silage Input (t_{wwt} $week^{-1}$)	6.6	7.5	10.5	12.8	8.9	9.1
Min. Silage Input (t_{wwt} $week^{-1}$)	6.6	4.7	2.3	2.3	3.4	2.6
Max Digestate Recirc. Input (t_{wwt} $week^{-1}$)	0.8	15.5	8.9	25.3	5.6	18.4
Min Digestate Recirc. Input (t_{wwt} $week^{-1}$)	0.8	0	0	3.7	0	0
Required Digester Size (m^3)	230	216	300	278	271	224
Liquid Digestate Produced (t_{wwt} a^{-1})	1,740	747	1,734	746	1,737	746
Solid Digestate Produced (t_{wwt} a^{-1})	193	83	193	83	193	83
Liquid Digestate Bank Max. Storage (m^3)	927	434	913	476	933	412
Solid Digestate Bank Max. Storage (m^3)	103	47	101	52	103	44
Liquid Digestate Recirc. (t_{wwt} a^{-1})	39	468	237	419	164	519
Max. OLR (kg VS m^{-3} day^{-1})	2.46	2.30	2.40	2.43	2.42	2.47
Min. OLR (kg VS m^{-3} day^{-1})	2.46	1.34	1.35	0.32	1.65	0.96
Average OLR (kg VS m^{-3} day^{-1})	2.46	1.67	1.89	1.30	2.09	1.61
HRT Range (days)	40	40 - 77	40 - 59	40 - 322	40 - 52	40 - 108
Annual VS Ratio (Slurry VS : Grass VS)	56 : 44	30 : 70	56 : 44	30 : 70	56 : 44	30 : 70
Max. Biogas Flow (m^3 hr^{-1})	11.1	9.4	16.6	15.9	14.3	11.3
Min. Biogas Flow (m^3 hr^{-1})	11.1	8.7	6.2	2.9	7.4	6.5
Gross CH_4 Output (m^3 a^{-1})	52,856	41,912	55,146	43,127	54,174	42,255
Gross Energy Output (GJ a^{-1})	1,897	1,504	1,979	1,548	1,944	1,516
Average CH_4 Output (m^3 CH_4 t_{wwt}^{-1})	25.7	44.8	26.8	46.1	26.3	45.2

Table 4-6: Zero-grazing (ZG) and pasture-based (PB) characteristics for three gas demand scenarios.

4.4 EU RED II Sustainability

Table 4-7 shows the results of applying the EU recast REDII sustainability criteria towards the scenarios investigated in this work.

Scenario	Methane Losses %	Total emissions g $CO_{2\text{-eq}}$ MJ^{-1} CH_4	Sustainable for heat? < 14.4 g $CO_{2\text{-eq}}$ MJ^{-1} CH_4	Sustainable for transport? < 32.9 g $CO_{2\text{-eq}}$ MJ^{-1} CH_4
ZG-C	1	-3.27	Yes	Yes
	2	0.78	Yes	Yes
	3.55	8.86	Yes	Yes
PB-C	1	7.47	Yes	Yes
	2	12.55	Yes	Yes
	3.55	20.61	*No*	Yes
ZG-W	1	-2.88	Yes	Yes
	2	2.21	Yes	Yes
	3.55	10.30	Yes	Yes
PB-W	1	7.45	Yes	Yes
	2	12.53	Yes	Yes
	3.55	20.59	*No*	Yes
ZG-S	1	-3.05	Yes	Yes
	2	2.04	Yes	Yes
	3.55	10.12	Yes	Yes
PB-S	1	7.47	Yes	Yes
	2	12.55	Yes	Yes
	3.55	20.61	*No*	Yes

Table 4-7: Scenario emissions per MJ of biomethane per annum.

ZG scenarios with methane losses of 1% result in negative emissions, due to the inherent low methane losses in the system, the substantive emissions reduction awarded due to the improved slurry management system (-54 kg $CO_{2\text{-eq}}$ t_{wwt}^{-1} of slurry, as per RED II (European Parliament and European Commission, 2018)), and the higher ratio of dairy slurry VS in the digester compared to the PB scenarios.

4.5 Discussion

4.5.1 The effect of slurry availability on biomethane production

Given a fixed farm size, ZG systems maximise the potential for biomethane production. The seasonal availability of slurry in the PB scenarios reduces overall biomethane production and therefore gross energy output by ca. 21%. To counteract this reduction in biomethane output there are solutions outside the defined analysis; extra silage (beyond the 10 ha allocated towards AD) or other feedstocks may be added to the AD plant to increase the annual biomethane production. However, if slurry or other animal by-products such as food waste is obtained from outside the farm, it may be necessary to undertake pasteurisation prior to digester feeding as per the existing animal by-product regulations (Department of Agriculture Food and the Marine, 2009, 2014). Farmers also run the risk of making their AD plant less sustainable (as per the RED II recast) if more grass silage is used as feedstock due to the increased emissions from the cultivation of the silage, leading to an increase in the emissions per MJ of biomethane.

Gas demand seasonality has a minimal impact on the overall gas outputs, with a difference of less than 5% between the three ZG scenarios, and a difference of less than 3% between the three PB scenarios. Whilst the total annual slurry and silage inputs within the ZG scenarios are identical, the gas outputs from them differ due to the timing and quantity of the inputs and the different VS ratios during digestion. The same is true of the PB scenarios. However, the seasonal availability of slurry in the PB scenarios best matches the winter gas demand profile. Scenario PB-W requires significant amounts of digestate recirculation at the start and end of the peak winter gas demand period as slurry is no longer available; this leads to the elevated HRT (table 5). The seasonal availability of slurry does not correspond well to the summer gas demand profile, this necessitates very large amounts of liquid digestate recirculation during the peak summer demand period for scenario PB-S.

4.5.2 Digester size

The digester size required in the PB scenarios are smaller in size as compared to the ZG scenarios (from 6% to 17% smaller); the reduction in slurry feedstock in the PB scenarios leads to a lower maximum daily mass flow-rate. In effect, the PB scenarios may reduce the capital costs associated with digester construction, with the trade-off

being a potentially less sustainable biomethane product. However, the specific gas demand has a significant effect on the digester size. Meeting a seasonal (summer or winter) gas demand requires a larger digester (from 3.7% to 30% larger) compared to that of a constant gas demand owing to a higher daily mass input during peak demand periods which could increase the capital cost of an AD plant.

4.5.3 Digestate recirculation and storage

Increased recirculation requirements may have implications on the sustainability and operational costs of the AD plant, as large amounts of electricity may be required to recirculate the digestate and keep the solids content low. Each scenario requires some degree of digestate recirculation, while PB scenarios required significantly more recirculation than their respective ZG counterpart owing to limited slurry availability.

In the constant gas demand scenarios, the effect of slurry seasonality means that scenario PB-C requires over 12 times the amount of digestate recirculation compared to scenario ZG-C, as without slurry, the only feedstock used for input is grass silage with high solids content. Slurry availability also affects the gas production profile of scenario PB-C, as proportionally more silage is fed to the digester when livestock are on pasture in PB-C to compensate for the gas lost by not having slurry available to provide a constant annual biomethane output. This increase of silage feeding in the summer for PB-C results in additional digestate recirculation required to reduce the higher solids content of the feedstock.

In the winter gas demand scenarios, scenario PB-W requires 78% more digestate recirculation compared to scenario ZG-W owing to the seasonal availability of slurry. In scenario PB-W, the seasonality of slurry mostly affects operation outside of the peak demand period, however, livestock are outdoors for 9 weeks (weeks 12-15 and 41-45) of the peak demand period. During these weeks, significant liquid digestate recirculation is required to maintain the desired TS content of the digester. To combat high recirculation requirements, the silage feeding regime could be altered to coincide fully with the slurry feeding regime instead of the peak demand period.

In the summer gas demand scenarios, PB-S required 217% more recirculation than scenario ZG-S owing to the lack of availability of slurry. Scenario PB-S requires the most digestate recirculation of any scenario in this work. During the weeks in which the livestock are outdoors significant liquid digestate recirculation (70% of the total liquid digestate produced) is required to keep the digester solids content at 12%. This level of digestate recirculation is impractical and would have major cost and logistics implications for the AD plant operator.

Low rates of digestate recirculation can result in increased methane yields as the substrate may be digested for longer periods of time (Thamsiriroj and Murphy, 2011). However, liquid digestate recirculation can result in increased pH and alkalinity of the digester, which can allow for higher OLR values and more stable methane yields from the digester. Digestate recirculation must be closely monitored to assess its impact on the digestion process. If the digestion process is not efficient, continuous liquid recirculation may eventually lead to inhibited digestion processes due to an overaccumulation of organic and inorganic substances (Nordberg *et al.*, 2007).

The seasonal availability of slurry (PB scenarios) implies that farms in the PB scenarios require significantly less digestate storage than the farms in the ZG scenarios. Farmers may be able to repurpose existing slurry storage solutions towards liquid digestate, as their maximum liquid digestate storage requirements are lower than their required slurry storage volume. If additional storage solutions must be built to facilitate the digestate, farms in the ZG scenarios will have higher capital costs than those in the PB scenarios, as they produce far more digestate.

Less digestate is produced in the PB scenarios. Farmers must take this into consideration when planning how much digestate they require to be spread on land and whether they will need to purchase additional fertiliser. This may be an advantage for farmers if they would otherwise produce more digestate than their land required. However, digestate can also be sold as a commodity – less digestate produced will return less revenue to the farmer.

4.5.4 Organic loading rate

Both slurry availability and the specific gas demand have an effect on the OLR of the digesters. Seasonal availability of slurry in winter results in a lower average OLR in the PB scenarios compared to ZG systems. Peak OLR values may be similar; however, when livestock have pasture access, the summer OLR values are based on silage input to the digester as there is no slurry available. Digestate recirculation is not modelled as having an impact on the OLR in this work as a high VS destruction is assumed in digestion (minimising VS in liquid digestate) and therefore the VS in the liquid digestate have already been digested.

Gas demand seasonality results in a larger digester volume, which affects the OLR. In the winter gas demand scenarios, the OLR decreases significantly between weeks 16 and 40, as livestock have pasture access and no slurry is available, and also due to the fact that most of the silage is input during the peak demand period. The OLR varies less in the summer gas demand scenarios than in the winter gas demand scenarios as most of the silage is input whilst slurry is unavailable but is still lower on average than the constant gas demand scenarios. The peak demand period occurs mostly whilst cows have pasture access, leading to increased silage VS input during weeks 10-39.

Across all scenarios, however, the OLR is low compared to values considered optimal for gas production – an increase in the OLR could increase methane yields, however it would reduce the HRT which could inhibit digestion performance (Wall *et al.*, 2014).

The models presented herein assume that once the peak demand period commences, the digester inputs may be increased immediately– however, in real-world applications it is likely that the increase in OLR would happen over a longer period of time to avoid process instability.

4.5.5 Biogas flowrate

Reduced slurry availability in the PB scenarios results in lower biogas flow-rates than ZG scenarios. In the PB-C scenario, whilst the biomethane output is modelled as constant at all times, the biogas composition varies (due to the differing

composition of biogas from two feedstocks), leading to variations in raw biogas flow-rates.

Both slurry availability and gas demand have a significant effect on biogas flow-rates. However, if gas demand is constant throughout the year, managing biogas flow-rates is much simpler than with a fluctuating demand profile. When gas demand peaks during either the winter or summer periods, biogas flow-rates fall drastically outside the peak demand period. This large variation in biogas flow-rates is atypical for AD and may present problems for plant operators that wish to upgrade their biogas to biomethane, as generally, AD plants operate based on relatively constant biogas flow-rates. This problem presents itself most in scenario PB-W, where the period of low biogas flow-rate occurs for 25 weeks of the year. In this scenario, more silage may need to be reserved towards weeks 16-40 to increase the biogas flow-rate. It may be more plausible for biogas plants in regions with pasture-based farming to simply shut down in summer whilst cows are outdoors, and slurry is not being collected.

Low biogas flow-rates may be a problem for all scenarios as current upgrading systems are expensive for flowrates of less than 100 $Nm^3\ hr^{-1}$ and are rare at flowrates of less than 40 $Nm^3\ hr^{-1}$ (IEA, 2014). Biogas storage may be required on farms operating small-scale AD plants to facilitate intermittent upgrading of biogas or mobile upgrading solutions (Gil-Carrera *et al.*, 2019) that need high biogas flowrates. Alternatively, a number of farms may co-operate and upgrade their biogas centrally by transporting their biogas to a central upgrading facility via biogas pipeline (Wall, Dumont and Murphy, 2018), overcoming the low biogas flow-rates.

4.5.6 Environmental sustainability and biomethane use

System methane losses are the biggest factor in determining the sustainability of the scenarios described. System methane losses of less than 2% will help AD operators ensure that the biomethane produced is sustainable, whether the end-use is heat or transport.

The seasonal availability of slurry in PB scenarios does affect the sustainability of the AD plant. The amount of silage digested in each scenario does not change, however the PB scenarios have less slurry to digest than the ZG scenarios, resulting

in higher proportions of grass silage being used. This can increase the GHG emissions intensity of the resulting biomethane. On average, the PB scenarios produce 10.7 g $CO_{2\text{-eq}}$ MJ^{-1} CH_4 more than their ZG counterparts. Methane losses of 3.55% suggests that the AD plants which operate using seasonally available slurry are not deemed sustainable if the end use of the biomethane is heat. Overall lifecycle negative emissions are only possible in the ZG scenarios with methane losses of 1%. The net increase in emissions in the PB scenarios compared to the ZG scenarios is primarily due to increased methane yield per t_{wwt}, and therefore system methane losses per t_{wwt}, over an annual period with proportionally increased silage use in digestion. Full sustainability calculations for each scenario can be found in Appendix B.1.

Seasonal gas demand has no significant effect on sustainability, as sustainability calculations are based on annual average VS ratios and biomethane production. However, slight variations exist in the emissions due to the timing of feedstock inputs and their varying co-digestion methane yields. This work assumes that slurry goes directly from the cow to the digester, and therefore no fugitive emissions are associated with slurry storage. However, operators should consider whether their own slurry management system will have fugitive emissions. Methods to minimise fugitive methane emissions include the use of covered digestate storage. Higher grass cultivation emissions may also lead to unsustainable biomethane.

4.6 Conclusion

The hypothesis of this work proved correct, in that pasture-based farming AD systems can adapt to function at times when there is limited feedstock availability and seasonal gas demand, despite the effects on the operation of the system. However, if on-farm AD is to be employed in countries where livestock have pasture access for multiple months of the year, the implications of seasonal slurry availability, and also in conjunction with seasonal gas demand, have to be analysed.

Seasonal slurry availability can result in 21% less biomethane production if the slurry that is not being collected whilst cows have pasture access is not replaced with an alternative feedstock. If this is counteracted by the proportional increase of silage input (or other feedstocks), sustainability and pasteurisation requirements must be considered. If the other feedstock(s) in the AD process have a high solids content, limited slurry availability necessitates that significant quantities of liquid digestate be recirculated to control the solids content of the digester. Seasonal availability of slurry decreases the required digester size – by up to 17% in the scenarios investigated. Optimal OLR values may be difficult to reach for farmers operating pasture-based systems due to the lack of slurry for long periods of the year. The actual desire to reduce the OLR may not be an issue as the prohibition on land spread of slurry and/or digestate during winter requires significant winter storage, which is offered by the AD tanks.

Gas demand seasonality was found to have implications on the operations of on-farm AD plants. Facilitating seasonal gas demand profiles may require larger AD plants – up to 30% larger in the scenarios investigated. Facilitating seasonal gas demand profiles requires larger AD plants – up to 30% larger in the scenarios investigated. Seasonal gas demand requires AD plants to recirculate large amounts of liquid digestate during certain weeks of the year, particularly if no slurry is available, with scenario PB-S requiring 519 t a^{-1} of liquid digestate recirculation. A seasonal gas demand can result in significantly lower OLRs, especially for AD plants facilitating a winter gas demand with pasture-based livestock. Facilitating seasonal gas demands can also affect the biogas flow-rates of on-farm AD plants, which may be a limiting factor depending on the end-use of the biomethane, or if it is to be upgraded or stored on-site.

The sustainability of on-farm AD plants may be affected by seasonal slurry availability due to proportionally higher grass concentrations added to the digester, with seasonal slurry availability causing an increase of ca. 11 g $CO_{2\text{-eq}}$ per MJ of biomethane in the scenarios investigated. Emissions associated with grass cultivation may make on-farm AD plants that are overly reliant on grass unsustainable. Achieving whole lifecycle negative emissions may be difficult with lower proportions of slurry. Alongside the slurry to grass VS ratios, on-farm AD plant operators should focus on reducing their grass cultivation emissions and lowering methane slippage from the digester to ensure the sustainability of the biomethane produced. Future works should analyse the changing chemical composition of digestate produced by AD plants operating with seasonally available slurry, to investigate whether this would change the digestate spreading strategy of the farmer. Additional works should also analyse whether the changing OLR values of an AD plant fed with seasonally available feedstocks has a significant effect on the quantity of biomethane produced.

References

Beil, M. and Beyrich, W. (2013) '15 - Biogas upgrading to biomethane', in A. Wellinger, J. Murphy, and D. Baxter (eds) Woodhead Publishing Series in Energy. Woodhead Publishing, pp. 342–377. Available at: https://doi.org/https://doi.org/10.1533/9780857097415.3.342.

CSO (2021) Milk Statistics - CSO - Central Statistics Office. Available at: https://www.cso.ie/en/statistics/agriculture/milkstatistics/ (Accessed: 27 May 2021).

Department of Agriculture Food and the Marine (2009) CN11 Conditions for approval and operation of biogas plants treating animal by-products in Ireland. Available at: https://www.gov.ie/en/publication/8c7cd-conditions-for-abp-processing-operations/ (Accessed: 17 August 2020).

Department of Agriculture Food and the Marine (2014) CN9 Conditions for approval and operation of on-farm biogas plants transforming own animal by-products. Available at: https://www.gov.ie/en/publication/8c7cd-conditions-for-abp-processing-operations/.

Drosg, B. et al. (2015) IEA Task 37: Nutrient Recovery by Biogas Digestate Processing. Available at: http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical Brochures/NUTRIENT_RECOVERY_RZ_web1.pdf (Accessed: 30 September 2021).

European Parliament and European Commission (2018) 'Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)', Official Journal of the European Union, 61, pp. 82–209.

Geraghty, R. (2011) Benchmarking Resource Efficiency in Irish Dairy Processing. Available at: https://www.leanbusinessireland.ie/includes/documents/Resource Efficiency Dairy Processing Ireland TOTAL JUNE 2011.pdf (Accessed: 4 November 2021).

Gil-Carrera, L. et al. (2019) 'Feasibility study of an off-grid biomethane mobile solution for agri-waste', Applied Energy, 239(January), pp. 471–481. Available at: https://doi.org/10.1016/j.apenergy.2019.01.141.

Hennessy, T. et al. (2011) National Farm Survey of Manure Application and Storage Practices on Irish Farms. Available at: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf (Accessed: 1 April 2019).

IEA (2014) Upgrading Plant Lists - IEA Bioenergy Task 37, IEA Bioenergy Task 37. Available at: http://task37.ieabioenergy.com/plant-list.html (Accessed: 14 August 2020).

Long, A. et al. (2021) 'Implications of European Union recast Renewable Energy Directive sustainability criteria for renewable heat and transport: Case study of willow biomethane in Ireland', Renewable and Sustainable Energy Reviews, 150, p. 111461. Available at: https://doi.org/10.1016/J.RSER.2021.111461.

Long, A. and Murphy, J.D. (2019) 'Can green gas certificates allow for the accurate quantification of the energy supply and sustainability of biomethane from a range of sources for renewable heat and or transport?', Renewable and Sustainable Energy Reviews, 115, p. 109347. Available at: https://doi.org/10.1016/j.rser.2019.109347.

McEniry, J. et al. (2013) 'How much grassland biomass is available in Ireland in excess of livestock requirements?', Irish Journal of Agricultural and Food Research, 52(1), pp. 67–80. Available at: http://www.jstor.org/stable/23631018.

McGeever, A.H. et al. (2019) 'Assessing the terrestrial capacity for Negative Emission Technologies in Ireland', Carbon Management, 10(1), pp. 1–10. Available at: https://doi.org/10.1080/17583004.2018.1537516.

Murphy, J.D., McKeogh, E. and Kiely, G. (2004) 'Technical/economic/environmental analysis of biogas utilisation', Applied Energy, 77(4), pp. 407–427. Available at: https://doi.org/10.1016/j.apenergy.2003.07.005.

Murphy, J.D. and Thamsiriroj, T. (2013) 'Fundamental science and engineering of the anaerobic digestion process for biogas production', in The Biogas Handbook: Science, Production and Applications. Woodhead Publishing, pp. 104–130. Available at: https://doi.org/10.1533/9780857097415.1.104.

Nordberg, Å. et al. (2007) 'Anaerobic digestion of alfalfa silage with recirculation of process liquid', Bioresource Technology, 98(1), pp. 104–111. Available at: https://doi.org/10.1016/J.BIORTECH.2005.11.027.

O'Callaghan, T. et al. (2017) Dairy products from grass are simply better. Available at: https://www.teagasc.ie/media/website/publications/2017/Segment-006-of-Todays-Farm-July-Aug2017.pdf (Accessed: 11 October 2021).

Ó Céileachair, D. et al. (2021) 'Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane', Applied Energy, 303, p. 117627. Available at: https://doi.org/10.1016/j.apenergy.2021.117627.

Scott, A. and Blanchard, R. (2021) 'The Role of Anaerobic Digestion in Reducing Dairy Farm Greenhouse Gas Emissions', Sustainability. Available at: https://doi.org/10.3390/su13052612.

SEAI (2020) Anaerobic Digestion for On-farm Uses-Implementation Guide. Available at: https://www.seai.ie/publications/Anaerobic Digestion - Implementation Guide (Accessed: 31 August 2021).

Shine, P. et al. (2020) 'Energy Consumption on Dairy Farms: A Review of Monitoring, Prediction Modelling, and Analyses', Energies, 13(5). Available at: https://doi.org/10.3390/en13051288.

Smyth, B.M., Murphy, J.D. and O'Brien, C.M. (2009) 'What is the energy balance of grass biomethane in Ireland and other temperate northern European climates?', Renewable and Sustainable Energy Reviews, 13(9), pp. 2349–2360. Available at: https://doi.org/10.1016/j.rser.2009.04.003.

Teagasc (2020) Grass10. Available at: https://www.teagasc.ie/crops/grassland/grass10/ (Accessed: 27 August 2020).

Teagasc et al. (2021) Teagasc National Farm Survey 2020 Preliminary Results.

Thamsiriroj, T. and Murphy, J.D. (2011) 'Modelling mono-digestion of grass silage in a 2-stage CSTR anaerobic digester using ADM1', Bioresource Technology, 102(2), pp. 948–959. Available at: https://doi.org/10.1016/J.BIORTECH.2010.09.051.

UNFCCC and UN (2021) 'The Glasgow Climate Pact', in 2021 United Nations Climate Change Conference (COP26). Glasgow: UNFCCC. Available at: https://ukcop26.org/cop26-presidency-outcomes-the-climate-pact/.

Wall, D.M. et al. (2014) 'Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry', Bioresource Technology, 173, pp. 422–428. Available at: https://doi.org/10.1016/j.biortech.2014.09.126.

Wall, D.M., Dumont, M. and Murphy, J.D. (2018) Green gas - Facilitating a future green gas grid through the production of renewable gas, IEA Bioenergy Task 37. Edited by J.D. Murphy. IEA Bioenergy. Available at: https://www.ieabioenergy.com/blog/publications/green-gas-facilitating-a-future-green-gas-grid-through-the-production-of-renewable-gas/ (Accessed: 17 July 2023).

Wall, D.M., O'Kiely, P. and Murphy, J.D. (2013) 'The potential for biomethane from grass and slurry to satisfy renewable energy targets', Bioresource Technology, 149, pp. 425–431. Available at: https://doi.org/https://doi.org/10.1016/j.biortech.2013.09.094.

Wall, D.P., Plunkett, M. and Teagasc (2020) Major and Micro nutrient advice for productive agricultural crops. Available at: https://www.teagasc.ie/media/website/publications/2020/Major--Micro-Nutrient-Advice-for-Productive-Agricultural-Crops-2020.pdf (Accessed: 8 October 2021).

5 Logistical considerations and challenges in deploying virtual biomethane pipelines to serve on-farm biogas plants

Logistical considerations and challenges in deploying virtual biomethane pipelines to serve on-farm biogas plants

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Abstract:

On-farm anaerobic digestion plants served by virtual biomethane pipelines may be used in areas with no gas grid infrastructure access to improve manure (slurry) management and to produce and deliver renewable gas. A modelling analysis of a simulated virtual biomethane pipeline is presented whereby gas is collected from 100 on-farm biogas plants fed with slurry and grass silage feedstocks and delivered to a market entry point (depot). In total, 7 scenarios are presented in the analysis. In scenarios 1-4, the biogas is upgraded on-site by the digester operator, the biomethane is collected by the haulage vehicle(s) and transported to a single depot. The impact of an additional depot on vehicle routing is investigated in scenarios 5 and 6. Scenario 7 investigates the use of a mobile-upgrading and compression unit, which would allow biogas plant operators to forego the installation and operation of biogas upgrading facilities. In scenario 3 (which considers the largest capacity biomethane haulage vehicles and a single delivery depot) all 100 anaerobic digestion plants are visited over the course of one week using 4 routes, with a total aggregated distance travelled of 205 km. Scenario 7 requires a total routing distance in excess of 613 km to visit all 100 biogas plants and requires long routing times and periods of downtime at each site due to the slow upgrading speed of the mobile unit. The weekly greenhouse gas emissions due to vehicle routing from each scenario are calculated. Assuming diesel-fuelled haulage vehicles, scenario 7 routing results in 431 kg $CO_{2\text{-eq}}$ $week^{-1}$, a 167% increase in vehicle route emissions compared to

scenario 3 (161 kg $CO_{2\text{-eq}}$ $week^{-1}$). Additionally, whilst the mobile-upgrading unit may alleviate financial challenges, they carry significant logistical challenges, and their resultant higher routing emissions will impact the sustainability of the collected biomethane. Biomethane fuelled haulage vehicles may address this concern if the biomethane is sustainably sourced.

Keywords: Virtual biomethane pipeline, vehicle routing problem, slurry, grass silage, simulation, biogas transportation.

5.1 Introduction

Countries that participated in COP26 have agreed to limit the increase in global average temperatures to 1.5 °C above pre-industrial levels by reducing greenhouse gas (GHG) emissions and financing low emissions pathways (UNFCCC and UN, 2021). EU member states are obligated, under the Renewable Energy Directive (RED), to increase the share of renewable energy in their overall energy consumption (European Parliament and European Commission, 2018). Ireland, for example, has committed to achieving a 34% renewable energy share by 2030 (Department of Communications Climate Action and Environment, 2020). Natural gas accounts for almost 31% of Ireland's total primary energy requirement (SEAI, 2019). Gas Networks Ireland (GNI), the Irish gas network operator, has subsequently set a target of 20% renewable gas on the network by 2030 (GNI, 2019). Meanwhile, Ireland's agricultural sector accounted for 37.5% of the total annual GHG emissions in 2021, with 11.7% of agricultural emissions coming from manure management practices (Environmental Protection Agency, 2022). In essence, the decarbonisation of Ireland's natural gas network and agricultural sector are both essential to fulfilling the country's COP26 and EU RED obligations. Anaerobic digestion (AD) provides an important means by which Ireland's abundant agricultural biomass resources could be utilised to produce sustainable biogas and biomethane (renewable gas) (O'Shea, Kilgallon, *et al.*, 2016a) whilst also reducing agricultural GHG emissions (Wall, O'Kiely and Murphy, 2013). Ireland has set out to reduce its GHG emissions from agriculture by 25% by 2030 (Department of the Environment Climate and Communications, 2022); it is thought that AD can assist in this undertaking.

The abundance of cattle manure (hereafter referred to as slurry) and the intrinsic expertise in the growth, harvesting, and storage of grass present two significant opportunities to establishing on-farm AD in Ireland (Beausang, McDonnell and Murphy, 2021). The availability of slurry on Irish dairy farms may present a valuable resource for on-farm anaerobic digestion to produce biogas and reduce the fugitive methane emissions associated with the storage of slurry. There are approximately 18,000 family-owned dairy farms operating throughout the Republic of Ireland (Moscovici Joubran *et al.*, 2021). In 2020 there were approximately 1.6 million dairy cows in Ireland (CSO, 2020). Grass silage may be considered the crop of choice for AD (with mixed-species swards most amenable to sustainability due to lower

fertiliser requirements); other energy crops such as maize silage are not as commonly harvested in Ireland (IEA Bioenergy: Task 37, 2019).

Ó Céileachair *et al.* (2021) previously determined that over one third of the on-farm biomethane resource in Ireland was decentralised, that is, more than 12.5 km away from gas grid infrastructure. The distributed nature of this resource suggests that the transportation of these renewable gases from on-farm AD plants to the end user(s) is an avenue for research and optimisation. The delivery of renewable gas (biogas) from a producer to an end user can be achieved through different means depending on whether it is upgraded to biomethane (via the removal of CO_2 from the biogas) or not. If the biogas is not upgraded, it must be used either on-site or transported via a biogas pipeline, as has been demonstrated in the Netherlands (IEA Bioenergy: Task 37, 2017). Transporting biogas via compressed cylinders, whilst possible, poses problems due to the CO_2 content of the biogas (typically 40 – 50 $\%_{vol}$) (Hovland, 2017). A virtual pipeline is a gas delivery system that transports biomethane via haulage of gas cylinders as opposed to traditional pipeline infrastructure, and is commonly used in areas where there is no gas grid access or in countries that have limited gas grid infrastructure (Udaeta, 2012).

In a traditional virtual biomethane pipeline, on-site biogas upgrading and biomethane storage is employed by the biogas plant operator and the biomethane is collected by a haulier. As an alternative to traditional virtual biomethane pipelines, a mobile-upgrading and compression unit may be used (Gil-Carrera *et al.*, 2019). A mobile-upgrading and compression unit may travel to an AD plant site, upgrade biogas (which is stored on-site) to biomethane via pressure swing absorption (PSA), then store that biomethane in the mobile-upgrading unit whilst the unit travels to another AD plant site and repeats the process. Such a mobile-upgrading and compression unit system may alleviate the financial constraint on individual biogas plants by allowing the sharing of a biogas upgrading unit with other plants in proximity. A flow chart of an operating virtual biomethane pipeline supply chain as may exist in a region that has a pasture-based farming system can be seen in Figure 5-1.

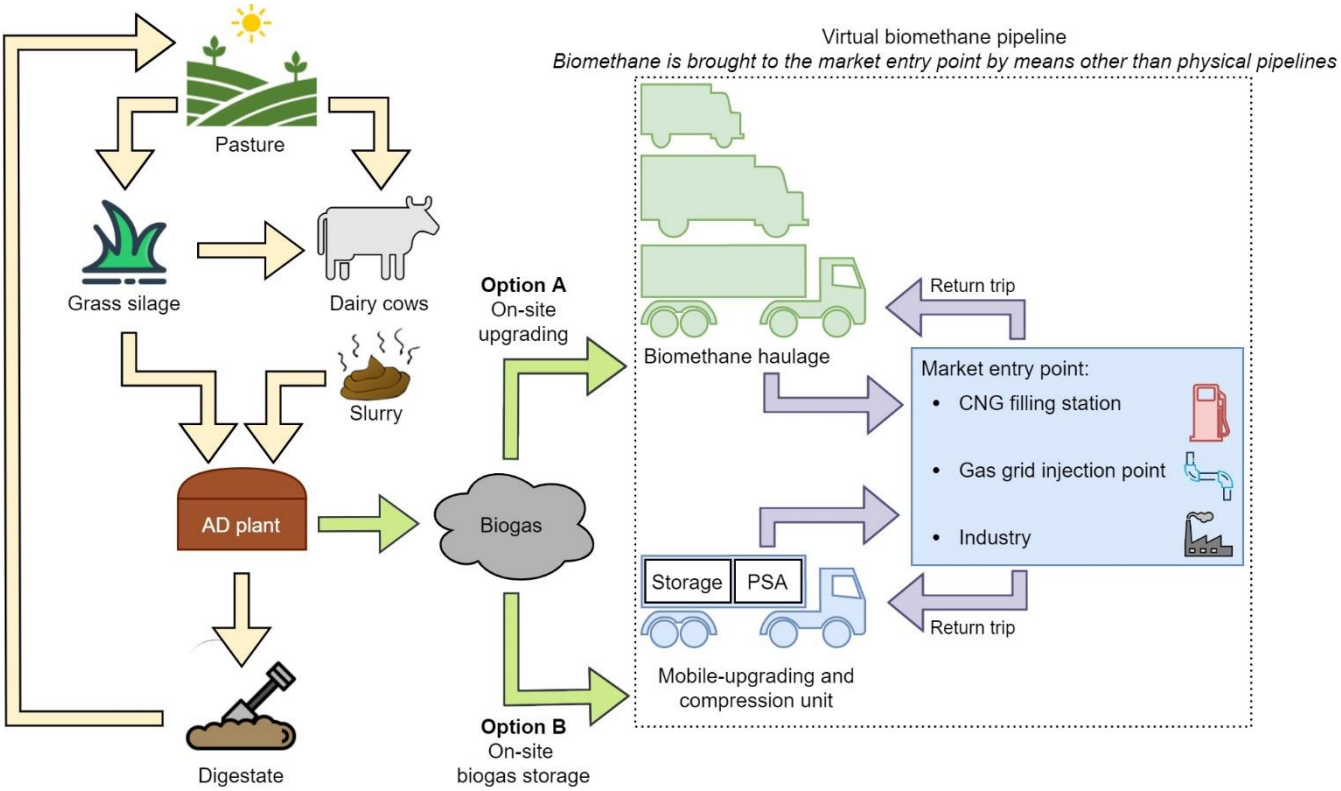


Figure 5-1: A virtual biomethane pipeline process supply chain, where biomethane is moved via haulage to the market entry point.

The collection and transportation of biomethane produced by on-farm small-scale AD facilities (O'Connor, E. Ehimen, *et al.*, 2021) share many characteristics with the logistical supply chain of raw milk from supplier to processor (O'Callaghan, O'Connor and Goulding, 2021). Analogous to milk, biomethane must be safely stored on site and regularly collected using purpose-built haulage trucks that must be able to access and exit the site safely. Previous works by Butler *et al.* (2005), O'Callaghan *et al.* (2018) and Paredes-Belmar *et al.* (2021) have reported on the collection and transportation of raw milk. Virtual biomethane pipeline operators must find the most optimal routing system in order to both maximise profits and ensure that the biomethane produced is priced competitively on the market. The optimisation of such virtual biomethane pipelines may be achieved through the use of vehicle routing problem (VRP) techniques and solutions.

Of particular interest for this work is the VRP variant known as the capacitated vehicle routing problem (CVRP) (Laporte and Semet, 2002). The CVRP is a VRP in which the vehicles have a carrying capacity limitation of the items or products that they pick up at each location – this would be of paramount importance to the transportation of products such as gases.

A virtual biomethane pipeline fleet may comprise of one vehicle size or many – depending on the road and routing requirements of the virtual pipeline network. A routing operator may decide to service some stops with small vehicles, and other stops with larger vehicles. This flexibility in vehicle configuration allows for further optimisation of routing than restricting the network to one vehicle type. The number of depots may also be a deciding factor in the logistical viability of a virtual biomethane pipeline – biomethane produced by the network must have an end-user, and it is possible that one depot may not have enough biomethane demand to justify the virtual pipeline network.

The aim of this paper is to assess the logistical challenges and considerations of a virtual biomethane pipeline, serving on-farm AD plants, based on a VRP model. The innovation in this paper is that it provides a method to optimise vehicle routing for virtual biomethane pipelines based on CVRP techniques that are commonly used for other industries. The hypothesis of this work is that these VRP techniques may be applied to the optimisation of virtual biomethane pipelines to evaluate the logistical viability of different collection strategies, and to identify challenges that may arise in the implementation of such systems. Seven virtual biomethane pipeline scenarios, of differing configurations (vehicle size ranging from 10 to 45 ft, one or two depots, etc.), each serving 100 small-scale on-farm AD plants, will be investigated in this work. All farms produce biogas with slurry and grass silage (if there is surplus to feeding requirements available). The farms are within an area of approximately 400 km^2. The method considers two types of virtual pipelines:

1. A conventional virtual pipeline in which haulage vehicles collect biomethane (which is upgraded on-farm by the AD plant operator) from the on-farm AD plants.
2. A virtual pipeline which uses mobile-upgrading and compression units, whereby the unit visits the AD plants, upgrades the biogas, and subsequently transports the resultant biomethane from the AD plants.

The transportation emissions resultant from operating the optimised routes are also calculated. The preferred scenario will be the one that includes for shortest routing distance, which in turn leads to the lowest emissions due to transport GHG

emissions. However, the merits and challenges associated with each scenario and their parameters must also be considered and will be evaluated in the analysis.

The methodology developed in this work could be applied to any region, and also to any configuration and size of AD plants and depots, in order to determine the optimal vehicle routing to or from the depot(s) and the biomethane source. The specific objectives of this work are to:

i. Investigate the logistical considerations of operating a virtual biomethane pipeline with either single use or concurrent use of 10, 20, or 45 ft haulage vehicles.
ii. Assess the logistical implications of an additional depot on the virtual pipeline.
iii. Outline the logistical implications of operating a virtual pipeline with mobile-upgrading and compression units.
iv. Calculate the transport-specific greenhouse gas emissions resultant from the haulage routes for each scenario.

5.2 Methodology

5.2.1 Farm locations and sizes

One hundred (100) farm locations were selected from a region in southern Ireland where dairy farming is the main class of agriculture practiced. The farms were selected using satellite imagery available through Google Maps from a land area of approximately 400 km^2. The three features used to identify a potential dairy farm for the analysis were: slurry storage; silage storage; and cattle shed facilities. Once the farm locations were selected, variable farm sizes and stocking rates , based on nationally available farm size and stocking rate statistics, were applied randomly to each of the farms (Hanrahan *et al.*, 2018). Irish farm stocking rates for dairy herds range from 2 to 3 cows ha^{-1} (Humphreys, Barrett and Fenger, 2019). Two potential depot locations (A & B) were selected, using satellite imagery through Google Maps in the same area, by identifying industry locations.

5.2.2 Dairy slurry and grass silage feedstocks

The number of cows on each farm in this work can be calculated by dividing the farm size by the stocking rate (both randomly assigned). In Ireland, cattle are housed for a typical period of between 16 to 22 weeks per year, over the winter months, and the slurry storage requirement for dairy cow slurry is 0.33 m^3 cow^{-1} $week^{-1}$ (Hennessy *et al.*, 2011), assumed to be equivalent to 0.33 t_{wwt} cow^{-1} $week^{-1}$. It is assumed in this work that the cows are housed for 18 weeks of the year, and that this slurry can be stored and used at a constant rate throughout the year. Therefore, a dairy farm in Ireland that has 100 cows will collect ca. 594 m^3 of dairy cow slurry per year. The total dairy slurry resource at each farm in terms of wet tonnes (t_{wwt}) was calculated using Eq. (5.1).

Eq. (5.1); dairy slurry resource per farm, in tonnes, ($m^{dairy\ slurry}$):

$$m^{dairy\ slurry} = N_{dairy\ cows} * S_{dairy\ cows} * T_{housed} \quad (5.1)$$

In Eq. (5.1), $m^{dairy\ slurry}$ is the mass of feedstock in tonnes, $N_{dairy\ cows}$ is the number of dairy cows on each farm, and $S_{dairy\ cows}$ is the slurry storage requirements per cow in m^3 per week, and T_{housed} is the number of weeks the dairy cows are housed per annum.

Grass silage yields in some regions in Ireland could be 10.66 t DM ha^{-1} a^{-1} with correct fertiliser application practices (McEniry *et al.*, 2013). Grass silage production is less than the actual grass growth. It has been reported that farms growing an average of 14 t DM ha^{-1} a^{-1} across the entire farm could support a dairy cow stocking rate of 2.5 cows ha^{-1} with a concentrate supplementation of 500 kg cow^{-1} (O'Donovan and Egan, 2019). Grazed grass and silage grass requirements per dairy cow were reported by McEniry *et al.* to be 3,671 kg DM^{-1} $head^{-1}$ and 1,495 kg DM^{-1} $head^{-1}$, respectively. The grazed grass and silage grass requirements per farm were calculated using Eq. (5.2).

$$m^{\theta\ req.} = N_{dairy\ cows} * M^{\theta\ req.}_{dairy\ cows} \tag{5.2}$$

Where $m^{\theta\ req.}$ is the total required mass of grass in t DM (where θ represents grazed grass or silage) for dairy cow feeding across the farm, N is the number of dairy cows, and $M^{\theta\ req.}_{dairy\ cows}$ is the required mass of grass in t DM (grazed or silage) per dairy cow.

Eq. (5.3) and Eq. (5.4) were used to calculate the required hectares under grazed grass and silage grass at each farm:

$$H_{grazed} = \frac{m^{grazed\ req}}{Y grazed} \tag{5.3}$$

$$H_{silage} = \frac{m^{silage\ req}}{Y silage} \tag{5.4}$$

where H is the hectares of land under each grass (grazed or silage), $m^{\theta\ req}$ the mass of each grass type, in t DM, required for dairy cow feeding, and Y^{θ} the yields of grazed grass or grass silage, in t DM per hectare (assumed to be optimal values of 14 t DM ha^{-1} and 10.66 t DM ha^{-1}, respectively). The authors are aware that, in reality, some areas of a farmer's land may be used for both grazing and for harvesting silage, and that many hectares will have multiple purposes depending on each farmer's individual circumstances and local climate conditions; this methodology provides a minimum available amount that should be available each year.

Eq. (5.5) was used to find the number of hectares each farm could dedicate to harvesting silage for AD.

$$H_{AD} = H_{Farm} - \left(H_{grazed} + H_{silage}\right) \quad (5.5)$$

Where H_{AD} is the number of hectares which are available to dedicate to AD and H_{Farm} is the farm's total land area (randomly assigned). If a farm had "negative" hectares available to dedicate to AD, H_{AD} was set to 0 as there is no land available to dedicate to AD.

Eq. (5.6) was used to find the amount of silage each farm could dedicate to AD.

$$m_{AD}^{silage} = H_{AD} * Y^{silage} \quad (5.6)$$

Where m_{AD}^{silage} is the available mass of silage that can be used for AD in t DM, and Y^{silage} are the silage yields in t DM per hectare. A constant rate of silage consumption was considered throughout each week in a year. Table 5-1 shows the characteristics of dairy slurry and grass silage used to calculate the weekly biomethane outputs from each farm. The methane yields of Irish grass silage used in this work, as reported by Wall *et al.* (2014, 2013), and additionally by Allen *et al.* (2016), are higher than those in European countries (Pakarinen *et al.*, 2008; Ravina *et al.*, 2019).

Feedstock	**Dry Solids (%$_{wwt}$)**	**Volatile Solids (%$_{wwt}$)**	**Specific Methane Yield (L CH_4 kg^{-1} VS)**	**CH_4 % in Biogas (%)**	**Sources**
Dairy Slurry	8.75	6.69	143	54.2	(Wall, O'Kiely and Murphy, 2013; Wall *et al.*, 2014)
Grass Silage	29.27	26.84	400	51.2	(Wall, O'Kiely and Murphy, 2013; Wall *et al.*, 2014)

Table 5-1: Feedstock characteristics.

5.2.3 Biomethane haulage

The different biomethane haulage vehicles used for the storage and transportation of biomethane in the VRP solver, and their respective properties, are shown in Table 5-2. Information on the various trailers were found on a manufacturer's website (Quantum Fuel Systems, 2022).

Vehicle Name	VPLite8 (towable)	VPLite21/20'	VPLite51/45'
Haulage vehicle length (ft) [1]	10	20	45
Empty mass (kg)	4,892	9,799	19,526
Full mass (kg)	6,599	14,280	30,344
Biomethane storage capacity (Nm^3) *	2,452	6,436	15,536

1 Feet used as vehicle length unit as per industry standard.

* Nm^3 conditions are natural gas when at 0 °C and absolute pressure of 1.01325 bar occupies the volume of 1 m^3.

Table 5-2: CNG trailers used for VRP analysis.

The flow-rate for filling the CNG haulage vehicles was 97 Nm^3 min^{-1}, based on CNG trailer filling specifications from an industrial supplier (Clean Energy Fuels, 2022). The mobile-upgrading and compression unit as described by Gil-Carrera *et al.* (2019) had a trailer length of 45 ft, a biogas upgrading capacity of 250 Nm^3 hr^{-1}, and a biomethane storage capacity of 4,200 Nm^3.

5.2.4 VRP solver and prescribed scenarios

To solve the Capacitated Vehicle Routing Problem presented in this work, the authors have utilised the VRP Spreadsheet Solver (Erdoğan, 2017), which is an open-source Microsoft Excel GIS-based tool for solving various categories of the CVRP. These include problems that incorporate issues relating to multiple haulage capacities, varied supplier production volumes, and multiple depot constraints. The VRP Spreadsheet solver utilises a variant of the Adaptive Large Neighbourhood Search as described by Pisinger and Ropke (2007). GPS location data for AD site locations and the depots are entered, along with associated weekly biomethane or biogas volumes that were assigned to each AD site. The road distances in kilometres between all of the AD sites were calculated by the tool, using Microsoft Bing Maps, and stored. Additionally, the road distances between each AD site and the depots (customer sites) used in each scenario were calculated.

Seven scenarios were constructed to demonstrate the versatility of the model in relation to virtual pipeline design. These scenarios are outlined in Table 5-3. In scenarios 1-6, on-site biogas upgrading and storage of the resultant biomethane is

employed, and the biomethane haulage trucks are filled when they arrive on-site. The driving hours in scenarios 1-6 are 9 hours per day; that is, the haulage vehicles may be away from the depot for 9 hours before returning. For scenarios 4-6, multiple capacity haulage vehicles and/or multiple depots were used for collection routing. Scenario 7 employs mobile-upgrading and compression units, of which there is only one type of vehicle, with on-site biogas storage until the mobile-upgrading and compression unit arrives to upgrade the biogas to biomethane and transport it offsite. In scenario 7 the maximum driving time is 17 hours per day; this is to facilitate the slow biogas upgrading process of the mobile upgrading unit (see Appendix C.1, Table C-2, Farm 84, 4,230 Nm^3 biogas $week^{-1}$, divided by 250 Nm^3 hr^{-1} upgrading capacity, 16 hours and 55 mins). The authors would advise that depending on the scheduling regime and/or legal conditions of the region, this may require more than one driver per route per day.

Scenario	Description	No. of Vehicle Types	Vehicle Length (ft) [1]	Vehicle Biomethane Capacity (Nm^3 $vehicle^{-1}$)	No. of Depots
1	Small capacity, single depot, on-site upgrading	1	10	2,452	1
2	Medium capacity, single depot, on-site upgrading	1	20	6,436	1
3	Large capacity, single depot, on-site upgrading	1	45	15,536	1
4	Multi capacity, single depot, on-site upgrading	3	10 20 45	2,452 6,436 15,536	1
5	Medium capacity, multi depot, on-site upgrading	1	20	6,436	2
6	Multi capacity, multi depot, on-site upgrading	2 2	20 45 20 45	6,436 15,536 6,436 15,536	2
7	Mobile-upgrading, single depot, on-site biogas storage	1	40	4,200	1

1 Feet used as vehicle length unit as per industry standard.

Table 5-3: VRP scenarios analysed.

Based on the simulated data the solver employs large neighbourhood search algorithms to find the optimum distance that must be traversed to complete the collection and delivery of all the biogas that is produced at various AD sites to the required depot(s). For each scenario, the solver ran for 1 hour on five devices simultaneously, to provide for enough time to find results close to the hypothetical optimal. A 1-hour runtime was chosen as the tool, as, according to analyses by the tool developer, for problems with 100 customers, optimal solutions can be found within 1 hour (Erdoğan, 2017). The best result obtained (shortest total route length) was then chosen for analysis. The model generates the number of routes required to

service each site, given a set working-hour time. If the results for a scenario indicate that five routes per week are required to service each site by the vehicle type specified, this may be interpreted as five vehicles running in one day, one vehicle running on five separate days within a 7-day week, and so on, and would be dependent on the virtual pipeline operators desired deployment strategy. There are many configurations which may be employed by the virtual pipeline operator that may further reduce the number of vehicles required (vehicles operating multiple routes per day and/or night, etc.).

5.2.5 Virtual pipeline emissions

Emissions resulting from the vehicle movements in each scenario were calculated using emission factors obtained from the UKs Department for Environment, Food and Rural Affairs (DEFRA), provided in kg $CO_{2\text{-eq}}$ km^{-1}, for diesel fuelled heavy goods delivery vehicles (HGVs) (Department for Environment Food and Rural Affairs, 2021). Emissions were calculated, in kg $CO_{2\text{-eq}}$ $week^{-1}$, by multiplying the distance travelled by each vehicle type by the emissions factor, accounting for the change in load between stops as more gas is collected. DEFRA provide emissions factors for different vehicle types at 0%, 50%, and 100% laden. A vehicle that is transporting no biomethane (an empty vehicle) was considered 0% laden, whereas a vehicle with gas capacity at 100% was considered 100% laden. The emissions factor was linearly interpolated for percentages between theses available data points (see Figure 5-2). To account for the mass of the vehicles used in this work for scenarios 1-6 (see Table 5-2), it was assumed that the 10 ft vehicles were rigid body vehicles of between 3.5 and 7.5 tonnes, that 20 ft vehicles were between 7.5 and 17 tonnes, and that 45 ft trucks were articulated trucks. For scenario 7, it was assumed that the 40 ft truck was an articulated truck. Further details on the methodology used by DEFRA to obtain these emissions factors can be found in Appendix C.2 (Department for Business Energy and Industrial Strategy, 2021).

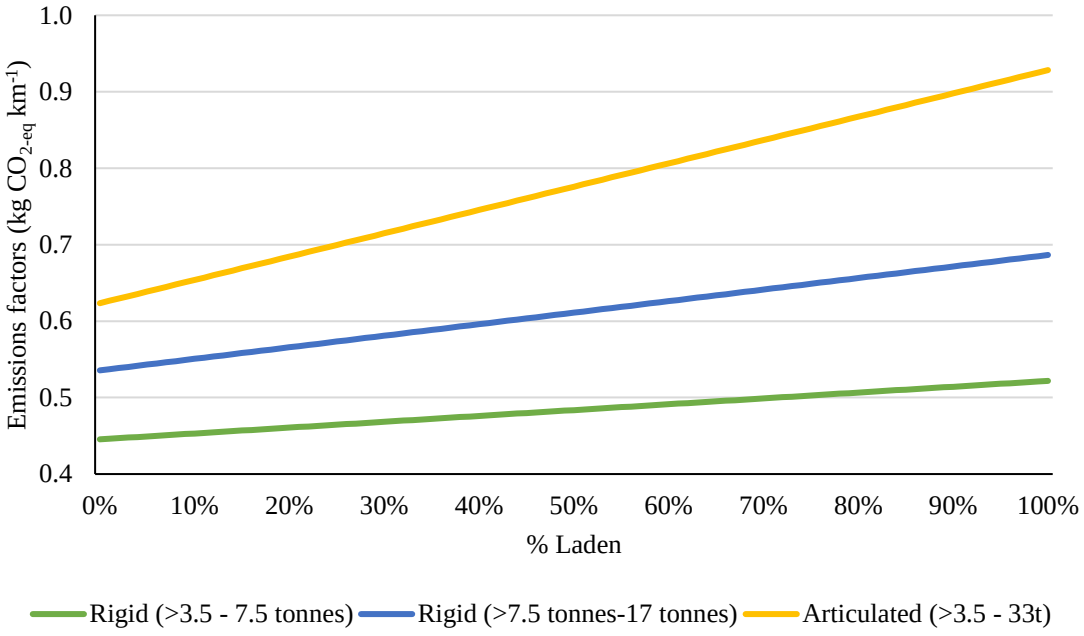


Figure 5-2: Emissions factors for different vehicle types (Department for Environment Food and Rural Affairs, 2021).

5.2.6 Model assumptions and analysis caveats

A volatile solids (VS) reduction of 80% was assumed for the AD plants at each farm, which is within the range of values reported in previous works concerning the digestion of cattle slurry and grass silage, such as by Nizami *et al.* (2010) and O'Shea *et al.* (2016b). This work assumes that each AD plant can both upgrade their biogas and compress the resultant biomethane for scenarios 1 - 6. Farms are also assumed to have suitable equipment to decant this biomethane from an on-farm storage tank to biomethane haulage vehicles. The impact of slurry seasonality (Ó Céileachair *et al.*, 2022) or energy demand seasonality (Liebetrau *et al.*, 2020) is not considered within this work and has been dealt with separately by other outputs of these authors. Another assumption is that the availability of low-flowrate biogas upgrading technologies will be cost effective in the future. Small-scale upgrading technologies that can operate economically are currently in development (technical readiness level 8-9) (Ljung *et al.*, 2022). Within these constraints and applying these assumptions the authors contend that the methodology outlined in this work is suitable and widely applicable for the optimisation of virtual biomethane pipelines, despite the small gas outputs of the farms in the work.

This academic exercise modelled on potential farm sites and real-world livestock and land use data from the Republic of Ireland is an attempt to discern the value of

utilising VRP techniques in designing a virtual biomethane pipeline and identifying operational challenges and considerations. As the farms in this work are modelled on real-world data, it is inevitable that some of the farms modelled here would be unable to upgrade and compress the biomethane that is produced owing to their small scale; technologies that upgrade biogas at flow-rates of less than 10 m^3 hr^{-1} are both rare and expensive (IEA, 2014). It was decided to analyse small-scale AD plants, as an alternative to well established models which can serve large AD plants, for the following reasons: they are representative of the farm sizes in the study region; maximum utilisation of the biomethane resource in the region would increase energy security in the region; the availability of natural gas can be hugely impacted by events such as the war in Ukraine which has impacted greatly on price making biomethane a cheaper substitute for natural gas; if the slurry is not used in an AD plant fugitive emissions from the storage of slurry would occur and as such AD is required to decarbonise these farms. This analysis serves to identify the key bottlenecks, such as low biogas flowrates or long biogas upgrading times, in the development of virtual biomethane pipelines in countries with small farms that do not have grid access and that want to use their biogas for purposes other than electrical power or heat generation.

5.3 Results

5.3.1 Farm locations and gas outputs

A list of the 100 farms modelled in this work, their respective herd sizes, slurry, and silage feedstock quantities available for AD, and weekly biogas and biomethane outputs can be found in Appendix C, Table C-1 and Table C-2. The total volume of biomethane that could be produced across all farms is 60,270 Nm^3 $week^{-1}$. The average biomethane production from all on-farm AD plants is modelled as 603 m^3 $week^{-1}$, with the largest AD plant producing 2,168 m^3 $week^{-1}$ and the smallest producing 87 m^3 $week^{-1}$. Biogas production from the on-farm AD plants is modelled as ranging from 1.1 to 25 m^3 hr^{-1}, or 183 to 4,200 m^3 $week^{-1}$. The location of the 100 farms, and depots A and B, covering an area of 400 km^2, can be seen in Figure 5-3 (Depot B only applies to scenarios 5 and 6 where a multi depot approach is investigated).

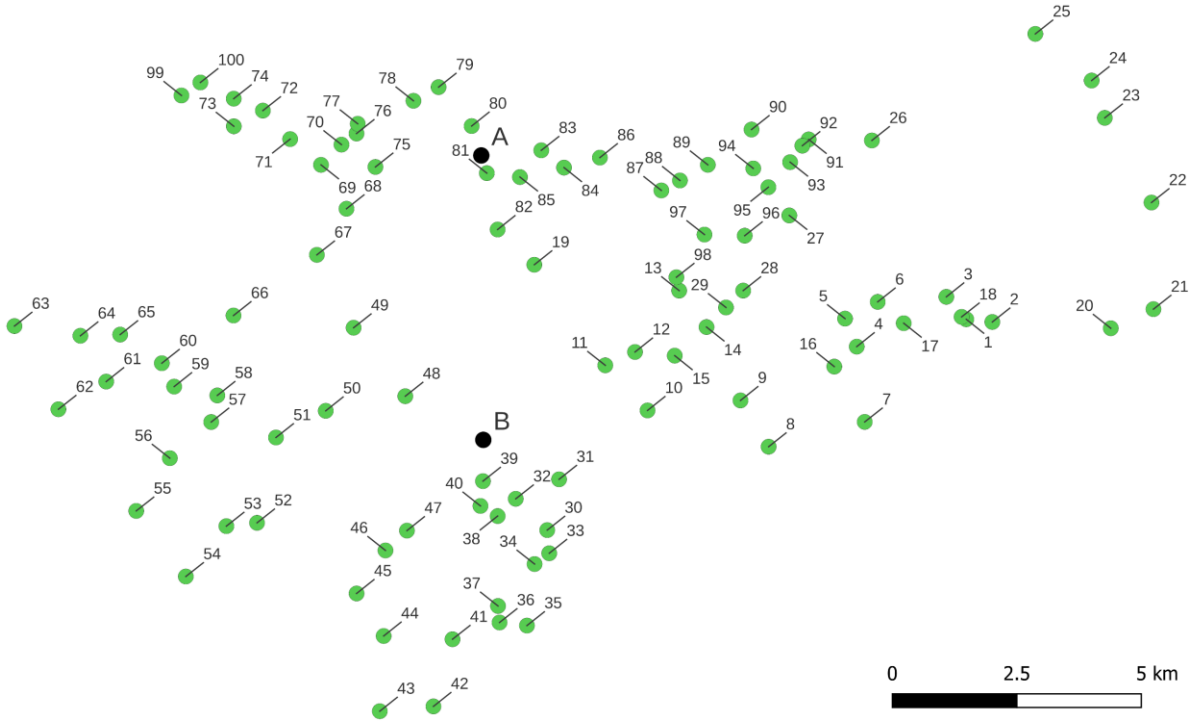


Figure 5-3: Location of 100 on-farm AD plants, Depot A and Depot B.

5.3.2 Scenario routing distances and emissions

The VRP Spreadsheet Solver was used to generate the results shown in Table 5-4 and Table 5-5. Table 5-4 shows the individual results and the shortest distances for each route for scenario 3 – which consists of one large capacity vehicle, a single delivery depot, and on-site biogas upgrading. Scenario 3 requires 4 routes to service

all 100 farms on a weekly basis – indicating that one vehicle may be used on four separate days of the week, or whichever configuration is desired by the virtual pipeline operator. Full routing distance results for each scenario can be found in Appendix C.3.

Route	No. of AD sites served	Biomethane collected (Nm^3 $week^{-1}$)	Total distance (km)
1	19	15,405	33.52
2	29	15,411	74.87
3	27	14,826	55.45
4	25	14,628	41.65
Total	**100**	**60,270**	**205.49**

Table 5-4: Scenario 3 routing results.

Table 5-5 shows the optimised routing results from all 7 scenarios.

Scenario	Description	Vehicle Length (ft)	Vehicle Biomethane Capacity (Nm^3 $vehicle^{-1}$)	Depot	No. of AD sites served	No. of weekly routes required	Total routing distance (km)
1	Small capacity, single depot, on-site upgrading	10	2,452	A	100	26	559
2	Medium capacity, single depot, on-site upgrading	20	6,436	A	100	10	287
3	Large capacity, single depot, on-site upgrading	45	15,536	A	100	4	205
4	Multi capacity, single depot, on-site upgrading	10	2,452	A	0	0	263
		20	6,436		73	8	
		45	15,536		27	1	
5	Medium capacity, multi depot, on-site upgrading	20	6,436	A	35	5	261
				B	65	6	
6	Multi capacity, multi depot, on-site upgrading	20	6,436	A	11	3	219
		45	15,536		19	1	
		20	6,436	B	13	1	
		45	15,536		57	4	
7	Mobile-upgrading, single depot, on-site biogas storage	40	4,200	A	100	29	613

Table 5-5: Scenario vehicles and total routing distance.

Table 5-6 shows each scenario's average time spent collecting biomethane from each farm, and the average time it takes to complete each route.

Scenario	Average time on farm (hh:mm)	Average time per route (hh:mm)
1	00:07	00:50
2	00:06	01:39
3	00:06	03:45
4	00:06	01:48
5	00:06	01:31
6	00:06	01:45
7	05:47	16:32

Table 5-6: Average scenario time on farm and per route.

Figure 5-4 show the visual routing results for scenario 3 (Large capacity, single depot, on-site upgrading). When only one haulage vehicle type is considered (Scenarios 1 to 3: single depot, on-site upgrading), the optimal vehicle routing solution can be found by choosing the haulage vehicle with the largest biomethane storage capacity (scenario 3, large 45 ft vehicle) which can reduce the total routing distance by up to 63 % as compared to using 10 ft haulage vehicles as in scenario 1. When three vehicle types were available to choose from (scenario 4: multi capacity, single depot, on-site upgrading), the optimal vehicle routing solution was found by using a combination of routes served by medium sized haulage vehicles and the largest haulage vehicle. The combination of vehicle types used in scenario 4 increases routing distance by 28% as compared with scenario 3 (large 45 ft haulage vehicle).

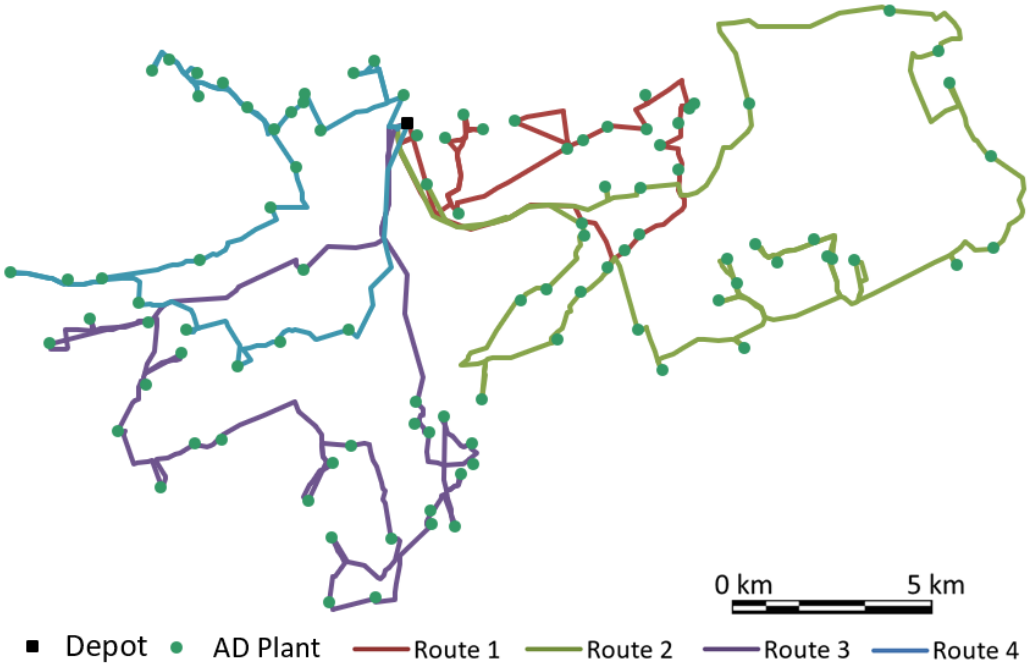


Figure 5-4: Routing requirement for scenario 3 (large capacity (45 ft), single depot, on-site upgrading).

The inclusion of an additional depot, as in scenario 5 (medium capacity truck, multi depot, on-site upgrading) reduces the overall route distance by 9% as compared with scenario 2 (medium capacity truck, single depot, on-site upgrading), which uses similarly sized vehicles. Figure 5-5 shows scenario 6 (multi capacity, multi depot, on-site upgrading), where the additional use of the largest trucks allows for a further optimisation of scenario 5, reducing the total route length by 16%.

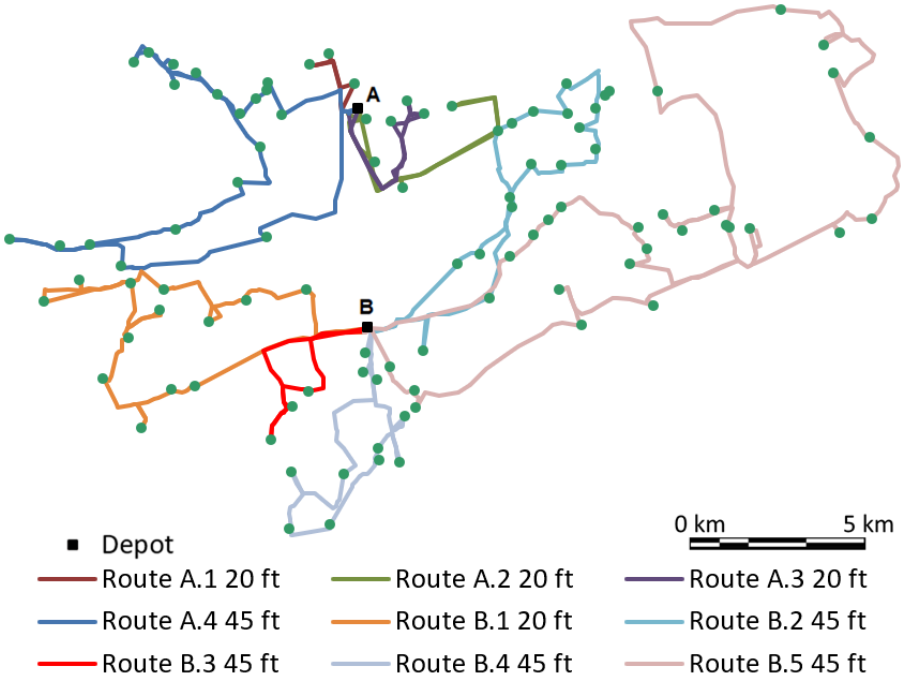


Figure 5-5: Routing requirement for scenario 6 (multi capacity, multi depot, on-site upgrading).

Scenario 7 requires a significant amount of time to be spent by the mobile-upgrading unit at each AD plant site, with the average route taking over 16 hours, and an average of almost 6 hours spent at each AD plant site (see Table 5-6). The implementation of scenario 7 as opposed to scenario 3 (large capacity truck, single depot, on-site upgrading) increases total routing distance by 198%. Weekly emissions resultant from the optimised routing in each scenario can be seen in Figure 5-6. Full emissions results can be found in Appendix C.3. Due to the long routing distances combined with a high emissions factor associated with articulated trucks fuelled by diesel, scenario 7 results in increased weekly routing emissions ranging from 60% - 205% as compared to scenarios 1-6.

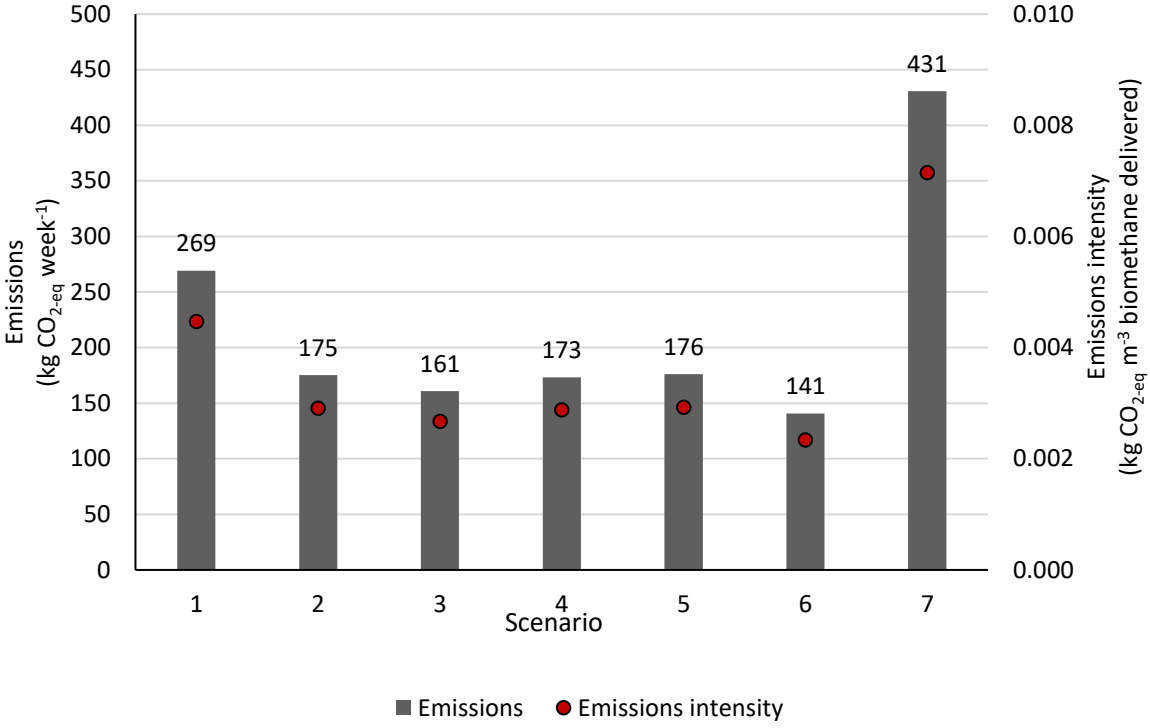


Figure 5-6: Weekly emissions per scenario.

5.4 Discussion

5.4.1 Conventional virtual biomethane pipeline (scenarios 1-6)

Scenarios with a lower weekly route requirement, such as scenario 3 (large capacity, single depot), have more freedom in choosing which day of the week, and therefore a day with less congestion, to operate the virtual pipeline. A low number of routes per week may allow for more efficient use of drivers and vehicles, reducing capital and operational costs.

Smaller haulage vehicles as used in scenario 1 (small capacity, single depot) may be suited to rural areas with roads of more difficult terrain. The total number of weekly truck movements for scenario 1 (26 routes, average distance 21.5km and average of 3.85 AD sites per route) could be a source of objection from local residents. However, in times of peak milk production, a truck route may collect milk from the farm multiple times weekly – it is likely that additional weekly routes for the collection of biomethane would not result in much local objection. Operators have the flexibility to choose to spread the 26 routes over the week to counter this.

In scenario 2 (medium capacity, single depot), the medium capacity vehicles allow for 10 routes (of average length 28.7 km serving on average 10 AD facilities per route); this is a 48% reduction in total routing distance than Scenario 1. Scenario 2 may allow for less vehicles to be purchased than in scenario 1, due to a lower number of total routes (10 vs. 26), which could lower capital and operational costs. Medium capacity vehicles may represent the best balance between capacity and ease of driver operation.

Scenario 3 (large capacity, single depot) only has four weekly routes (of average length 51.5 km serving on average 25 AD facilities per route), allowing for less traffic movements on the roads. Scenario 3 may allow for the lowest capital and operational costs of all scenarios, as one haulage vehicle could serve the entire virtual pipeline with little logistical difficulty, due to there being only four weekly routes in total. The driving of a 45 ft haulage vehicle may be more challenging on rural roads and would require a more experienced and technically qualified driver than a 10 ft haulage vehicle would require.

In scenario 4 (multi capacity, single depot), where various vehicle sizes are analysed as available, the result indicates small haulage vehicles would not be proposed; this suggests that the smallest capacity haulage vehicles result in longer overall routing distances. Scenario 4 can be viewed as a variation of scenario 2 (medium capacity vehicles only), in that it requires the same medium capacity haulage vehicles, but with the addition of a large capacity haulage vehicle which reduces the weekly routing distance by 24 km (8% reduction on Scenario 2). This small saving in weekly routing distance may not be worth the additional cost of a 45 ft haulage vehicle, particularly as the weekly emissions savings in scenario 4 are insignificant at only 2 kg $CO_{2\text{-eq}}$ $week^{-1}$ lower than scenario 2 (see Figure 5-6).

In scenario 5 (medium capacity, multi depot), which uses the same vehicles as scenario 2 (medium capacity, single depot), but incudes for two depots (market entry points, or biomethane consumers), the total number of routes increases by 1 but the total weekly routing distance is 26 km shorter, as the AD plant sites can be "split" between the depots. This indicates that virtual biomethane pipeline routing can be modular – if scenario 2 is first established, and subsequently another consumer becomes available in the future, the routing methodology can easily be adapted to include the addition of a new depot. It may also be possible to share one vehicle between two depots, depending on the logistical configuration of the virtual pipeline.

Scenario 6 (multi capacity, multi depot) can be seen as a further refinement of scenario 5 (medium capacity, multi depot) where 2 vehicle sizes are available. The option of using the largest haulage vehicle reduces the total weekly routing distance by over 42 km and requires 2 fewer routes. The purchase of a large 45 ft haulage vehicle might be outside the capital expenditure range of the route operator, or may be unsuitable to rural roads, but may allow for more flexibility in which routes and scenarios to run. It may also be possible to share vehicles between depots, allowing for only the purchase of one 20 ft vehicle and one 45 ft vehicle to operate all routes in scenario 6.

Conventional virtual biomethane pipeline scenarios have an advantage in that the average time spent on each farm collecting the biomethane is low (between 6 and 7 minutes on average), due to the relatively fast filling flow-rate for the CNG haulage vehicles (see section 5.2.3). Of the conventional virtual pipeline scenarios, Scenario

1 has the shortest average route time, and Scenario 3 has the longest – this is due to the biomethane storage capacity of the haulage vehicles; the 10 ft vehicles have a lower storage capacity and are at capacity after visiting only a small number of farms, and 45 ft vehicles have a larger storage capacity and thus can visit a large number of farms. In scenarios 1-6, it may be possible for a vehicle to conduct multiple routes in one day.

On the whole, these scenarios are modular and may be adapted for use by the virtual pipeline operator depending on logistical circumstances – the purchase of one 20 ft haulage vehicle and one 45 ft haulage vehicle may allow the virtual pipeline operator to employ scenarios 2, 3, 4, 5 and 6 to their desire, depending on their deployment strategy and scheduling regime.

5.4.2 Mobile-upgrading unit virtual biomethane pipeline (scenario 7)

The use of mobile-upgrading may allow for lower capital costs across the virtual pipeline system, as the AD plant operators may share the upgrading equipment instead of investing in it individually. This may in turn lead to less operating and maintenance costs throughout the system, as only a few upgrading units need to be maintained. However, this may also lead to periods of downtime that may be logistically challenging – if some of the mobile-upgrading units break down and/or require maintenance, it may be impossible to collect biomethane from the biogas plants for a period of time which may be problematic for the plant operators as they may fill their biogas storage facilities to capacity during this downtime.

The use of mobile-upgrading systems would require the on-farm storage of raw biogas, and whilst the biogas volumes may be relatively small in energy terms, the storage of such biogas may require reasonable physical storage (diaphragm tank, or other equivalent). The use of on-site upgrading facilities would also require on-site gas storage; however, it is in biomethane form, which gives the producer additional flexibility as to its end-use (e.g., agricultural vehicle fuel). Storage of raw biogas brings additional regulation challenges as the gas is bespoke and can be corrosive; the storage of such gas may face challenges depending on jurisdictional criteria. The storage costs of biogas as opposed to biomethane may be substantially higher due to compliance issues, which would be stricter than biomethane storage.

In scenario 7 (mobile-upgrading and compression unit, single depot), the unit can visit all farms only through the extension of the working day to 17 hours, as compared with scenarios 1-6 (9 hours). This may increase employment related costs compared to scenarios 1-6. The legality of 17-hour working hours may also be problematic and thus require two drivers for routes which spend 17 hours on the road. A 9-hour working day for scenario 7 would mean that the mobile-upgrading unit would need to visit the larger AD plants more than once weekly. As an example, the mobile-upgrading and compression unit is required to spend almost 17 hours per week at Farm 84, which is the largest biogas producer in this work (over 4,200 Nm^3_{biogas} $week^{-1}$), to upgrade the biogas produced there (see Appendix C.1, Table C-2). This would be difficult to arrange logistically and may be unfeasible or inconvenient for the farmer to host a 40 ft vehicle on-site for such a period of time. An AD plant which produces such an amount of biogas may not be suitable for inclusion in a virtual pipeline with mobile upgrading. Indeed, from Table 5-5, it can be seen that there was an increase in the number of routes required to complete the collections using the mobile-upgrading unit compared to scenario 3, which uses similarly sized vehicles.

It is worth noting that the biogas produced on the AD plants in this work is at a small-scale. Mobile-upgrading units may be unsuited for larger AD plants; a 500 kW_e digester which produces over 35,000 Nm^3_{biogas} $week^{-1}$ would require the mobile-upgrading unit to spend at least 140 hours $week^{-1}$ on site- upgrading the biogas (biogas upgrading capacity 250 m^3 hr^{-1}). Furthermore, the mobile-upgrading unit biomethane storage capacity of 4,200 Nm^3 is insufficient for one trip to such a 35,000 Nm^3_{biogas} $week^{-1}$ facility and would require about 5 trips (7,000 Nm^3_{biogas} equates to 4,200 $Nm^3_{biomethane}$) to facilitate such an AD plant. A 1 MWe digester which produces over 70,000 Nm^3_{biogas} $week^{-1}$ would require a total upgrading time of 280 hours $week^{-1}$ – this is more than hours that exist in a week (168 hours), indicating that at larger scales, multiple mobile-upgrading units would need to be active simultaneously to upgrade all of the biogas at such a site. Weekly routes for mobile-upgrading units may become logistically unfeasible at larger scales and may require daily biogas upgrading and collection, and perhaps from more than one mobile-upgrading unit. This likely deems such an approach unfeasible at larger scales. With larger AD plants, a dedicated on-site biogas upgrading system makes

more logistical and technical sense, with the biomethane being collected via conventional virtual pipeline, as in scenarios 1-6. On-site biogas upgrading systems at large scale are commonplace in biomethane systems.

If mobile-upgrading units spend most of their time stationary on one-site, the logistical benefits of them may be called into question, as the general advantage of the units being mobile is lost. Improving biogas upgrading capacities of the mobile upgrading units beyond 250 m^3 hr^{-1} would alleviate most logistical difficulties of such virtual pipelines.

The largest farm digester proposed (Farm 84, see Appendix C.1) could produce 4,230 Nm^3_{biogas} $week^{-1}$ (equivalent to a 60 kW_e digester) would require the mobile upgrading system to be on site for just short of 17 hours $week^{-1}$. Overnight biogas upgrading may be convenient for mobile-upgrading systems if they are upgrading large quantities of biogas.

Mobile-upgrading technology is immature, and there is little publicly available information on the implementation of such systems. Indicatively, there has been information on this used with similar flow-rates and feedstocks as in this work; a business model developed by Bennamann (2023) describes a mobile-upgrading virtual pipeline where a mobile-upgrading unit is delivered to a farm for a day and is collected another day that week. The business model described indicates a relay style virtual pipeline, as described by Bose et al., (2019).

The slow upgrading capacity of the mobile-upgrading units leads to scenario 7 spending, on average, almost 6 hours at each AD plant, with the average route time at almost 17 hours. The logistical feasibility of this is extremely questionable, and may require further optimisation, such as a scheduling or relay system as described by Bose *et al.*, (2019). The routes in scenario 7 have such long run-times due to the parameters set out in section 5.2.4; If the working hours for scenario 7 would be reduced, it is likely that many farms would need to be visited twice weekly to upgrade their biogas, and more routes would therefore be required. Direct translation from a conventional virtual biomethane pipeline to a mobile-upgrading virtual biomethane pipeline might not be logistically sound.

5.4.3 Transport routing sustainability

For scenarios 1-3, in which there is only one vehicle type and one depot, lower transport related GHG emissions are possible by reducing total route length, which is achieved by using the largest capacity haulage vehicles available (Table 5-2). However, for scenarios 2 through 5, the maximum difference in total weekly emissions is small at 9% (Figure 5-6). Scenario 6 has the lowest weekly emissions associated with transport by diesel fuelled truck at 141 kg $CO_{2\text{-eq}}$ $week^{-1}$; the reason for the low GHG emissions is the presence of two depots (lowering total routing distance) and the availability of multiple vehicle options (20 ft vehicles have a lower emissions factor than 45 ft vehicles, as per Figure 5-2), further optimising the total routing distance. Scenario 1 has high emissions due to the large number of routes and the long transportation distance required to serve all AD sites with the small capacity trucks. Scenario 7 has the highest transport emissions of any scenario, at 431 kg $CO_{2\text{-eq}}$ $week^{-1}$, due to the large number of routes required, leading to long travel distances, and the high emission factor of articulated trucks. The high transport emissions related to the mobile-upgrading scenario must be considered and accounted for as they will impact the sustainability of the biomethane produced in these systems as per EU RED II recast (European Parliament and European Commission, 2018), which may counter any capital expenditure benefits associated with such an upgrading regime. The energy demand for the upgrading of biogas by all scenarios may also lead to further emissions depending on the energy source of the upgrading process. The analysis in this work assumes that the trucks serving the AD plant sites are diesel-fuelled; if the trucks were to be fuelled by biomethane, the virtual biomethane pipeline may be considered sustainable, but only if the biomethane used passes EU RED II sustainability criteria. It may also be possible, depending on regional policies that the biomethane produced may have a net-zero emissions contribution, as the CO_2 content may be considered biogenic (European Biogas Association, 2020).

5.4.4 Study limitations and future research

This study assesses the logistical challenges and considerations of a virtual biomethane pipeline, serving on-farm AD plants, based on a VRP model. As such it does not investigate the potential financial feasibility of such methods. A full techno-economic analysis of the scenarios investigated in this work would further reveal

whether the scenarios are viable or not, or what financial or technological barriers need to be tackled. The capital and operational costs of running the truck routes should be the focus of future research. Future research could also investigate characteristics such as AD plant size and the biogas upgrading capability and the subsequent effect this has on the supply chain for the scenarios raised. Co-operatives may be formed by farmers to ensure larger AD plants are developed to support economies of scale; in such a case, the transportation of feedstocks to the central co-operative digester should be optimised.

The study parameters chosen for this analysis are highly influential in the results obtained. The biogas output, number of farms, and study region covered would significantly change the number of vehicles required, the routing distance and $CO_{2\text{-eq}}$ emissions of each of the scenarios, and the overall logistical set-up. A small number of AD plants would require significantly less routes and therefore would have implications on truck movements and transport emissions. If the biogas plants had a much higher weekly biogas output, the logistical feasibility of the mobile-upgrading units would be further called into question.

5.5 Conclusion

A virtual pipeline is proposed for the land transportation of biomethane from distributed sources to centralised depots. Seven different scenarios for operating virtual pipelines from on-farm anaerobic digestion plants to a market entry point, or depot, have been investigated using vehicle routing problem (VRP) techniques in this study. Using farm locations as the sites for appropriately sized AD plants where grass silage and cattle manure (slurry) are the feedstocks, routes were designed for the practical collection of the produced biomethane. The seven scenarios that were analysed in this work illustrate how varying the capacity of vehicle fleets, and delivery to a single depot or multiple locations alters the numbers of routes, total routing distances and transport related GHG emissions.

Scenarios which only use one vehicle type may reduce their overall routing distance by selecting the largest biomethane haulage vehicles. Scenarios which have multiple vehicle types available to choose from generally use medium and large-sized haulage vehicles; the use of multiple vehicle sizes did not reduce routing length when compared with the scenario which used the largest haulage vehicle. The inclusion of an additional depot allows for reduced overall routing distance when compared with scenarios which used similarly sized vehicles and only one depot.

The use of mobile-upgrading and compression units, as portrayed in scenario 7, may allow for less capital cost on the biogas plant operator, but the slow biogas upgrading rate may limit the logistical viability and requires significantly more routes than other scenarios with similarly sized vehicles; Scenarios with higher route transportation emissions will impact the sustainability of the biomethane per EU RED II criteria.

The model is applied to Ireland but is applicable to any region. The importance of this research is partly based on the fact that Ireland, on a per capita basis, emits high levels of methane due to its comparatively large agricultural sector. High agricultural emissions, a large resource potential, and an increased drive for energy security in RePowerEU, may allow countries such as Ireland to establish a network of on-farm AD plants supported by virtual biomethane pipelines.

References

Allen, E. et al. (2016) ‘A detailed assessment of resource of biomethane from first, second and third generation substrates’, Renewable Energy, 87, pp. 656–665. Available at: https://doi.org/10.1016/j.renene.2015.10.060.

Beausang, C., McDonnell, K. and Murphy, F. (2021) ‘Assessing the environmental sustainability of grass silage and cattle slurry for biogas production’, Journal of Cleaner Production, 298, p. 126838. Available at: https://doi.org/10.1016/j.jclepro.2021.126838.

Bennamann (2023). Bennamann Energy Ltd. Available at: https://bennamann.com/bennamann-energy-ltd/ [Accessed July 17, 2023].

Bose, A. et al. (2019) ‘Techno-Economic Design and Social Integration of Mobile Thermal Energy Storage (M-TES) within the Tourism Industry’, International Journal of Sustainable Energy Planning and Management, 22, pp. 95–108. Available at: https://doi.org/10.5278/IJSEPM.2544.

Butler, M., Herlihy, P. and Keenan, P. (2005) ‘Integrating information technology and operational research in the management of milk collection’, Journal of Food Engineering, 70, pp. 341–349. Available at: https://doi.org/10.1016/j.jfoodeng.2004.02.046.

Clean Energy Fuels (2022) TrailerfillCNG - Clean Energy Compression. Available at: https://www.cleanenergyfuels.com/compression/cng-fueling-equipment/cng-dispensing-equipment/trailerfillcng/ (Accessed: 20 July 2021).

CSO (2020) Crops and livestock. Routledge. Available at: https://www.cso.ie/en/releasesandpublications/er/clsjf/cropsandlivestocksurveyjunefinal2019/ (Accessed: 11 August 2020).

Department for Business Energy and Industrial Strategy (2021) 2021 Government Greenhouse Gas Conversion Factors for Company Reporting: Methodology Paper for Conversion factors, Final Report. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1049346/2021-ghg-conversion-factors-methodology.pdf (Accessed: 2 March 2023).

Department for Environment Food and Rural Affairs (2021) Greenhouse gas reporting: conversion factors 2021. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021 (Accessed: 24 October 2022).

Department of Communications Climate Action and Environment (2020) National Energy & Climate Plan. Available at: https://www.gov.ie/en/publication/0015c-irelands-national-energy-climate-plan-2021-2030/# (Accessed: 7 September 2020).

Department of the Environment Climate and Communications (2022) Sectoral Emissions Ceilings. Available at: https://www.gov.ie/en/publication/76864-sectoral-emissions-ceilings/ (Accessed: 25 October 2022).

Environmental Protection Agency (2022) Agriculture. Environmental Protection Agency (EPA). Available at: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/agriculture/ (Accessed: 25 October 2021).

Erdoğan, G. (2017) 'An open source Spreadsheet Solver for Vehicle Routing Problems', Computers & Operations Research, 84, pp. 62–72. Available at: https://doi.org/10.1016/J.COR.2017.02.022.

European Biogas Association (2020) The potential of biomethane for a faster decarbonisation of transport should not go to waste. Available at: https://www.europeanbiogas.eu/wp-content/uploads/2020/09/Potential-of-biomethane-in-the-transport-sector.pdf (Accessed: 26 October 2022).

European Parliament and European Commission (2018) 'Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)', Official Journal of the European Union, 61, pp. 82–209.

Gil-Carrera, L. et al. (2019) 'Feasibility study of an off-grid biomethane mobile solution for agri-waste', Applied Energy, 239(January), pp. 471–481. Available at: https://doi.org/10.1016/j.apenergy.2019.01.141.

GNI (2019) The Future of Renewable Gas in Ireland. Available at: https://www.gasnetworks.ie/corporate/company/our-commitment/environment/renewable-gas/ (Accessed: 16 January 2019).

Hanrahan, L. et al. (2018) 'Factors associated with profitability in pasture-based systems of milk production', Journal of Dairy Science, 101(6), pp. 5474–5485. Available at: https://doi.org/10.3168/JDS.2017-13223.

Hennessy, T. et al. (2011) National Farm Survey of Manure Application and Storage Practices on Irish Farms. Available at: https://www.teagasc.ie/media/website/publications/2011/TeagascNationalFarmSurveyOfManureApplication.pdf (Accessed: 1 April 2019).

Hovland, J. (2017) Compression of raw biogas: A feasibility study. Available at: https://www.biogas2020.se/wp-content/uploads/2017/06/2217020-1compressionrawbiogas.pdf (Accessed: 26 October 2021).

Humphreys, J., Barrett, D. and Fenger, F. (2019) Optimum stocking rate on the grazing platform of fragmented dairy farms. Available at: https://www.teagasc.ie/media/website/publications/2019/Optimum-stocking-rate-on-the-grazing-platform-of-fragmented-dairy-farms.pdf (Accessed: 16 June 2022).

IEA (2014) Upgrading Plant Lists - IEA Bioenergy Task 37, IEA Bioenergy Task 37. Available at: http://task37.ieabioenergy.com/plant-list.html (Accessed: 14 August 2020).

IEA Bioenergy: Task 37 (2017) GREEN GAS HUB: Provision of biogas by farmers by pipe to a Green Gas Hub with a centralised upgrading process. Available at: https://www.ieabioenergy.com/blog/publications/green-gas-hub-provision-of-biogas-by-farmers-by-pipe-to-a-green-gas-hub-with-a-centralised-upgrading-process/.

IEA Bioenergy: Task 37 (2019) Country reports. Available at: http://task37.ieabioenergy.com/country-reports.html (Accessed: 9 July 2021).

Laporte, G. and Semet, F. (2002) '5. Classical Heuristics for the Capacitated VRP', in, pp. 109–128. Available at: https://doi.org/10.1137/1.9780898718515.ch5.

Liebetrau, J. et al. (2020) 'Integration of biogas systems into the energy system'.

Ljung, E. et al. (2022) Production of vehicle gas with ash filter technology at farm level. Available at: https://www.ri.se/en/what-we-do/projects/production-of-vehicle-gas-with-ash-filter-technology-at-farm-level (Accessed: 4 November 2022).

McEniry, J. et al. (2013) 'How much grassland biomass is available in Ireland in excess of livestock requirements?', Irish Journal of Agricultural and Food Research, 52(1), pp. 67–80. Available at: http://www.jstor.org/stable/23631018.

Moscovici Joubran, A. et al. (2021) 'Invited review: A 2020 perspective on pasture-based dairy systems and products', Journal of Dairy Science, 104(7), pp. 7364–7382. Available at: https://doi.org/10.3168/jds.2020-19776.

Nizami, A.S. et al. (2010) 'Role of leaching and hydrolysis in a two-phase grass digestion system', Energy and Fuels, 24(8), pp. 4549–4559. Available at: https://doi.org/10.1021/ef100677s.

O'Callaghan, S., O'Connor, D. and Goulding, D. (2018) 'Distance Optimisation of Milk Transportation From Dairy Farms Distance Optimisation of Milk Transportation From Dairy', Agriculture & Food, 6(July), pp. 279–296. Available at: https://www.scientific-publications.net/get/1000028/1532007129523016.pdf.

O'Callaghan, S., O'Connor, D. and Goulding, D. (2021) 'A dynamic decision support model for the seasonal transportation of raw milk', International Journal of Dairy Technology, 74(1), pp. 32–43. Available at: https://doi.org/10.1111/1471-0307.12748.

O'Connor, S. et al. (2021) 'Biogas production from small-scale anaerobic digestion plants on European farms', Renewable and Sustainable Energy Reviews, 139, p. 110580. Available at: https://doi.org/10.1016/j.rser.2020.110580.

O'Donovan, M. and Egan, M. (2019) Grazing management: areas for improvement on dairy farms, Irish Dairying: Growing Sustainably. Teagasc. Available at: https://www.teagasc.ie/media/website/publications/2019/Moorepark19-Irish-Dairying-booklet.pdf (Accessed: 24 May 2021).

O'Shea, R., Wall, D., et al. (2016) 'Assessment of the impact of incentives and of scale on the build order and location of biomethane facilities and the feedstock they utilise', Applied Energy, 182, pp. 394–408. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2016.08.063.

O'Shea, R., Kilgallon, I., et al. (2016) 'Quantification and location of a renewable gas industry based on digestion of wastes in Ireland', Applied Energy, 175, pp. 229–239. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2016.05.011.

Ó Céileachair, D. et al. (2021) 'Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane', Applied Energy, 303, p. 117627. Available at: https://doi.org/10.1016/j.apenergy.2021.117627.

Ó Céileachair, D. et al. (2022) 'The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant', Journal of Cleaner Production, 368, p. 133129. Available at: https://doi.org/10.1016/J.JCLEPRO.2022.133129.

Pakarinen, O. et al. (2008) 'Storing energy crops for methane production: Effects of solids content and biological additive', Bioresource Technology, 99(15), pp. 7074–7082. Available at: https://doi.org/10.1016/j.biortech.2008.01.007.

Paredes-Belmar, G., Montero, E. and Leonardini, O. (2021) 'A milk transportation problem with milk collection centers and vehicle routing', ISA Transactions [Preprint]. Available at: https://doi.org/10.1016/J.ISATRA.2021.04.020.

Pisinger, D. and Ropke, S. (2007) 'A general heuristic for vehicle routing problems', Computers & Operations Research, 34(8), pp. 2403–2435. Available at: https://doi.org/10.1016/J.COR.2005.09.012.

Quantum Fuel Systems (2022) Q-VP – Virtual Pipeline CNG Trailers. Available at: https://www.qtww.com/product/virtual-pipeline-cng/ (Accessed: 20 July 2021).

Ravina, M. et al. (2019) ‘MCBioCH4: A computational model for biogas and biomethane evaluation’, Journal of Cleaner Production, 227, pp. 739–747. Available at: https://doi.org/10.1016/j.jclepro.2019.04.224.

Sanyi Green Energy (2010) Mobile Biogas Upgrading System. Available at: https://www.fsmtoolbox.com/assets/pdf/MOBILE_BIOGAS_UPGRADING_SYSTEM.pdf (Accessed: 14 November 2022).

SEAI (2019) Energy in Ireland 2019 Report. Available at: https://www.seai.ie/publications/Energy-in-Ireland-2019-.pdf (Accessed: 8 September 2020).

Udaeta, M.E.M. (2012) ‘Natural Gas Virtual-Pipeline for Alternative Energy Distribution’, in J.L. de O. Bernal (ed.). Rijeka: IntechOpen, p. Ch. 6. Available at: https://doi.org/10.5772/48711.

UNFCCC and UN (2021) ‘The Glasgow Climate Pact’, in 2021 United Nations Climate Change Conference (COP26). Glasgow: UNFCCC. Available at: https://ukcop26.org/cop26-presidency-outcomes-the-climate-pact/.

Wall, D.M. et al. (2014) ‘Optimisation of digester performance with increasing organic loading rate for mono- and co-digestion of grass silage and dairy slurry’, Bioresource Technology, 173, pp. 422–428. Available at: https://doi.org/10.1016/j.biortech.2014.09.126.

Wall, D.M., O’Kiely, P. and Murphy, J.D. (2013) ‘The potential for biomethane from grass and slurry to satisfy renewable energy targets’, Bioresource Technology, 149, pp. 425–431. Available at: https://doi.org/https://doi.org/10.1016/j.biortech.2013.09.094.

6 A methodology for designing biogas pipelines

A methodology for designing biogas pipelines

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Abstract:

Dependence on fossil fuels has heightened global energy security issues. Anaerobic digestion (AD) is a technology that can provide locally produced biogas via low-pressure pipelines to local industries and offset the requirement for import of fossil fuel natural gas. A methodology was developed to optimise biogas pipeline layouts serving 10 number AD plants and 1 biogas end user. Two layout methods were considered: a minimum spanning tree (MST) with Steiner points, or a MST which followed the road network. In determining the connection order of the AD plants to the biogas user, two lexicographic heuristics were employed: connect the AD plants in order of largest producer of biogas to the smallest producer; or connect the AD plants in order of proximity to the pipeline network. Commercial software (SNAP) was used to calculate required diameters and material costs of each pipeline layout created. A road network MST connecting 10 AD plants to the biogas end user was calculated to cost 26% more than a Steiner MST. Multi-criteria decision analysis (MCDA) was used to rank biogas pipeline layouts based on criteria such as pipeline material cost and biogas flow-rate to the end user. In this analysis, Steiner MSTs always outperformed road network MSTs, except when pipeline material cost was of no importance. Scenarios which connected via the proximity heuristic almost always outperformed those which connected via the output heuristic.

Keywords:

Biogas, pipeline, GIS, layout, optimisation, decarbonisation

6.1 Introduction

Countries participant to the Glasgow Climate Pact at COP26 agreed to both reduce their greenhouse gas emissions and invest in decarbonisation pathways (UNFCCC and UN, 2021). Natural gas is seen as an important fuel in the decarbonisation of energy systems, as switching from coal or oil to gas can reduce CO_2 emissions by 40% (IEA, 2019). Recent geopolitical events in Russia and Ukraine have raised the importance of energy security in the EU (Mišík, 2022). A restricted supply of Russian gas could lead to an economic recession across the EU (Flanagan et al., 2022). Large industries, such as the glass or chemical industry, may need to shut down temporarily or even permanently if the supply of natural gas is disrupted (Reuters, 2022a); this in turn has a significant impact on the financial viability of the business. Indeed, many industries are seeking exemption from such supply disruptions (Reuters, 2022b). The EU has developed the REPowerEU plan to reduce its dependence on Russian fossil fuels and hasten the transition to sustainable fuels, whilst also saving energy, diversifying energy supplies, and increasing investments and reforms in the energy sector (European Commission, 2022).

Anaerobic digestion (AD) may provide a means in which decarbonisation and improved energy security can be achieved simultaneously. Industries could displace fossil fuels with sustainable biogas (a mixture of methane and carbon dioxide) produced from AD plants in their vicinity (Ó Céileachair et al., 2021).

If sustainable biogas is to be a realistic alternative to fossil fuels, it must be economically competitive and logistically feasible. Optimisation techniques and GIS solutions may be used to minimise the length of pipeline layouts that transport the biogas from the AD plant to the end user. The shortest way to connect multiple points (vertices) without forming a cycle is known as a minimum spanning tree (MST). A further optimisation of the MST is through the use of Steiner nodes: additional vertices in a network which can reduce the overall network length connecting all vertices. An example of such a Steiner node can be seen in Figure 6-1, where the vertices in the equilateral triangle (left) are connected via a MST, and the vertices in the identical equilateral triangle are connected via a Steiner MST (right).

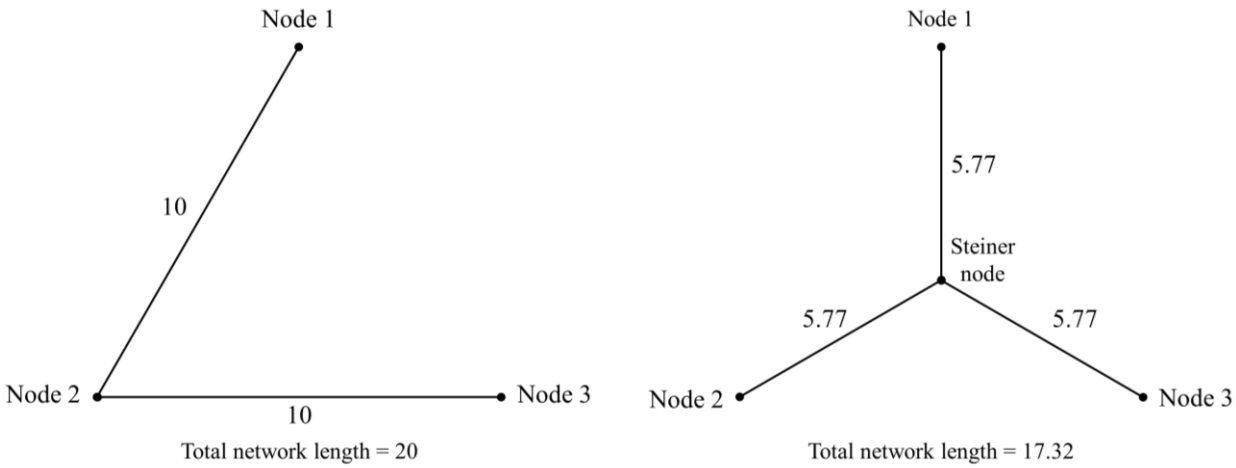


Figure 6-1: Comparison of standard MST (left) and Steiner MST (right).

Computational problems that are exceedingly difficult to solve even with the use of supercomputers or specialised hardware are known as NP-hard (non-deterministic polynomial time) problems. NP-hard problems, such as the travelling salesman problem, have no known algorithm for quickly solving them on a regular computer (Knuth, 1974). Solving Steiner node problems is NP-hard (Mitchell, 2000), and thus GIS heuristics may be employed to find such nodes. Heuristic approaches, akin to "short-cuts", are used to find solutions, which may or may not be optimal, for complex problems such as NP-hard problems. Lexicographic approaches – breaking down complex decisions into a series of simple comparisons based on a predetermined hierarchical criteria – may also be employed in the designing of pipeline layouts. For instance, how many AD plants should be connected to the end user and in which order they should be connected? Should total biogas flow-rates to the user be prioritised, or should biogas plants be connected in order of proximity to the network? A multi-criteria decision analysis (MCDA), comparing pipeline material costs and biogas flow-rates may be employed to determine which pipeline network layout and connection methodology is best from the perspective of the biogas pipeline network operator when considering multiple criteria. The most common model employed in MCDA for sustainable energy systems is the weighted sum method (Wang et al., 2009).

Commercial software is often used in optimisation processes to save time and improve operational efficiency. SNAP Service Calculator (DNV, 2023), a software component of Gas Toolbox provided by DNV (an international accredited registrar and classification society), is used by national gas grid operators, utilities, and

consultancies, to design and analyse low-pressure pipeline networks. SNAP can either design or analyse pipeline networks, calculating the minimum pipe diameters required, minimising pipeline material costs. A simple gas network analysis tool such as SNAP may allow biogas pipeline developers to design, analyse, and cost prospective biogas pipeline networks, without them needing to invest time in calculations and optimisations derived from first principles.

To the author's knowledge, whilst previous works have designed and analysed biogas pipeline networks and used GIS techniques to design pipeline network layouts via Kruskal's algorithm, no prior works have determined the MST with multiple Steiner nodes connecting biogas producers to a central end user, nor have any previous works determined the road network MST connecting AD plants to a central end user. Lexicographic approaches, such as designing pipeline networks by connecting nodes in order of biogas output to maximise flow-rates or by connection to minimise total pipeline network length by connecting nodes in order of proximity to the overall network, have also not been developed in previous works. Furthermore, previous works have not conducted a MCDA of the designed layouts to optimise the network from the operator's perspective. Whilst prior works have calculated pressure profiles in biogas pipelines from first principles, no methodology to repurpose natural gas pipeline optimisation software for biogas network design has been developed. Subsequently, the proposed objectives of this paper with respect to developing a biogas pipeline are:

i. Use GIS to design Steiner MST and road network MST biogas pipeline layouts.
ii. Compare the costs of Steiner MST and road network MST biogas pipeline layouts.
iii. Determine the correlation between biogas pipeline material costs, and biogas flow-rates or total pipeline length.
iv. Use MCDA to identify which pipeline network layouts are the best choice for a network operator.

6.2 Methodology

6.2.1 Anaerobic digestion plant locations

As a case study, the location of the AD plants and biogas user was selected in an area of approximately 120 km^2 in Ireland, near the national road network, using Google Maps (Google, 2022). QGIS, an open-source geographic information system application, was used to map the locations of the AD plants and biogas user. A GIS file of the road network was sourced from OpenStreetMap (OpenStreetMap, 2022). Ten AD plants were positioned randomly in the vicinity of a biogas user (also randomly placed), with varying biogas production rates (see Table 6-1), based on biogas production outputs typical from on-farm AD plants (O'Connor *et al.*, 2020). An origin destination matrix showing the straight-line distances between all of the AD plants and biogas user is shown in Table 6-2. The co-ordinates of all locations can be found in Appendix D.1, Table D-1. Methane (CH_4) concentration in the biogas was assumed to be 60%$_{vol}$, with the remainder assumed to be carbon dioxide (CO_2). Figure 6-2 shows the AD plant sites, numbered 1-10 from largest biogas producer to smallest producer (see Table 6-1). It was assumed that the biogas user has a demand equal to that of the biogas produced at all AD plants (32,000 Nm^3 $week^{-1}$). Nm^3 conditions are when natural gas at 0 °C and absolute pressure of 1.013 bar occupies the volume of 1 m^3.

AD plant	Biogas Output	
	Nm^3 hr^{-1}	**Nm^3 $week^{-1}$**
1	29.8	5,000
2	27.4	4,600
3	25.0	4,200
4	22.6	3,800
5	20.2	3,400
6	17.9	3,000
7	15.5	2,600
8	13.1	2,200
9	10.7	1,800
10	8.3	1,400
Total	**190.5**	**32,000**

Table 6-1: AD plant biogas outputs.

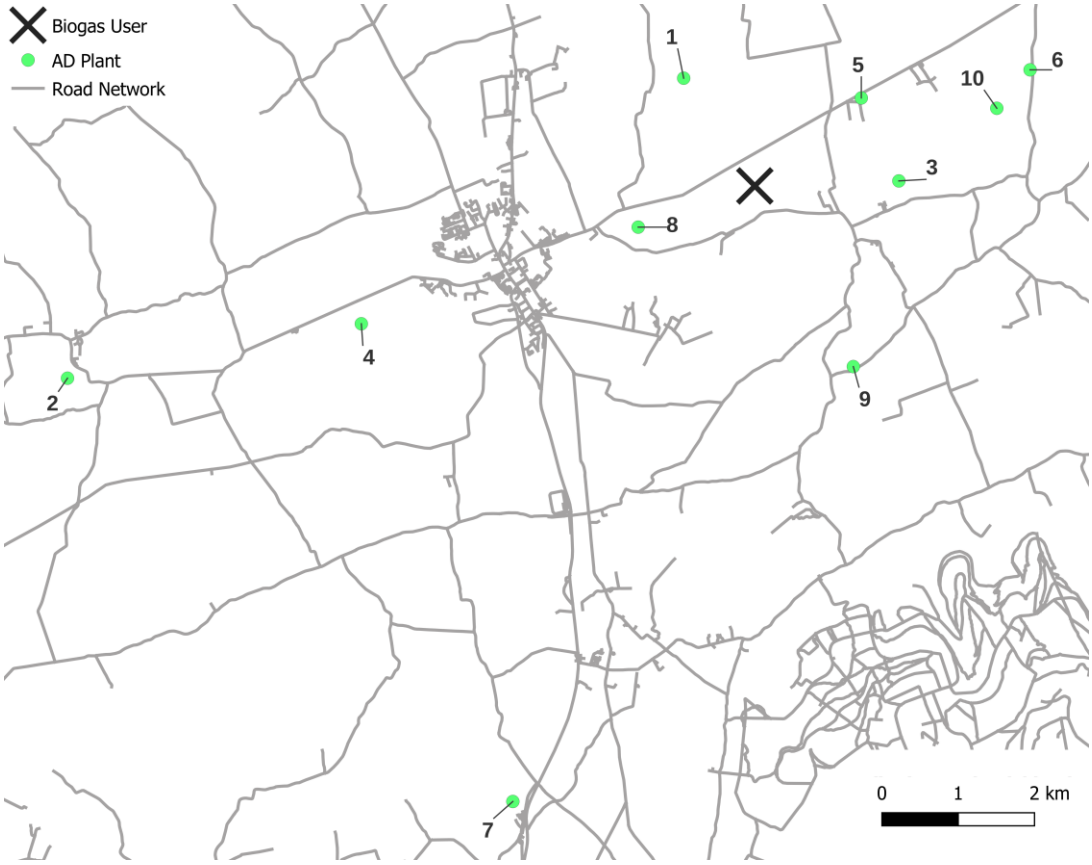


Figure 6-2: AD plant site and biogas user locations, and road network.

Distance (m)	1	2	3	4	5	6	7	8	9	10	Biogas user
1	0	8,980	3,124	5,308	2,342	4,541	9,726	2,038	4,380	4,122	1,690
2	8,980	0	11,198	3,916	11,031	13,245	8,047	7,736	10,300	12,681	9,353
3	3,124	11,198	0	7,289	1,192	2,252	9,568	3,470	2,502	1,597	1,889
4	5,308	3,916	7,289	0	7,188	9,374	6,559	3,843	6,472	8,793	5,463
5	2,342	11,031	1,192	7,188	0	2,243	10,277	3,378	3,517	1,781	1,809
6	4,541	13,245	2,252	9,374	2,243	0	11,731	5,533	4,522	666	3,915
7	9,726	8,047	9,568	6,559	10,277	11,731	0	7,693	7,232	11,069	8,657
8	2,038	7,736	3,470	3,843	3,378	5,533	7,693	0	3,359	4,950	1,621
9	4,380	10,300	2,502	6,472	3,517	4,522	7,232	3,359	0	3,868	2,694
10	4,122	12,681	1,597	8,793	1,781	666	11,069	4,950	3,868	0	3,330
Biogas user	1,690	9,353	1,889	5,463	1,809	3,915	8,657	1,621	2,694	3,330	0

Table 6-2: Origin destination matrix of distance between each AD plant, and the AD plants and the biogas user.

6.2.2 GIS layout design

In designing the biogas pipeline layouts connecting all AD plants and the biogas user, two layout methodologies were considered: connect via shortest possible route (Steiner MST) or via the road network (road network MST).

For the Steiner MST pipeline layout, Steiner points were generated between each of the AD plant sites, to create shorter total pipeline layout than point-to-point MSTs

would allow. To find the potential Steiner nodes, a 100m x 100m grid of potential Steiner nodes was overlaid on the same area as the AD plant and biogas user nodes.

For the road network MST pipeline layout, a connecting line was created between the AD plant sites and the closest point on the road network, then the shortest path along the road network connecting each AD plant site to the biogas user was created. It is assumed that the biogas end user can consume all of the biogas produced by the 10 AD plants considered. A full QGIS guide for the generation of Steiner nodes and connecting line between AD plant sites and road network can be found in Appendix D.2.

As well as designing pipeline networks which connect all AD plants to the biogas user, pipeline networks connecting a selection of the AD plant sites to the biogas user were also designed. In deciding which AD plant sites to select for pipeline networks, and in which order to add them, two lexicographic heuristics were employed:

i. Output Heuristic: Connect the AD plants to the biogas user and/or pipeline network in the order of largest biogas output to smallest biogas output (order of cumulative connection being AD plant 1 through to AD plant 10). Figure 6-3 illustrates a flowchart methodology of this heuristic. The scenario outputs from this heuristic are numbered i to x (see Table 6-4).
ii. Proximity Heuristic: Connect the AD plants to the biogas user and/or pipeline network in order of proximity to the biogas user or AD plant that is already on the pipeline network. The order of cumulative connection for the Steiner MST is as follows: AD plant 8, 1, 5, 3, 10, 6, 9, 4, 2, 7, respectively. The order of cumulative connection for the road network MST is as follows: AD plant 8, 3, 5, 9, 10, 6, 1, 4, 2, 7, respectively. Figure 6-4 illustrates a flowchart methodology of this heuristic. The scenario outputs from this heuristic are named A to J (see Table 6-5 and Table 6-6).

These heuristics were chosen for analysis as the biogas pipeline operator will seek to either maximise biogas flowrate or minimise pipeline length. Each connection heuristic, combined with either connecting the AD plants to the biogas user via Steiner MST or road network MST, give a total of 40 pipeline layout scenarios (10

AD plants, two layout methodologies, two connection heuristics), described below in Table 6-3 to Table 6-6.

Connection heuristic	Steiner MST	Road network MST
Output	MST.(i-x)	R.(i-x)
Proximity	MST.(A-J)	R.(A-J)

Table 6-3: Connection heuristic scenarios.

AD plant connected	Output heuristic scenario code	Steiner MST	Road network MST
1	i	MST.i	R.i
2	ii	MST.ii	R.ii
3	iii	MST.iii	R.iii
4	iv	MST.iv	R.iv
5	v	MST.v	R.v
6	vi	MST.vi	R.vi
7	vii	MST.vii	R.vii
8	viii	MST.viii	R.viii
9	ix	MST.ix	R.ix
10	x	MST.x	R.x

Table 6-4: Output heuristic scenario codes.

AD plant connected	Proximity heuristic scenario code	Steiner MST
8	A	MST.A
1	B	MST.B
5	C	MST.C
3	D	MST.D
10	E	MST.E
6	F	MST.F
9	G	MST.G
4	H	MST.H
2	I	MST.I
7	J	MST.J

Table 6-5: Steiner MST proximity heuristic scenario codes.

AD plant connected	Proximity heuristic scenario code	Road network MST
8	A	R.A
3	B	R.B
5	C	R.C
9	D	R.D
10	E	R.E
6	F	R.F
1	G	R.G
4	H	R.H
2	I	R.I
7	J	R.J

Table 6-6: Road network MST proximity heuristic scenario codes.

Each pipeline layout was designed independently of the layout that precedes it – in other words, each design is treated as if there are no pre-existing pipelines and is not a modular addition to the previous design.

Output heuristic, Steiner MST: The *v.net.steiner* GRASS tool in QGIS (GRASS Development Team, 2020), was used to create a Steiner MST between AD plant 1 (the largest biogas producer) and the biogas user, then a new layout was created between AD plants 1 and 2 (the second largest biogas producer) and the biogas user, and so on, until all 10 output heuristic Steiner MST layouts (MST.i to MST.x) were created.

Output heuristic, road network MST: The *v.net.steiner* GRASS tool was used, connecting AD plant 1 and the biogas user via the road network, and subsequently for connecting AD plants 1 and 2 via the road network, and so on, until all 10 output heuristic road network MST layouts (R.i to R.x) were created.

Proximity heuristic, Steiner MST: The *v.net.steiner* GRASS tool in QGIS (GRASS Development Team, 2020), was used to create a Steiner MST between AD plant 8 (the closest AD plant to the biogas user) and the biogas user, then a new layout was created between AD plants 8 and 1 (the next closest plant to the network) and the biogas user, and so on, until all 10 proximity heuristic Steiner MST layouts (MST.A to MST.J) were created.

Proximity heuristic, road network MST: The *v.net.steiner* GRASS tool was used, connecting AD plant 8 (closest AD plant via road network to the biogas user) and the biogas user via the road network, and subsequently for connecting AD plants 8 and 3 (the next closest AD plant via the road network), and so on, until all 10 output heuristic road network MST layouts (R.A to R.J) were created.

For example, for the proximity heuristic, the scenarios in which AD plants 8, 1, 5, 3 and 10 are connected to the biogas user via MST with Steiner nodes is scenario MST.E (Table 6-5), and the scenario in which AD plants 8, 3, 5, 9 and 10 are connected to the biogas user via MST along the road network is scenario R.E (see Table 6-6).

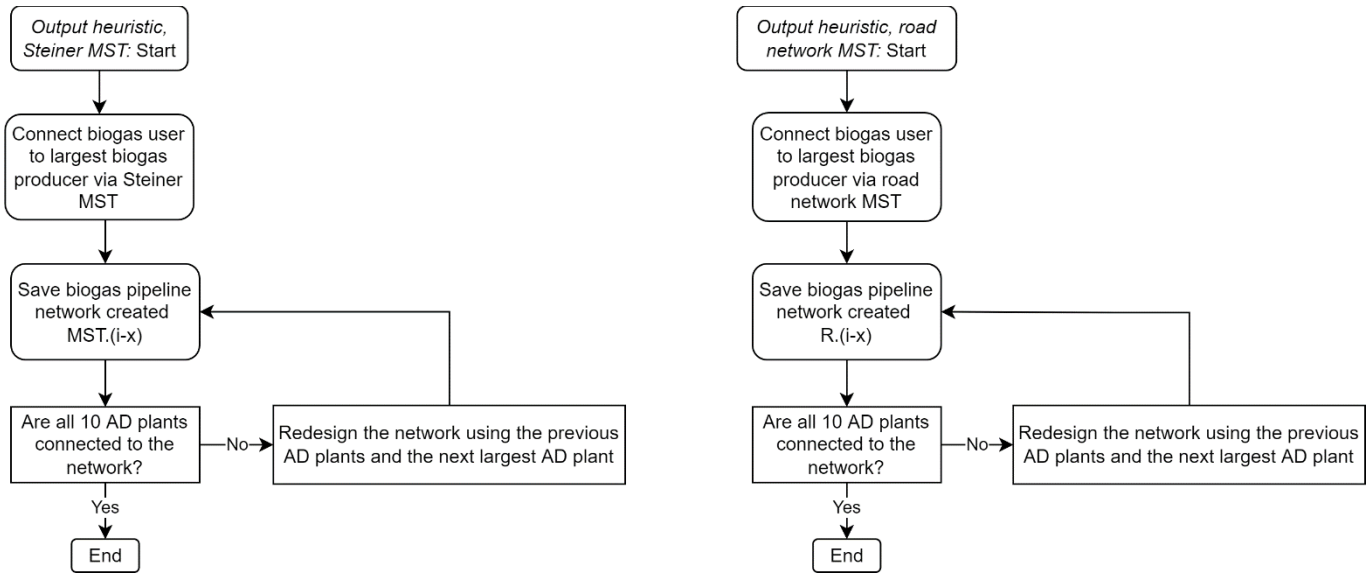


Figure 6-3: Flowchart methodology for output heuristic.

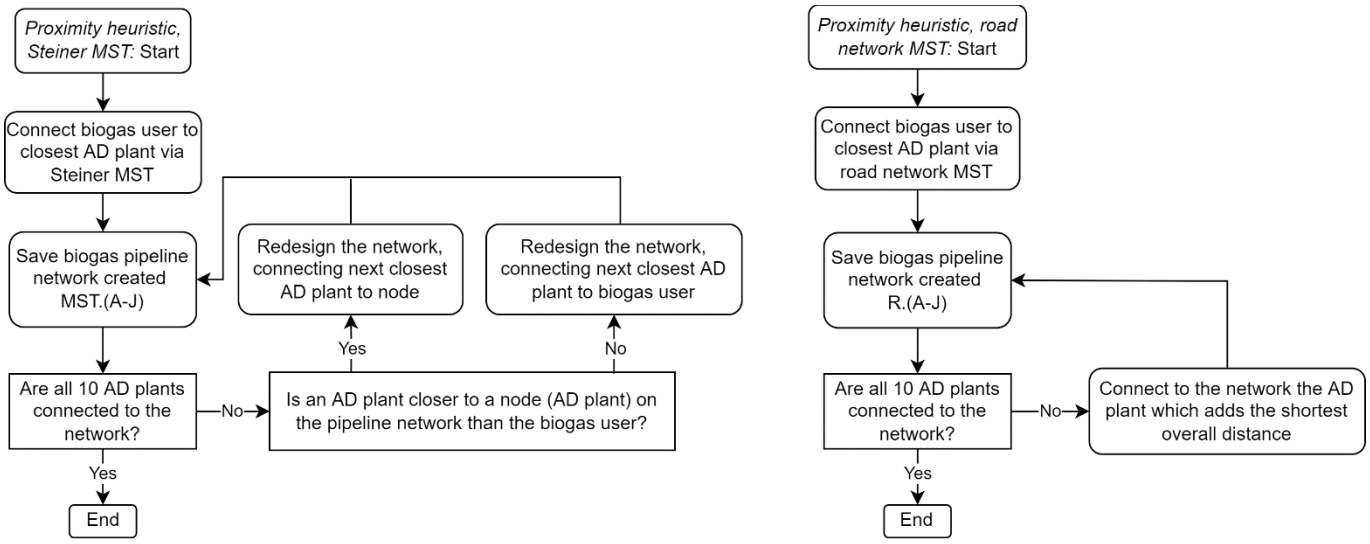


Figure 6-4: Flowchart methodology for proximity heuristic.

6.2.3 Pipeline network design and material costs

SNAP was used to design and analyse the pipeline network layouts created and to calculate the pipeline material costs. The input data for SNAP was comprised of the pipe lengths and nodes, the pressures at the biogas producers (AD plants) and the gas demand at the end user. The SNAP software optimises the pipeline diameter based on pipeline costs so as to minimise the network cost, and the output results provided the pipeline diameters in the network assessed. SNAP is designed for use with gas networks transporting natural gas to domestic users for heating, where an “infinite” gas supply at the source node is assumed, and a gas demand flow-rate is specified by the user at each of the demand nodes. This is the reverse of the design objective of work, which requires user-specified gas flowrates from the source nodes, and a

demand node which accepts all gas in the network. Therefore, the flow direction of the scenarios in this work was "reversed", that is, the biogas user is the "producer", and the AD plants were the "demand" nodes – this allows SNAP to model the pipeline diameters and costs. This correctly designs the required pipelines for the actual flow direction, as pipeline diameter is not dependent on flow direction. Full instructions on the SNAP design process, and the input and output data, can be found in Appendix D.3. The pipeline factors are shown in Table 6-7, and were sourced from a local supplier, Irish Tube & Fittings Supply Limited. The pipeline materials used for analysis were polyethylene (SDR17 PN10).

Nominal diameter (mm)	Internal diameter (mm)	Cost (€ m^{-1})
16	11.15	€0.36
20	15.15	€0.40
25	20.15	€0.56
32	25.75	€1.35
63	50.9	€5.09
90	79.2	€6.18
125	110.3	€11.72
180	158.75	€24.23
250	220.75	€46.62
315	278.25	€73.92
355	313.5	€94.08

Table 6-7: Polyethylene (SDR17 PN10) pipeline diameters and costs per unit length.

6.2.3.1 SNAP requirements

To conduct the analysis, SNAP requires the input of gas characteristics, including gas density, gas specific gravity, and gas dynamic viscosity. As SNAP is usually used for the design of methane pipelines, the default application characteristics are set to CH_4 characteristics, and so must be changed by the user to biogas characteristics. A compressibility factor (Z-factor) of 1 was assumed for biogas at 60% CH_4, given the low-pressure profiles of the pipelines (Trávníček et al., 2017). The desired gauge pressure at the biogas user was 150 mbar (absolute pressure of 1.163 bar). The desired gauge pressure will be the pressure at which the biogas density, specific gravity, and dynamic viscosity will be calculated for use in SNAP. The design temperature of the biogas system was 15 °C, as per the Irish gas network operator's code of operations (GNI, 2019).

The density of the biogas (ρ_{biogas}) in kg m^{-3} can be found using Eq. (6.1):

$$\rho_{biogas} = \left(\rho_{CH_4} * \%vol_{CH_4}\right) + \left(\rho_{CO_2} * \%vol_{CO_2}\right) \quad (6.1)$$

where ρ_{CH4} and ρ_{CO2} are the densities in kg m^{-3} of both methane and carbon dioxide at 15 °C and absolute pressure of 1.163 bar, and $\%vol_{CH_4}$ and $\%vol_{CO_2}$ are the percentage volume of both methane and carbon dioxide in the biogas (60% and 40%, respectively).

The specific gravity of biogas (SG_{biogas}) was found using Eq. (6.2):

$$SG_{biogas} = \frac{\rho_{biogas}}{\rho_{air}} \quad (6.2)$$

where ρ_{biogas} is the density of biogas in kg m^{-3} as found through Eq. (6.1) and ρ_{air} is the density of air in kg m^{-3} (at 15 °C and absolute pressure of 1.163 bar for both).

The dynamic viscosity of the biogas mixture (μ_{ga}) in Pascal seconds (Pa s), at 15 °C and absolute pressure of 1.163 bar, which is different from that of natural gas, was calculated using Eq. (6.3);

$$\mu_{ga} = \frac{\sum_{i=1}^{N} y_i \mu_i \sqrt{M_{gi}}}{\sum_{i=1}^{N} y_i \sqrt{M_{gi}}} \quad (6.3)$$

where y_i is the mole fraction of the i^{th} component, μ_i is the viscosity in Pa-s of the i^{th} component of the gas mixture at the desired temperature and pressure, M_{gi} is the molecular weight of the i^{th} component of the gas mixture (16 and 44 for CH_4 and CO_2, respectively), and N is the number of components of the gas mixture (N=2, as there are two gases). These values for both methane and carbon dioxide at 15 °C and at gauge pressure 150 mbar (1.163 bar absolute pressure) were found from Lemmon et al. (2023) and are shown in Table 6-8.

	CH_4 (i=1)	**CO_2 (i=2)**
y_i	0.6	0.4
μ_i	1.0257*10^{-5} Pa-s	1.3722*10^{-5} Pa-s
M_{gi}	16	44

Table 6-8: Component factors of CH_4 and CO_2 at 15 °C and 1.163 bar (Lemmon et al., 2023).

At 15 °C and 1.163 bar, the density of CH_4 and CO_2 are 0.78054 kg m^{-3} and 2.1503 kg m^{-3}, respectively (Lemmon et al., 2023) – note that these values for the density of the gases are different from at either normal or standard conditions, due to the different temperature and pressure conditions. Therefore, as CH_4 and CO_2 represent

60% and 40% of the biogas mixture, respectively, the density of the biogas can be found by inputting these values into Eq. (6.1):

$$\rho_{biogas} = \left(\rho_{CH_4} * \%vol_{CH_4}\right) + \left(\rho_{CO_2} * \%vol_{CO_2}\right) \quad (6.4)$$

$$= (0.78054\ kg\ m^{-3} * 0.6) + (2.1503\ kg\ m^{-3} * 0.4)$$

$$= 1.328444\ kg\ m^{-3}$$

The density of air at 15 °C and 1.163 bar is 1.39966 kg m^{-3} (Czernia and Szyk, 2023), given an annual average relative humidity of 82% (Met Éireann, 2010). Using Eq. (6.2), the specific gravity of biogas at 0 °C and 1.163 bar absolute pressure was found:

$$SG_{biogas} = \frac{\rho_{biogas}}{\rho_{air}} = \frac{1.328444\ kg\ m^{-3}}{1.39966\ kg\ m^{-3}} = 0.949 \quad (6.5)$$

The dynamic viscosity of biogas at 1.163 bar absolute pressure was found by inputting the values from Table 6-8 into Eq. (6.3), of which the calculation is shown here:

$$\mu_{ga} = \frac{y_1\mu_1\sqrt{M_{g1}} + y_2\mu_2\sqrt{M_{g2}}}{y_1\sqrt{M_{g1}} + y_2\sqrt{M_{g2}}} \quad (6.6)$$

$$= \frac{\left(0.6 * (1.0753 * 10^{-5}) * \sqrt{16}\right) + \left(0.4 * (1.4436 * 10^{-5}) * \sqrt{44}\right)}{\left(0.6 * \sqrt{16}\right) + \left(0.4 * \sqrt{44}\right)}$$

$$= 1.2687 * 10^{-5}$$

These factors were user-set at the input stage of the pipeline network design files in SNAP.

6.2.4 Multicriteria decision analysis: pipeline material cost vs. system biogas flow-rate

A MCDA was conducted in which each scenario's pipeline material cost and biogas flow-rate were considered. Normalised values for each criterion were obtained based on the identification of utopia and nadir points as per O'Shea *et al.* (2022). The utopia point was identified as a hypothetical point consisting of the best values of pipeline material cost and biogas flowrate. The nadir point was identified as a hypothetical point consisting of the worst values of pipeline material cost and biogas flowrate. The un-normalised value obtained by an alternative j for a criterion i can is expressed as $c_{i,j}$. The utopia value for criterion i is expressed as c_i^{Utopia} and the

nadir value for criterion i is expressed as c_i^{Nadir}. The normalised value (x) for a given criterion i for a given alternative j based on the deviation from utopia is expressed on an interval of [0,1] as in Eq. (6.7):

$$x_{i,j} = \frac{\left|c_i^{Utopia} - c_{i,j}\right|}{\left|c_i^{Utopia} - c_i^{Nadir}\right|} \tag{6.7}$$

For pipeline material cost, the scenario with the lowest cost represented the utopia, and the scenario with the highest cost the nadir. For biogas flow-rate to the end user, the highest flow-rate represented the utopia and the lowest flow-rate the nadir. The weighted-sum model, the most commonly used MCDA method (Triantaphyllou, 2000), was employed to determine the scenarios with the best compromise between pipeline material costs and biogas flow-rates. The weighted sum model can be described by Eq. (6.8):

$$I_j = \sum_{i=1}^{n} w_i x_{ij} \tag{6.8}$$

Where I_j is the composite index for a scenario, n is the number of criteria, w_i the importance weighting of the ith criterion, and $x_{i,j}$ the normalised value of the j^{th} scenario for the i^{th} criterion. This methodology allows for the assessment of the scenarios at various levels of weighted importance for pipeline material cost; different weightings of importance were applied to pipeline material costs vs. biogas flow-rate to the end user, from 0 to 1 in steps of 0.10. The scenario with the lowest value I is deemed the best performing, the scenario with the second lowest value of I is deemed the second best performing, and so on (scenarios are ranked based on the value of I in ascending order, a rank of 1 implies that a scenario is the "best").

6.3 Results

6.3.1 Steiner MST vs. road network MST

Figure 6-5 shows two pipeline network layouts which connect all 10 AD plants to the biogas end user: a Steiner MST showing the shortest possible network layout, and a road network MST which follows the shortest possible road network route. The total length of the Steiner MST is 24.42 km long, and the total length of the road network MST is 31.89 km long. In each pipeline scenario, a total of 32,000 Nm^3 $week^{-1}$ of biogas is collected by the biogas user.

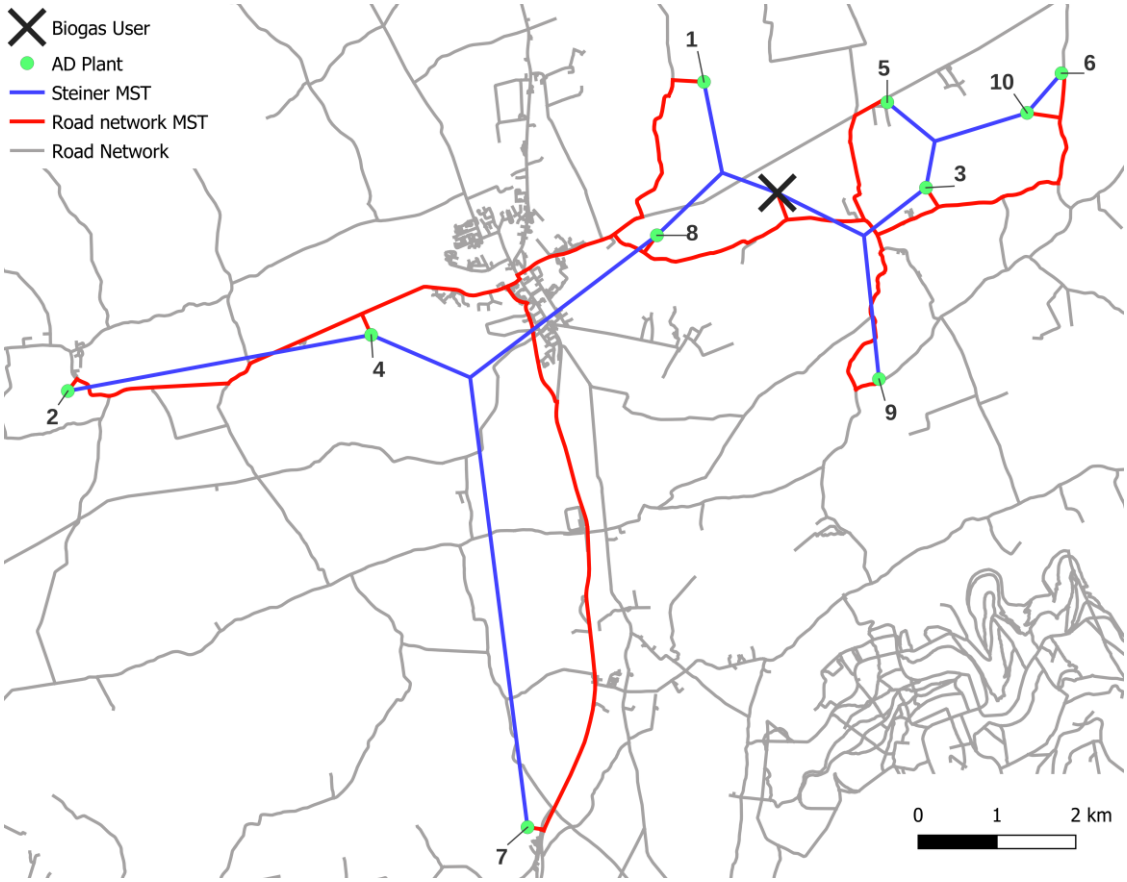


Figure 6-5: Biogas pipeline layouts connecting all AD plants either via Steiner MST or road network MST.

6.3.2 Output and proximity heuristics

6.3.2.1 Output heuristic

Table 6-9 and Table 6-10 show each proximity heuristic scenario's biogas production, pipeline length, required pipeline diameters, and pipeline network layout material cost. Note that the costs of scenarios MST.J and R.J are identical to MST.x and R.x, respectively, as these scenarios connect to the same number of AD plants regardless of connection heuristic.

Scenario	Biogas flow-rate		Pipeline diameters	Length	Total length	Cost
	($Nm^3\ hr^{-1}$)	($Nm^3\ week^{-1}$)	(mm)	(km)	(km)	(€)
MST.i	29.8	5,000	63	1.69	1.69	€ 8,602.56
MST.ii	57.1	9,600	63	0.66	10.56	€ 64,554.40
			90	9.90		
MST.iii	82.1	13,800	63	2.55	12.45	€ 74,170.28
			90	9.90		
MST.iv	104.8	17,600	63	2.74	12.59	€ 80,647.03
			90	8.78		
			125	1.06		
MST.v	125.0	21,000	63	2.22	13.48	€ 86,734.99
			90	10.20		
			125	1.06		
MST.vi	142.9	24,000	63	3.33	15.71	€ 99,293.76
			90	11.31		
			125	1.06		
MST.vii	158.3	26,600	63	3.33	22.07	€ 165,592.44
			90	12.81		
			125	5.93		
MST.viii	171.4	28,800	63	3.65	22.09	€ 159,568.84
			90	13.57		
			125	4.87		
MST.ix	182.1	30,600	63	5.51	24.34	€ 171,409.19
			90	13.96		
			125	4.87		
MST.x	190.5	32,000	63	4.45	24.42	€ 173,062.25
			90	15.09		
			125	4.87		

Table 6-9: Output heuristic MST.(i-x) scenarios' biogas production, required pipeline diameters, pipeline lengths, and pipeline material cost.

Scenario	Biogas flow-rate		Pipeline diameters	Length	Total length	Cost
	(Nm^3 hr^{-1})	(Nm^3 $week^{-1}$)	(mm)	(km)	(km)	(€)
R.i	29.8	5,000	90	5.63	5.63	€ 34,789.88
R.ii	57.1	9,600	90	13.35	13.35	€ 82,502.69
R.iii	82.1	13,800	63	2.38	15.73	€ 94,620.86
			90	13.35		
R.iv	104.8	17,600	63	2.67	16.02	€ 111,637.02
			90	10.55		
			125	2.80		
R.v	125.0	21,000	63	3.60	17.94	€ 122,442.09
			90	11.53		
			125	2.80		
R.vi	142.9	24,000	63	5.55	20.99	€ 139,208.56
			90	12.64		
			125	2.80		
R.vii	158.3	26,600	63	5.55	28.55	€ 194,712.36
			90	18.61		
			125	4.39		
R.viii	171.4	28,800	32	0.27	28.82	€ 199,630.03
			63	5.55		
			90	18.61		
			125	4.03		
			180	0.36		
R.ix	182.1	30,600	32	0.27	31.46	€ 213,067.33
			63	8.19		
			90	18.61		
			125	4.03		
			180	0.36		
R.x	190.5	32,000	32	0.27	31.89	€ 217,915.19
			63	6.16		
			90	21.06		
			125	4.03		
			180	0.36		

Table 6-10: Output heuristic R.(i-x) scenarios' biogas production, required pipeline diameters, pipeline lengths, and pipeline material cost.

6.3.2.2 Proximity heuristic

Table 6-11 and Table 6-12 show each proximity heuristic scenario's biogas production, pipeline length, required pipeline diameters, and pipeline network layout material cost. Note that the costs of scenarios MST.J and R.J are identical to MST.x and R.x, respectively, as these scenarios connect to the same number of AD plants regardless of connection heuristic.

Scenario	Biogas flow-rate		Pipeline diameters	Length	Total length	Cost
	($Nm^3\ hr^{-1}$)	($Nm^3\ week^{-1}$)	(mm)	(km)	(km)	(€)
MST.A	13.1	2,200	63	1.62	1.62	€ 8,249.21
MST.B	42.9	7,200	63	2.33	3.07	€ 16,442.08
			90	0.75		
MST.C	63.1	10,600	63	4.13	4.88	€ 25,651.62
			90	0.75		
MST.D	88.1	14,800	63	3.69	5.85	€ 32,145.91
			90	2.16		
MST.E	96.4	16,200	63	5.29	7.45	€ 40,274.84
			90	2.16		
MST.F	114.3	19,200	63	3.59	8.12	€ 46,240.48
			90	4.52		
MST.G	125.0	21,000	63	5.60	10.40	€ 58,152.27
			90	4.80		
MST.H	147.6	24,800	63	4.45	14.24	€ 83,151.49
			90	9.79		
MST.I	175.0	29,400	63	4.45	18.16	€ 111,484.19
			90	12.96		
			125	0.75		
MST.J	190.5	32,000	63	4.45	24.42	€ 173,062.25
			90	15.09		
			125	4.87		

Table 6-11: Proximity heuristic MST.(A-J) scenarios' biogas production, required pipeline diameters, pipeline lengths, and pipeline material cost.

Scenario	Biogas flow-rate		Pipeline diameters	Length	Total length	Cost
	($Nm^3\ hr^{-1}$)	($Nm^3\ week^{-1}$)	(mm)	(km)	(km)	(€)
R.A	13.1	2,200	63	2.62	2.62	€ 13,313.51
R.B	38.1	6,400	63	5.00	5.90	€ 25,431.68
R.C	58.3	9,800	63	5.56	6.91	€ 36,632.09
			90	1.35		
R.D	69.0	11,600	63	8.20	9.55	€ 50,070.41
			90	1.35		
R.E	77.4	13,000	63	10.83	12.43	€ 65,018.46
			90	1.60		
R.F	95.2	16,000	63	8.12	13.03	€ 71,684.74
			90	4.91		
R.G	125.0	21,000	32	0.27	16.32	€ 95,147.94
			63	5.87		
			90	9.81		
			125	0.36		
R.H	147.6	24,800	32	0.27	20.15	€ 129,772.48
			63	5.87		
			90	11.66		
			125	2.34		
R.I	175.0	29,400	32	0.27	24.33	€ 157,862.39
			63	6.16		
			90	15.09		
			125	2.80		
R.J	190.5	32,000	32	0.27	31.89	€ 217,915.19
			63	6.16		
			90	21.06		
			125	4.03		
			180	0.36		

Table 6-12: Proximity heuristic R.(A-J) scenarios' biogas production, required pipeline diameters, pipeline lengths, and pipeline material cost.

All designed pipeline layouts can be found in Appendix D.4. All SNAP input parameters and output text files for all scenarios in this work can be found in Appendix D.5. Figure 6-6 shows all scenario pipeline costs ranked from lowest to highest.

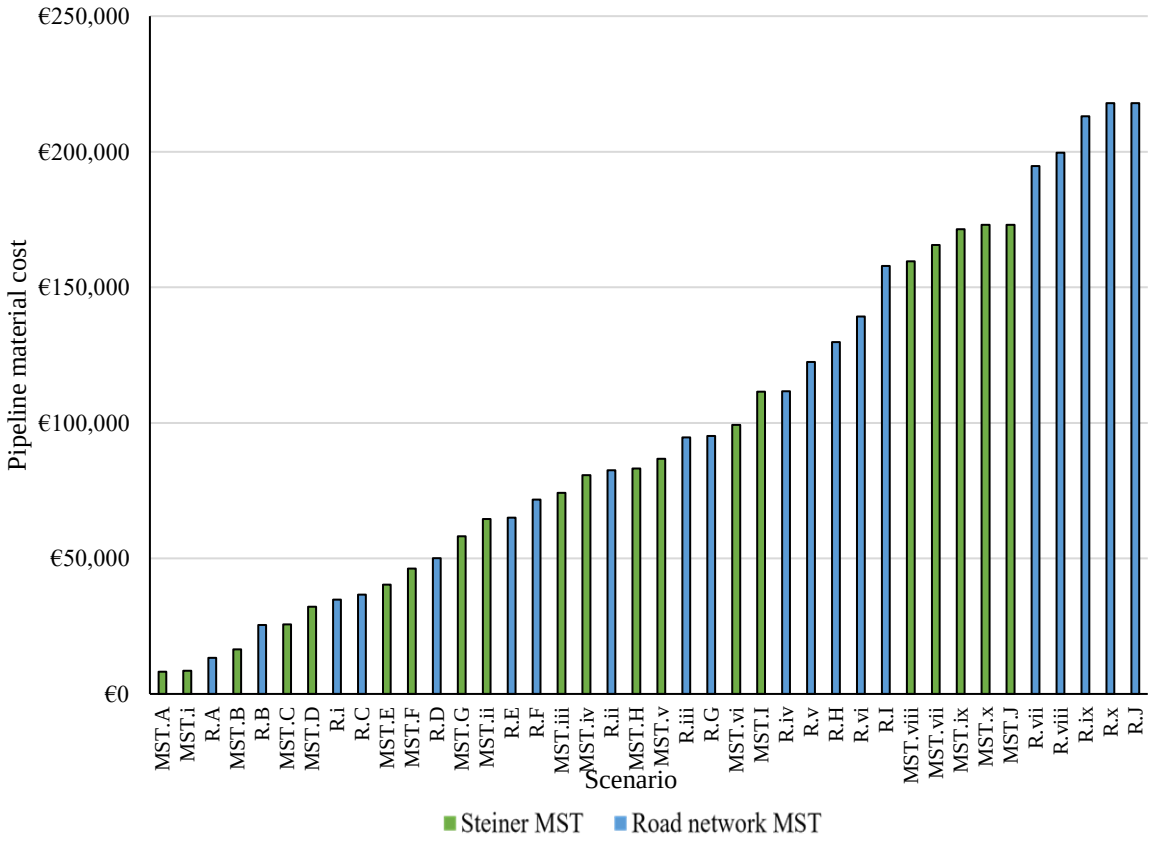


Figure 6-6: Scenarios ranked by pipeline material cost, from lowest to highest.

Figure 6-7 shows each scenario's pipeline material costs vs. biogas flow-rate, showing a strong correlation between the two variables ($R^2 = 0.8062$). This strong correlation is expected; more AD plants in the overall pipeline network will increase both biogas flow-rates and the pipeline materials required.

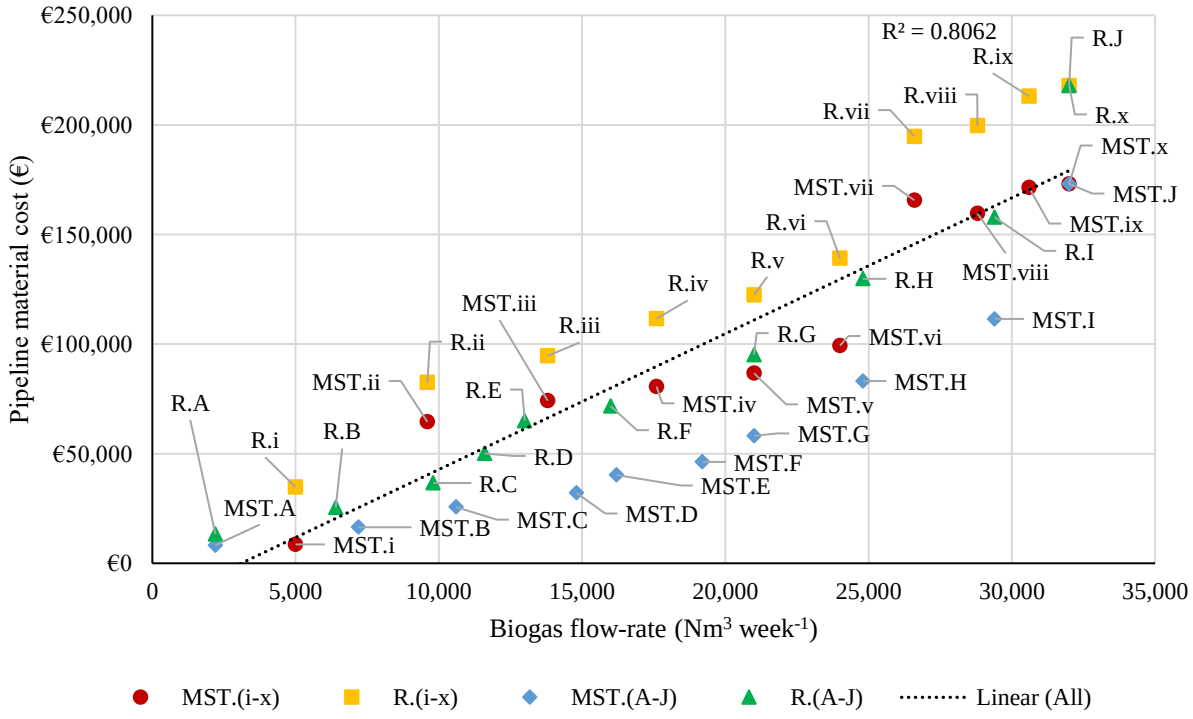


Figure 6-7: Scenario pipeline material cost vs. biogas flow-rate.

Figure 6-8 shows each scenario's pipeline material costs vs. total pipeline length, showing a very strong correlation between the two variables (R^2 = 0. 9689). This very strong correlation is expected; longer pipeline networks will require more pipeline materials, driving up costs.

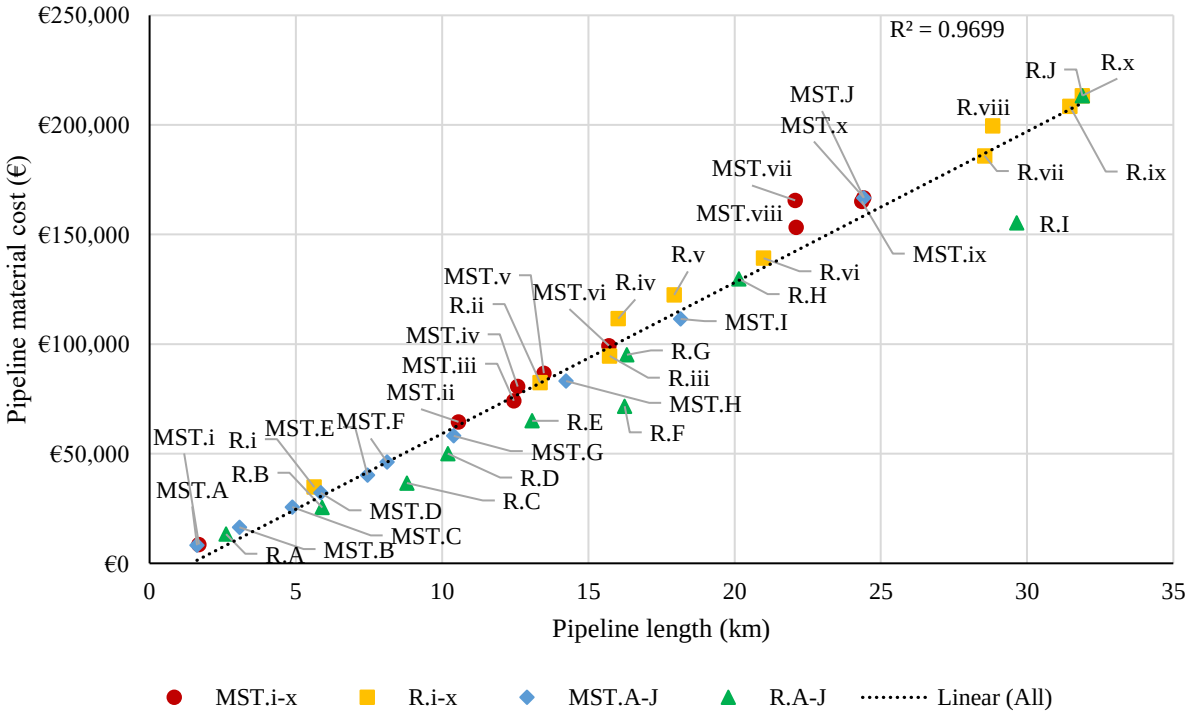


Figure 6-8: Scenario pipeline material cost vs. pipeline length.

6.3.3 MCDA: biogas output vs. pipeline material cost

Table 6-13 shows the utopia and nadir for pipeline material cost and pipeline network biogas flow-rate. The scenario with the lowest pipeline material cost (utopia) is MST.A, and the scenarios with the highest pipeline material costs (nadir) are R.x and R.J. The scenarios with the highest biogas flow-rates (utopia) are the scenarios which connect all AD plants to the biogas user (MST.x, R.x, MST.J, R.J). The scenarios with the lowest biogas flow-rates (nadir) are scenarios which connect the biogas user to the AD plant closest to it (proximity heuristic, scenarios MST.A and R.A).

	Pipeline material cost (€)	Biogas flow-rate ($Nm^3\ hr^{-1}$)
Utopia	€ 8,249.21	190.5
Nadir	€ 213,366.19	13.1

Table 6-13: Utopia and nadir for pipeline material cost and pipeline network flow-rate.

Figure 6-9 shows a MCDA chart, showing the deviation from biogas pipeline material cost utopia vs. biogas pipeline network flow-rate utopia.

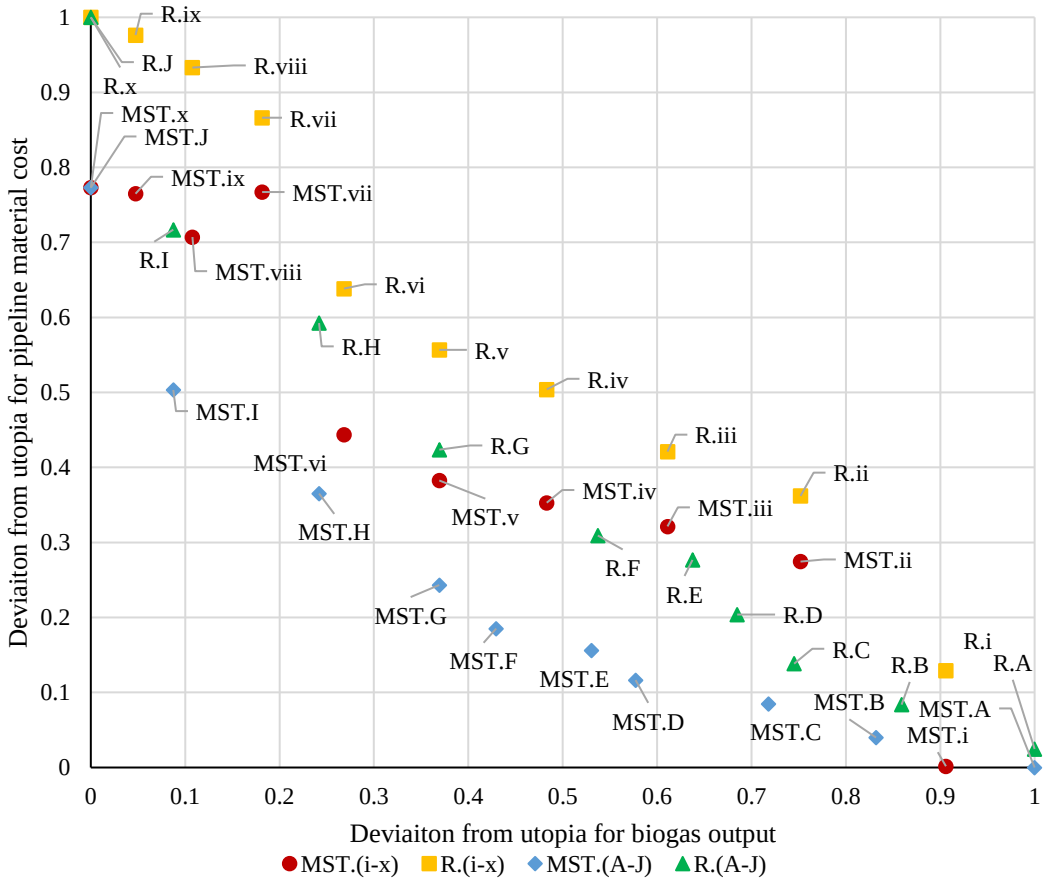


Figure 6-9: MCDA chart of deviation from utopia, for scenario pipeline material cost vs. scenario biogas output.

Table 6-14 shows the best performing scenarios for various levels of weighted importance between pipeline material cost and biogas flow-rate.

Weighted importance		Best overall performer	Best output heuristic performer		Best proximity heuristic performer	
Pipeline material cost	**Biogas flow-rate**		MST.	R.	MST.	R.
0.00	**1.00**	MST.x, R.x, MST.J, R.J *(tie)*	MST.x	R.x	MST.J	R.J
0.10	**0.90**	MST.x, MST.J *(tie)*	MST.x	R.x	MST.J	R.J
0.20	**0.80**	MST.x, MST.J *(tie)*	MST.x	R.x	MST.J	R.J
0.30	**0.70**	MST.I	MST.x	R.x	MST.I	R.I
0.40	**0.60**	MST.I	MST.x	R.x	MST.I	R.I
0.50	**0.50**	MST.I	MST.vi	R.vi	MST.I	R.G
0.60	**0.40**	MST.F	MST.i	R.i	MST.F	R.C
0.70	**0.30**	MST.D	MST.i	R.i	MST.D	R.B
0.80	**0.20**	MST.i	MST.i	R.i	MST.B	R.A
0.90	**0.10**	MST.i	MST.i	R.i	MST.A	R.A
1.00	**0.00**	MST.A	MST.i	R.i	MST.A	R.A

Table 6-14: Best performing scenarios via weighted sum-model for pipeline material cost vs. biogas output.

Figure 6-9 and Table 6-14 reveal that the scenarios labelled MST.(A-J) (blue diamond) are the best overall performers in the MCDA analysis; these scenarios simultaneously employ the shortest pipeline layout methodology (MST) and the proximity connection heuristic.

6.4 Discussion

The methodology proposed in this work provides a valuable source of information to industries, developers, or communities. Industries can quickly design hypothetical pipeline networks that suit their energy needs whilst also indicating the potential pipeline material costs of such networks, this in turn aids their decarbonisation strategies. Developers and communities can consider the uptake of AD systems by conducting feasibility studies of biogas pipeline networks in their region. This work is particularly relevant to areas with limited gas grid access, whereby digesters may be located in proximity to large energy users, or alternatively the biogas may be upgraded centrally and used as a transport fuel. This study adds to previous works by the authors by developing a design methodology which does not require significant knowledge of pipeline design methodologies and equations, nor of algorithmic optimisation techniques to solve for Steiner nodes (O'Shea et al., 2017).

GIS techniques can offer industries or biogas users a straightforward approach to designing biogas pipeline networks. Steiner MSTs allowed for the shortest possible biogas pipeline layouts in connecting AD plants with a biogas user; this minimises the pipeline material costs associated with the purchase of pipes and minimises any construction and maintenance costs. However, if the pipeline layouts traverse land that is not owned by the AD plant operators (or biogas user), landowners may object to having such infrastructure on their property.

Road network MST pipeline layouts require increased pipeline material costs compared with Steiner MSTs, and may result in increased traffic disruption, increasing the risk of objection by local residents and businesses. In scenarios which connect all 10 AD plants to the biogas user, pipelines which connect via the road network (R.x, R.J) cost almost 28% more than scenarios which connect via Steiner MST (MST.x, R.x). However, as the road networks in many countries are owned by the local and/or national governments, it may be easier to secure construction permission from authorities, especially if state bodies are involved in the business model of the biogas plants and pipelines. It is likely that the cost of the AD plants in a given network will overshadow the material costs of the pipelines.

A strong correlation exists between pipeline network material and biogas flow-rate to the end user ($R^2 = 0.8$), and also between pipeline material cost and total network

length (R^2 = 0.97). The stronger correlation between pipeline material costs and total network length was due to the long network length of the scenarios investigated (1.69 to 31.89 km).

Two heuristics for deciding the connection order of AD plants to the biogas user can be applied depending on the priorities of the biogas user. If a specific biogas flow-rate is the desired end result, as may be the case if the biogas user is a central upgrading facility, it may be sensible to connect large AD plants to the biogas user first, in order to have sufficient gas flow. If minimising biogas pipeline costs is desired, it may be logical to connect to the AD plants in a manner which both minimises the pipeline length whilst also maximising the biogas flow-rate. This may be the case if the cost of the biogas pipeline falls on the biogas user, or if the AD plants already exist and the biogas pipeline represents the majority of the capital investment.

The MCDA analysis revealed that Steiner MSTs always outperform road network MSTS, unless pipeline material costs are of no importance (see Table 6-14). If pipeline material costs have weighted importance between 0.10 and 0.90, connecting via the proximity heuristic is almost always of equal or better performance than connecting via the output heuristic, except when the weighted importance of pipeline material cost is 0.80 or 0.90; this results in MST.i being the best-ranking scenario.

A full techno-economic analysis would further enlighten as to the economic and technological viability of the scenarios investigated in this work. An analysis of the compression requirements to facilitate the biogas pipelines designed in this work would reveal the true energy balance of such systems.

It is worth noting that the results obtained are highly dependent on the individual scenario pipeline layouts, biogas outputs of the AD plants, and the study area covered. Analysis of other study areas or of different biogas outputs may significantly change the biogas pipeline sizing, logistical considerations, and the MCDA results.

6.5 Conclusion

GIS techniques can be employed to quickly design biogas pipeline networks and give approximate solutions to the Steiner node problem. A road network MST connecting 10 AD plants to a biogas user costs 28% more than connecting via Steiner MST. A very strong correlation exists between pipeline material costs and both biogas flow-rate and total pipeline network length (R2 = 0.8 and 0.97, respectively); this is expected as more materials are required for longer networks and higher flow-rates. A MCDA reveals that road network MSTs only have similar ranking to Steiner MSTs when pipeline material cost is of no importance. Scenarios which connect AD plants to the biogas user via the proximity heuristic almost always outperform scenarios which connect via the output heuristic.

References

Czernia, D. and Szyk, B. (2023) Air Density Calculator. Available at: https://www.omnicalculator.com/physics/air-density (Accessed: 11 April 2023).

DNV (2023) Gas Toolbox | Veracity by DNV. Available at: https://store.veracity.com/gas-toolbox (Accessed: 22 July 2023).

European Commission (2022) Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: REPowerEU Plan. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF (Accessed: 19 August 2022).

Flanagan, M. et al. (2022) How a Russian Natural Gas Cutoff Could Weigh on Europe's Economies, IMF Blog. Available at: https://blogs.imf.org/2022/07/19/how-a-russian-natural-gas-cutoff-could-weigh-on-europes-economies/ (Accessed: 19 August 2022).

GNI (2019) Code of Operations. Available at: https://www.gasnetworks.ie/docs/corporate/gas-regulation/Code-of-Operations-Version-5.03-Conolidated.pdf (Accessed: 11 April 2023).

Google (2022) Google Maps. Available at: https://www.google.com/maps.

GRASS Development Team (2020) v.net.steiner - GRASS GIS manual. Available at: https://grass.osgeo.org/grass78/manuals/v.net.steiner.html (Accessed: 28 September 2022).

IEA (2019) The Role of Gas in Today's Energy Transitions. OECD. Available at: https://doi.org/10.1787/ba7ee64f-en.. (Accessed: 7 September 2020)

Knuth, D.E. (1974) 'Postscript about NP-Hard Problems', SIGACT News, 6(2), pp. 15–16. Available at: https://doi.org/10.1145/1008304.1008305.

Lemmon, E.W. et al. (2023) 'Thermophysical Properties of Fluid Systems', in NIST Chemistry WebBook, NIST Standard Reference Database Number 69. Lindstrom,. Gaithersburg MD. Available at: https://doi.org/https://doi.org/10.18434/T4D303. (Accessed: 22 February 2023).

Met Éireann (2010) Cork 1981–2010 averages. Available at: https://www.met.ie/climate-ireland/1981-2010/cork.html (Accessed: 11 April 2023).

Mišík, M. (2022) 'The EU needs to improve its external energy security', Energy Policy, 165, p. 112930. Available at: https://doi.org/10.1016/j.enpol.2022.112930.

Mitchell, J.S.B. (2000) ‘Geometric Shortest Paths and Network Optimization’, in Handbook of Computational Geometry. North-Holland, pp. 633–701. Available at: https://doi.org/10.1016/B978-044482537-7/50016-4.

O’Connor, S. et al. (2020) ‘Economic and Environmental Analysis of Small-Scale Anaerobic Digestion Plants on Irish Dairy Farms’, Energies 2020, Vol. 13, Page 637, 13(3), p. 637. Available at: https://doi.org/10.3390/EN13030637.

O’Shea, R. et al. (2022) ‘Assessing decarbonisation pathways in the food and beverage sector: A multi-criteria decision analysis approach’, Journal of Cleaner Production, 371, p. 133534. Available at: https://doi.org/10.1016/J.JCLEPRO.2022.133534.

O’Shea, R., Wall, D.M. and Murphy, J.D. (2017) ‘An energy and greenhouse gas comparison of centralised biogas production with road haulage of pig slurry, and decentralised biogas production with biogas transportation in a low-pressure pipe network’, Applied Energy, 208, pp. 108–122. Available at: https://doi.org/https://doi.org/10.1016/j.apenergy.2017.10.045.

Ó Céileachair, D. et al. (2021) ‘Alternative energy management strategies for large industry in non-gas-grid regions using on-farm biomethane’, Applied Energy, 303, p. 117627. Available at: https://doi.org/10.1016/j.apenergy.2021.117627.

OpenStreetMap (2022) OpenStreetMap. Available at: https://www.openstreetmap.org/ (Accessed: 6 July 2022).

Reuters (2022a) As German gas rationing looms, industry begs exemptions. Available at: https://www.reuters.com/business/energy/german-gas-rationing-looms-industry-begs-exemptions-2022-08-09/ (Accessed: 22 September 2022).

Reuters (2022b) Energy crisis chips away at Europe’s industrial might. Available at: https://www.reuters.com/business/energy/energy-crisis-chips-away-europes-industrial-might-2022-11-02/ (Accessed: 8 December 2022).

Trávníček, P., Vítěz, T. and Koutný, T. (2017) ‘The Equation of State of Biogas’, Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 65(2), pp. 537–543. Available at: https://doi.org/10.11118/actaun201765020537.

Triantaphyllou, E. (2000) *Multi-Criteria Decision Making Methods: A Comparative Study*. New York, NY, USA: Kluwer Academic Publishers. Available at: https://doi.org/10.1007/978-1-4757-3157-6.

UNFCCC and UN (2021) ‘The Glasgow Climate Pact’, in 2021 United Nations Climate Change Conference (COP26). Glasgow: UNFCCC. Available at: https://ukcop26.org/cop26-presidency-outcomes-the-climate-pact/. (Accessed: 1 December 2021).

Wang, J.J. et al. (2009) ‘Review on multi-criteria decision analysis aid in sustainable energy decision-making’, Renewable and Sustainable Energy Reviews, 13(9), pp. 2263–2278. Available at: https://doi.org/10.1016/J.RSER.2009.06.021.

7 Conclusions and recommendations

7.1 Conclusions

This thesis explores the logistics that must be considered in the development of on-farm anaerobic digestion (AD) in Ireland, as a way of producing sustainable biogas and biomethane from on-farm feedstocks, providing an alternative to fossil fuels. The considerations that are studied in this work are: the decentralised resource and lack of gas grid access across rural areas of the country; the seasonal availability of cattle slurry as a feedstock; the implications of possible seasonal gas demand profiles amongst decentralised large energy users (LEUs); and how virtual biomethane pipelines or physical biogas pipelines would serve as energy delivery methods. Based on these considerations, eight research objectives were raised in section 1.2. These objectives are answered below:

i. Total potential on-farm biomethane resource in Ireland from surplus grass silage, dairy slurry, hay, and cereal straws, equates to 67 PJ a^{-1}, or 200% of national industry natural gas use. 17% of national on-farm biomethane resources are more than 15 km away from gas grid infrastructure, whilst within 15 km of a large energy user.
ii. Industries in Ireland with no gas-grid infrastructure access may offset existing fossil fuel and decarbonise using biomethane generated from locally sourced biomass. Two industry case studies indicated that the existing heat demand could be met with biomethane produced from biomass within 2.5 km of the industry site.
iii. The detrimental effects of seasonal slurry availability may mostly be addressed by the recycling of liquid digestate during times when slurry is not being collected. Facilitating a seasonal gas demand will require proper planning by the plant operator, and significant levels of digestate recirculation, to ensure dispatchable feedstock supplies are available.
iv. The seasonal availability of slurry may lead to less sustainable biomethane as per EU RED II guidelines. An Irish farm with 100 dairy cows and 10 ha of land dedicated towards grass silage for AD may face increased biomethane emissions of 11 g $CO_{2\text{-eq}}$ MJ^{-1} due to seasonal slurry availability as compared to year-round supply of slurry. This may dictate the end-use of the biomethane, as EU RED II maximum emissions criteria are more stringent

for heat than they are for transport. Facilitating a seasonal gas demand has a minimal effect on the sustainability of the biomethane produced.

v. Low biogas flowrates may be a limiting factor in the development of virtual biomethane pipelines serving on-farm AD plants in Ireland. Larger biomethane haulage vehicles allow for shorter routing distances and lower emissions associated with transportation of biomethane.

vi. Slow biogas upgrading speeds, a lack of sufficient biomethane storage, and high routing emissions associated with mobile-upgrading and compression units may result in such approaches being logistically unfeasible if operated similarly to a virtual biomethane pipeline.

vii. Steiner Minimum Spanning Trees (MSTs) are shorter and have lower material costs than road network MSTs. However, land access may pose a significant challenge in the construction of Steiner MSTs.

viii. A method was developed in which a Multi-Criteria Decision Analysis (MCDA) determined that connecting AD plants in order of proximity to a biogas user outperformed connecting in order of biogas output in 75% of cases which did not result in a tie.

7.2 Research implications and recommendations

Based on the conclusions of this work as listed in section 7.1, and with consideration of the MaREI research centre's three impact priorities of 1) informing policy, 2) supporting industry, and 3) empowering society, the following recommendations are made:

7.2.1 Policy

The results of this thesis show that the biomethane resources available from on-farm feedstocks in Ireland are significant. The gross biomethane resource from dairy slurry and surplus grass silage is enough to satisfy over 150% of national industrial natural gas demand. In conjunction with the total national on-farm biomethane resources, rural areas with no gas grid access have significant biomethane resources in their vicinity. Rural communities are heavily reliant on fossil fuels for transport and heating – biomethane serves as a potential alternative which addresses decarbonisation and energy security concerns simultaneously. The development of on-farm AD would also allow farmers to reduce their fugitive emissions related to current slurry management practices. This, in conjunction with the use of sustainable biomethane would aid the government in meeting their climate obligations as per COP26 and the Climate Action Plan (CAP). The government have a goal in place which will see the construction of 130 large-scale AD plants in Ireland by 2030 – there is no logistical reason that small-scale rural AD plants could not be built simultaneously in addition to the large-scale plants.

Lack of gas grid access means that, with decentralised AD, a question arises as to who or what will use any biomethane produced, if electricity is not the desired output. Transport for Ireland (TFI) Local Link vehicles fuelled by biomethane would provide rural communities with sustainably fuelled public transport, whilst providing a reliable customer for on-farm AD plant operators and promoting circular economy practices.

Sustainability concerns have been raised with the use of grass silage as an AD feedstock in recent times, especially when grass silage is used in high concentrations relative to animal manures; the seasonal availability of slurry in Ireland increases this likelihood. If multi-species swards prove to be a more sustainable option that have

less of a fertiliser requirement, policies should be in place to facilitate their uptake amongst farmers.

7.2.2 Industry

Emissions from agriculture represent over 37% of national greenhouse gas emissions in Ireland. The development of on-farm AD systems may lead to lowered agricultural emissions through improved slurry management practices, whilst also providing a revenue generating system that promotes circular economy practices, decarbonisation, and improves energy security. This will benefit all agriculture industries across Ireland, and not just those in rural areas. The production of digestate as a secondary output to biomethane provides a more local and sustainable alternative to synthetic fertilisers, that are less likely to see price fluctuations due to geopolitical events.

The use of biogas and biomethane in Ireland will enable the reduction of emissions from heat, transport, and LEUs, enabling industries to reduce their emissions as required by governmental policies. Recent geopolitical crises have also emphasised the potential for biomethane to both decarbonise industries and improve energy security.

7.2.3 Community

Development of on-farm AD will advance the implementation of the CAP, particularly in rural areas. Gas boilers should be able to switch easily to biomethane, whereas pilot schemes of biomethane vehicles would make visible to communities the benefits of locally produced, sustainable fuels. The use of biomethane as vehicle fuel on farms would advance circular economy practices in the community. Methodologies in this thesis may be adapted for feasibility studies nationwide and would provide accessible ways for local communities to investigate decarbonisation routes.

7.2.4 Future research

Whilst this thesis has made significant advances in the field of logistics related to on-farm AD, further research is recommended as follows:

i. This thesis demonstrates the significant biomethane resource available from on-farm biomass in Ireland. CSTRs, co-digesting slurry, and surplus grass

would be the most viable option for on-farm AD. A push towards the use of slurries as opposed to grass in AD would alleviate sustainability concerns but may also lead to a lower energy return. Further research should investigate as to whether on-farm AD system fed with slurry-only would be feasible in Ireland.

ii. Deeper resource and spatial analyses are recommended to determine co-location of feedstocks with either gas grid infrastructure access or industry end users.

iii. Whilst the work of this thesis focuses on grass silage as an energy crop, recent developments have suggested that multi-species swards may be a more sustainable option. Multi-species swards can improve on-farm biodiversity, require less fertiliser, increase total grass output, and decrease absolute emissions. Future research should investigate the biomethane potential of multi-species swards, co-digestion potential with slurry, and sustainability implications.

iv. If seasonally available slurry is to be used as a feedstock, the changing chemical and nutrient composition of any digestate produced should be investigated.

v. Potential improvements to mobile-upgrading and compression technologies should be further researched. Models for the optimum routing strategy (daily, weekly, etc.) of such mobile-upgrading units should be considered.

vi. Further research should investigate the total energy balance of biogas pipelines. Compression and parasitic demand requirements may be deciding factors in scenario feasibility from an energy perspective.

vii. The optimal AD plant size for the use of either virtual biomethane pipelines or biogas pipelines should be investigated. It is likely that due to logistics, capital costs, and/or technological limitations that the size of AD plants in a potential network may dictate whether virtual pipelines or biogas pipelines should be employed.

viii. A full techno-economic analysis would reveal the feasibility of both virtual biomethane pipelines and biogas pipelines as designed in this thesis.

ix. Capital costs and thin margins may pose significant threats to the development of decentralised on-farm AD. Analysis should discern which

policies could support decentralised AD and may include guaranteed feed-in-tariff rates or capital grants.

x. Further MCDA using criteria such as land access barriers or labour costs may give further indication as to the best performing biogas pipeline layouts.

Appendices

Appendix A

Appendix A.1

Mitchelstown located in Co. Cork, is the ED in Ireland with the most cattle; 9,808 in total.

ED	Bulls	Dairy Cows	Other Cows	*Other Cattle*	Total Cattle
Mitchelstown, Co. Cork	64	2,826	620	*6,298*	9,808

Table A-1: Cattle categories in Mitchelstown, Co. Cork.

Using the ratios in Table 3-1, the following approximation was made for the categories of *Other Cattle* in Mitchelstown. This same method was applied to every ED in Ireland.

ED	Cattle male: 2 years and over	Cattle female: 2 years and over	Cattle male: 1-2 years	Cattle female: 1-2 years	Cattle male: under 1 year	Cattle female: under 1 year
Mitchelstown, Co. Cork	474	551	1,028	1,315	1,415	1,514

Table A-2: Approximation of type of cattle in Mitchelstown, Co. Cork.

Appendix A.2

Athy Rural (Part Rural), in Co. Kildare in the Mid-East & Dublin region, is the ED in Ireland in which the most hectares of land are under cereal crops: 2,392 ha. Using the ratios in Table 3-2, the following approximation was made about the cereals harvested in Athy Rural (Part Rural). This same method was applied to every ED in Ireland.

ED	W. Wheat	S. Wheat	W. Barley	S. Barley	W. Oats	S. Oats	Other Cereals
Athy Rural (Part Rural)	919.61	37.69	781.42	452.27	158.29	32.66	10.05

Table A-3: Example calculation of cereal hectarage ratio.

Appendix A.3

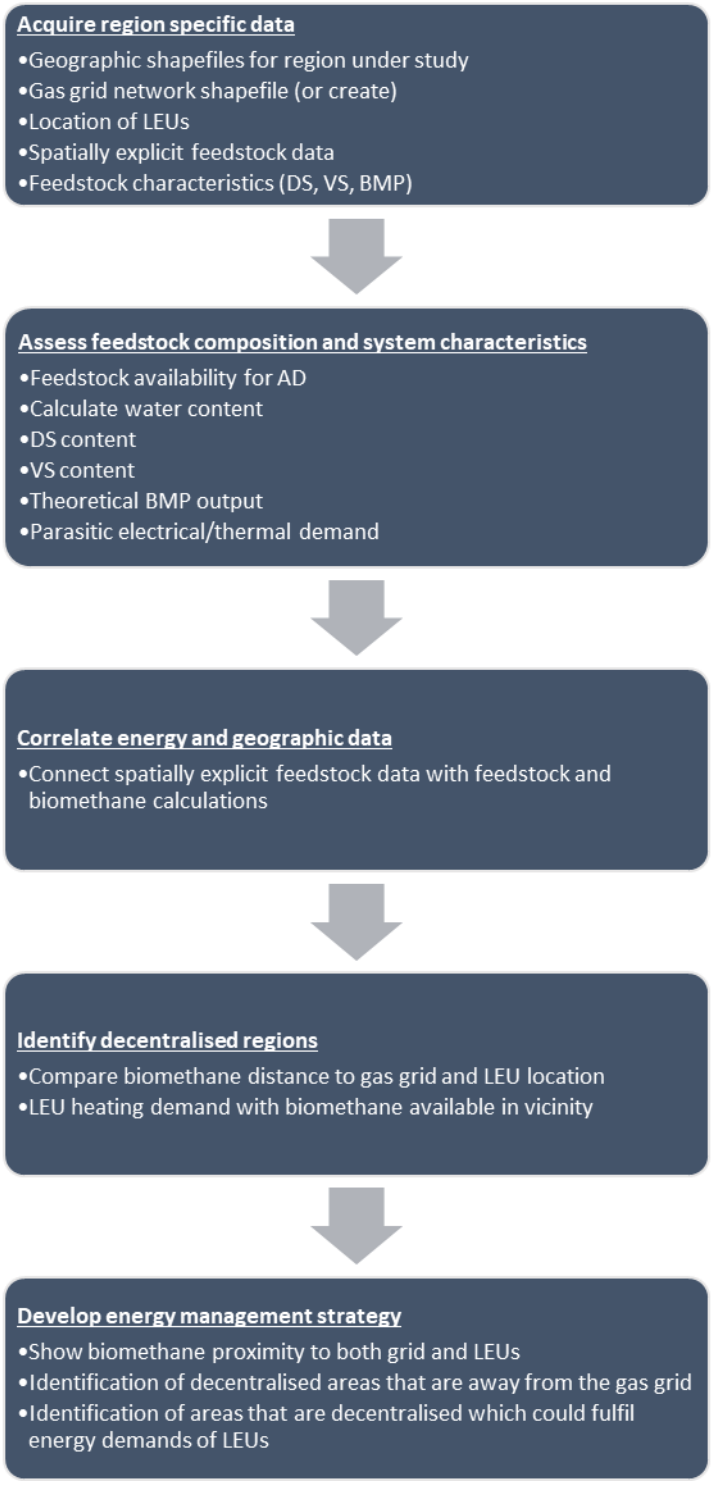


Figure A-1: Methodology flowchart.

Appendix A.4

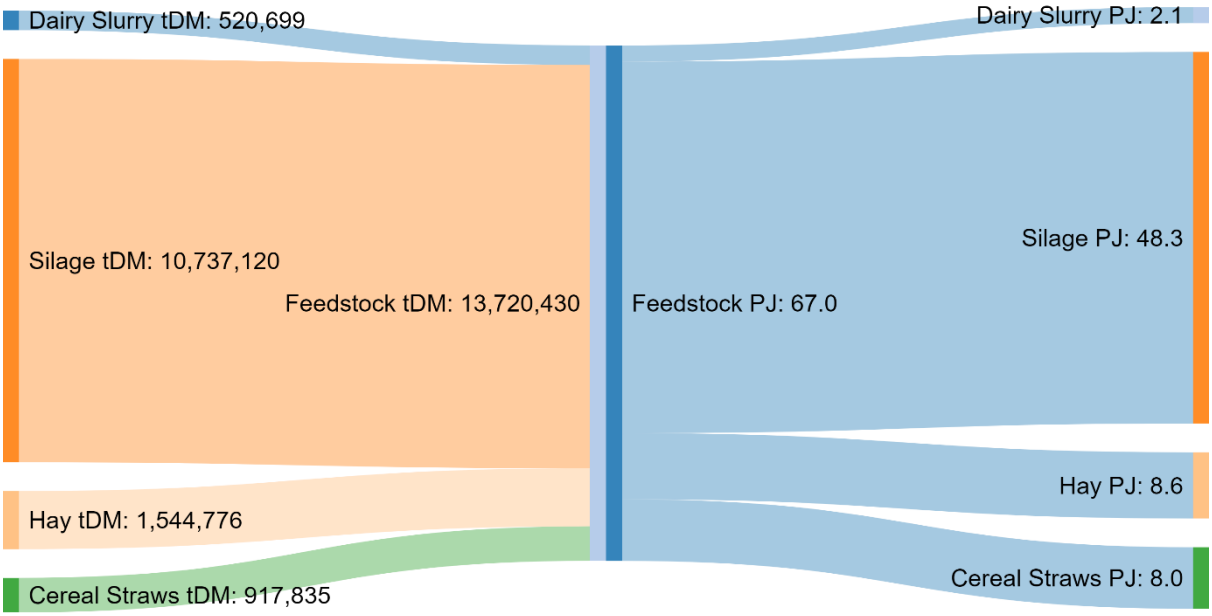


Figure A-2: Sankey diagram of feedstocks and energy output potentials.

Appendix A.5

For Facility A, energy consumption data from the 2019 AER was used. The AER states that 63% of the 42,709 GJ of energy consumed at Facility A in 2019 is from LPG.

For Facility B, energy consumption data from the 2019 AER was used. LPG used on-site is described as “natural gas” in the AER. Kerosene and gas oil used on-site are combined as one category and described as “Light fuel oil” in the 2019 AER. From the “light fuel oils”, only kerosene is considered in this analysis, as Facility B uses gas oil for transport purposes according to its 2018 AER. The 2019 AER does not, however, differentiate between fuel oil and gas oil in its energy consumption stats. The 2018 AER does – the ratio of fuel oil to gas oil in the 2018 was applied to the “light fuel oil” category in the 2019 AER to approximate the kerosene usage in 2019.

Appendix A.6

It is assumed that the LPG consumed at facilities A and B is either propane or butane, or a combination of both.

Fuel	Specific CO_2 Emissions (kg CO_2 GJ^{-1})
Biomethane	50
Propane	60
Butane	62
Kerosene	70

Table A-4: Specific CO2 emissions of specified fuels.

Facility A consumes 26,906.67 GJ worth of LPG per annum, emitting between 1,614,400.2 and 1,668,213.54 kg CO_2 a^{-1} per annum. If Facility A switched from LPG to biomethane, it would emit 1,345,333.5 kg CO_2 a^{-1}, giving CO_2 emissions savings of between 269,066.7 and 322,880.04 kg CO_2 a^{-1}.

Facility B consumes 9,431.87 GJ worth of LPG per annum, emitting between 565,912.2 and 584,775.94 kg CO_2 a^{-1}. Facility B also consumes 7,762.61 GJ worth of kerosene per annum, emitting 543,382.7 kg CO_2 a^{-1}. If Facility B switched its LPG and kerosene usage to biomethane, it would emit 859,724 kg CO_2 a^{-1}, giving CO_2 emissions savings of between 249,570.9 and 268,434.64 kg CO_2 a^{-1}.

Appendix B

Appendix B.1

Table B-1 shows the parameters used in Eq. (4.9).

Parameter	Value	Units	Source/Notes
$e_{ec,dairy\ cow\ slurry}$	0	kg $CO_{2\text{-eq}}$ t^{-1} FW	There are no emissions involved in the collection of slurry for on-farm AD. (Korres *et al.*, 2010; Long and Murphy, 2019)
$e_{ec,grass\ silage}$	70.98	kg $CO_{2\text{-eq}}$ t^{-1} FW	
$e_{td,feedstock,dairy\ cow\ slurry}$	0	kg $CO_{2\text{-eq}}$ t^{-1} FW	The feedstocks are on-farm and therefore do not need to be transported to the digester.
$e_{td,feedstock,grass\ silage}$	0	kg $CO_{2\text{-eq}}$ t^{-1} FW	
$e_{l,dairy\ cow\ slurry}$	0	kg $CO_{2\text{-eq}}$ t^{-1} FW	There are no land-use changes involved in the scenarios in this work.
$e_{l,grass\ silage}$	0	kg $CO_{2\text{-eq}}$ t^{-1} FW	
$e_{sca,dairy\ cow\ slurry}$	54	kg $CO_{2\text{-eq}}$ t^{-1} FW	(European Parliament and European Commission, 2018)
$e_{sca,grass\ silage}$	64.39	kg $CO_{2\text{-eq}}$ t^{-1} FW	See below subsections.
e_p	Varies by scenario	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	See below subsections.
$e_{td,product}$	1.22	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	(Long *et al.*, 2021)
e_u	0	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	N/A
e_{ccs}	0	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	N/A
e_{ccr}	0	g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$	N/A

Table B-1: Values assumed for emission calculation parameters.

More detailed sustainability calculations can be found in the tables in the following subsections.

	Scenario		ZG-C			PB-C			Source
	Methane Loss	(%)	1%	2%	3.55%	1%	2%	3.55%	
	Slurry VS%	(% of total annual mix)	56	56	56	30	30	30	
	Silage VS%	(% of total annual mix)	44	44	44	70	70	70	
Parameters on basis of kg t_{wwt}^{-1}	DS	(kg t_{wwt}^{-1})	122	121	121	162	162	162	
	VS	(kg t_{wwt}^{-1})	100	100	100	140	140	140	
	Water Content	(kg t_{wwt}^{-1})	878	879	879	838	838	838	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	26	26	26	45	45	45	
	CH_4 Energy	(MJ Nm^{-3})	36	36	36	36	36	36	
	C_p H_20	(kJ kg^{-1} °C^{-1})	4	4	4	4	4	4	
	Total Energy	(MJ CH_4 t_{wwt}^{-1})	922	922	922	1607	1607	1607	
Slurry Parasitic Demand	T_{final}	(°C)	37	37	37	37	37	37	
	T_0	(°C)	10	10	10	10	10	10	
	Δ T	(°C)	27	27	27	27	27	27	
	Feedstock Water Content	(kg t_{wwt}^{-1})	761	763	763	579	579	579	
	Feedstock Thermal Demand	(kJ kg t_{wwt}^{-1} °C)	3.18	3.19	3.19	2.42	2.42	2.42	
	Thermal demand	(kJ kg t_{wwt}^{-1})	85.97	86.20	86.20	65.45	65.45	65.45	
	Parasitic Thermal Demand	(m^3 CH_4 t_{wwt}^{-1})	2.40	2.40	2.40	1.82	1.82	1.82	
	% of Total Energy in CH4	(%)	9.33%	9.35%	9.35%	4.07%	4.07%	4.07%	
Grass Parasitic Demand	T_{final}	(°C)	37	37	37	37	37	37	
	T_0	(°C)	10	10	10	10	10	10	
	Δ T	(°C)	27	27	27	27	27	27	
	Feedstock Water Content	(kg t_{wwt}^{-1})	117	116	116	258	258	258	
	Feedstock Thermal Demand	(kJ kg t_{wwt}^{-1} °C)	0.49	0.48	0.48	1.08	1.08	1.08	
	Thermal demand	(kJ kg t_{wwt}^{-1})	13.27	13.09	13.09	29.19	29.19	29.19	
	Parasitic Thermal Demand	(m^3 CH_4 t_{wwt}^{-1})	0.37	0.36	0.36	0.81	0.81	0.81	
	% of Total Energy in CH4	(%)	1.44%	1.42%	1.42%	1.82%	1.82%	1.82%	
Electricity Demand	Macerating grass elec. demand	(kWh t_{wwt}^{-1})	2	2	2	2	2	2	(Smyth et al., 2009)
	Grass	(t_{wwt} Grass $t_{wwt\ mix}^{-1}$)	0.17	0.16	0.16	0.37	0.37	0.37	
	Macerating elec. demand	(kWh $t_{wwt\ mix}^{-1}$)	0.33	0.33	0.33	0.73	0.73	0.73	
	Mixing 10 - 15 % DS	(kWh $t_{wwt\ mix}^{-1}$)	10	10	10	10	10	10	(Murphy et al., 2004)
	Total elec demand	(kWh $t_{wwt\ mix}^{-1}$)	10.33	10.33	10.33	10.73	10.73	10.73	

Biogas Upgrading % Compressing	Energy Available for Upgrading	(MJ_{biogas} $t_{wwt\ mix}^{-1}$)	822.52	822.47	822.47	1512.77	1512.77	1512.77	
	Biogas CH_4 Concentration	(%)	54.75%	54.75%	54.75%	52.41%	52.41%	52.41%	
	Biogas Available for Upgrading	(m^3 biogas $t_{wwt\ mix}^{-1}$)	41.87	41.87	41.87	80.44	80.44	80.44	
	Energy Required for Upgrading	(kWh_{th} Nm^{-3}_{biogas})	0.58	0.58	0.58	0.58	0.58	0.58	(Beil and Beyrich, 2013)
	Upgrading Parasitic Demand	(MJ $t_{wwt\ mix}^{-1}$)	87.42	87.42	87.42	167.95	167.95	167.95	
	Methane Available for Upgrading	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	20.49	20.48	20.48	37.48	37.48	37.48	
	Energy Required for Compression	(kWh_e $m^{-3}_{biomethane}$)	0.11	0.11	0.11	0.11	0.11	0.11	(Beil and Beyrich, 2013)
	CH_4 Concentration	(%)	99%	99%	99%	99%	99%	99%	
	Elec. Required from Grid	(kWh_e $t_{wwt\ mix}^{-1}$)	2.28	2.28	2.28	4.16	4.16	4.16	
	Biomethane Yield	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	20.69	20.69	20.69	37.86	37.86	37.86	
System methane Losses	Methane Loss %	(%)	1.00%	2.00%	3.55%	1.00%	2.00%	3.55%	
	System Methane Loss	(m^3 CH_4 t_{wwt}^{-1})	0.20	0.41	0.73	0.37	0.75	1.33	
	System Methane Loss	**($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)**	**7.35**	**14.70**	**26.09**	**13.45**	**26.90**	**47.74**	
	System Methane	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	742.60	735.13	723.62	1358.54	1344.95	1323.90	
Carbon Sequestration	Soil Carbon Sequestration	(t C ha^{-1} y^{-1})	0.6	0.6	0.6	0.6	0.6	0.6	(McGeever et al., 2019)
	Soil Carbon Sequestration	(t CO_2 ha^{-1} y^{-1})	2.2	2.2	2.2	2.2	2.2	2.2	
	Soil Carbon Sequestration	(g $CO_{2\text{-eq}}$ t_{wwt}-1 Grass)	64,394	64,394	64,394	64,394	64,394	64,394	
Emissions from Biogas Generation	Electricity Emissions Factor	(kg CO_2 kWh^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	(Long et al., 2021)
	Electricity Demand	(kWh $t_{wwt\ mix}^{-1}$)	10.33	10.33	10.33	10.73	10.73	10.73	
	Emissions	(kg CO_2 $t_{wwt\ mix}^{-1}$)	2.07	2.07	2.07	2.15	2.15	2.15	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**2.79**	**2.82**	**2.86**	**1.58**	**1.60**	**1.62**	
Emissions from upgrading	Electricity Demand	(kWh $t_{wwt\ mix}^{-1}$)	2.28	2.28	2.28	4.16	4.16	4.16	
	Emissions	(kg CO_2 $t_{wwt\ mix}^{-1}$)	0.46	0.46	0.46	0.83	0.83	0.83	
	Emissions	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0.61	0.62	0.63	0.61	0.62	0.63	
	Methane Loss	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	0.20	0.41	0.73	0.37	0.75	1.33	
	Methane Density	(kg CH_4 m^{-3})	0.7177	0.7177	0.7177	0.7177	0.7177	0.7177	
	CH_4 Global Warming Potential		25	25	25	25	25	25	

	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	3.68	7.35	13.05	6.72	13.45	23.87	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**4.95**	**10.00**	**18.03**	**4.95**	**10.00**	**18.03**	
Total emissions from processing	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	6.20	9.88	15.57	9.71	16.43	26.85	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.35**	**13.44**	**21.52**	**7.14**	**12.22**	**20.28**	
Emissions from grid transportation	Emissions factor	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	1.22	1.22	1.22	1.22	1.22	1.22	(Long et al., 2021)
	Methane Yield	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	742.60	735.13	723.62	1358.54	1344.95	1323.90	
	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	0.91	0.90	0.88	1.66	1.64	1.62	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.23**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	
Parameters for Slurry	VS in Mix	(g kg^{-1})	556	560	560	302	302	302	
	DS	(g kg^{-1})	87.50	87.50	87.50	87.50	87.50	87.50	
	VS	(g kg^{-1})	66.90	66.90	66.90	66.90	66.90	66.90	
	Water Content	(g kg^{-1})	912.50	912.50	912.50	912.50	912.50	912.50	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	9.57	9.57	9.57	9.57	9.57	9.57	
	P_n - Energy Yield	(MJ kg_{wwt}^{-1})	0.34	0.34	0.34	0.34	0.34	0.34	
	I_n - Input to Digester	($t_{wwt\ n}$ $t_{wwt\ mix}^{-1}$)	0.83	0.84	0.84	0.63	0.63	0.63	
	W_n - Weighting Factor		0.83	0.84	0.84	0.63	0.63	0.63	
	S_n - Share of Energy Content		0.30	0.32	0.32	0.13	0.13	0.13	
Parameters for Grass	VS in Mix	(g kg^{-1})	444	440	440	698	698	698	
	DS	(g kg^{-1})	292.70	292.70	292.70	292.70	292.70	292.70	
	VS	(g kg^{-1})	268.40	268.40	268.40	268.40	268.40	268.40	
	Water Content	(g kg^{-1})	707.30	707.30	707.30	707.30	707.30	707.30	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	106.82	106.82	106.82	106.82	106.82	106.82	
	P_n - Energy Yield	(MJ kg_{wwt}^{-1})	3.83	3.83	3.83	3.83	3.83	3.83	
	I_n - Input to Digester	($t_{wwt\ n}$ $t_{wwt\ mix}^{-1}$)	0.17	0.16	0.16	0.37	0.37	0.37	
	W_n - Weighting Factor		0.17	0.16	0.16	0.37	0.37	0.37	
	S_n - Share of Energy Content		0.70	0.68	0.68	0.87	0.87	0.87	
Emissions Slurry	Cultivation (incl N_2O)	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0	0	0	0	0	0	
	Transport to Digester	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0	0	0	0	0	0	
	Emissions Savings	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**-54**	**-54**	**-54**	**-54**	**-54**	**-54**	
Emissions Grass	**Cultivation (incl N_2O)**	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	
	Transport to Digester	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0.00	0.00	0.00	0.00	0.00	0.00	

	Emissions Savings	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**
Emissions	**Processing**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.35**	**13.44**	**21.52**	**7.14**	**12.22**	**20.28**
	Transportation and Distribution	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.23**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**
	Fuel in Use	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
REDII Recast Calculations								
Slurry	**Sn**		**0.30**	**0.32**	**0.32**	**0.13**	**0.13**	**0.13**
	e_{ec}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0.00	0.00	0.00	0.00	0.00	0.00
	e_{td}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{l}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{sca}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-54.00**	**-54.00**	**-54.00**	**-54.00**	**-54.00**	**-54.00**
	Sn*SUM		-16.43	-17.27	-17.27	-7.14	-7.14	-7.14
Silage	Sn		0.70	0.68	0.68	0.87	0.87	0.87
	e_{ec}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**
	e_{td}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{l}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{sca}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**
	Sn*SUM		4.58	4.48	4.48	5.71	5.71	5.71
Product	**e_{p}**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.35**	**13.44**	**21.52**	**7.14**	**12.22**	**20.28**
	$e_{td,product}$	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.23**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**
Other	e_{u}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{ccs}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{ccr}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	Energy Yield	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	921.76	921.76	921.76	1607.40	1607.40	1607.40
	Emissions Pre-processing	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-12.85**	**-13.88**	**-13.88**	**-0.89**	**-0.89**	**-0.89**
	from Processing	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.35**	**13.44**	**21.52**	**7.14**	**12.22**	**20.28**
	from Tansport & Distribution	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.23**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**
	from Fuel in Use	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Sustainability Check for Heat	**Total Emissions**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-3.27**	**0.78**	**8.86**	**7.47**	**12.55**	**20.61**
	Conv. to heat @ 90% η	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	-3.63	0.87	9.85	8.30	13.94	22.90
	Heat Fossil Fuel Comparator	(g $CO_{2\text{-eq}}$ MJ^{-1})	80	80	80	80	80	80
	Emissions Saved	(%)	105%	99%	88%	90%	83%	71%

	Criteria	(%)	80%	80%	80%	80%	80%	80%
	Sustainable?		***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***No***
Sustainability Check for Transport	**Total Emissions**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-3.27**	**0.78**	**8.86**	**7.47**	**12.55**	**20.61**
	Transport Fossil Fuel Comparator	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	94	94	94	94	94	94
	Emissions Saved	(%)	103%	99%	91%	92%	87%	78%
	Criteria	(%)	65%	65%	65%	65%	65%	65%
	Sustainable?		***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***

	Scenario		ZG-W			PB-W			Source
	Methane Loss	(%)	1%	2%	3.55%	1%	2%	3.55%	
	Slurry VS%	(% of total annual mix)	56	56	56	30	30	30	
	Silage VS%	(% of total annual mix)	44	44	44	70	70	70	
Parameters on basis of kg t_{wwt}^{-1}	DS	(kg t_{wwt}^{-1})	122	122	122	162	162	162	
	VS	(kg t_{wwt}^{-1})	100	100	100	140	140	140	
	Water Content	(kg t_{wwt}^{-1})	878	878	878	838	838	838	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	27	27	27	46	46	46	
	CH_4 Energy	(MJ Nm^{-3})	36	36	36	36	36	36	
	C_p H_20	(kJ kg^{-1} °C^{-1})	4	4	4	4	4	4	
	Total Energy	(MJ CH_4 t_{wwt}^{-1})	962	962	962	1654	1654	1654	
Slurry Parasitic Demand	T_{final}	(°C)	37	37	37	37	37	37	
	T_0	(°C)	10	10	10	10	10	10	
	Δ T	(°C)	27	27	27	27	27	27	
	Feedstock Water Content	(kg t_{wwt}^{-1})	761	761	761	579	579	579	
	Feedstock Thermal Demand	(kJ kg t_{wwt}^{-1} °C)	3.18	3.18	3.18	2.42	2.42	2.42	
	Thermal demand	(kJ kg t_{wwt}^{-1})	85.97	85.97	85.97	65.45	65.45	65.45	
	Parasitic Thermal Demand	(m^3 CH_4 t_{wwt}^{-1})	2.40	2.40	2.40	1.82	1.82	1.82	
	% of Total Energy in CH4	(%)	8.94%	8.94%	8.94%	3.96%	3.96%	3.96%	
Grass Parasitic Demand	T_{final}	(°C)	37	37	37	37	37	37	
	T_0	(°C)	10	10	10	10	10	10	
	Δ T	(°C)	27	27	27	27	27	27	
	Feedstock Water Content	(kg t_{wwt}^{-1})	117	117	117	258	258	258	
	Feedstock Thermal Demand	(kJ kg t_{wwt}^{-1} °C)	0.49	0.49	0.49	1.08	1.08	1.08	
	Thermal demand	(kJ kg t_{wwt}^{-1})	13.27	13.27	13.27	29.19	29.19	29.19	
	Parasitic Thermal Demand	(m^3 CH_4 t_{wwt}^{-1})	0.37	0.37	0.37	0.81	0.81	0.81	
	% of Total Energy in CH4	(%)	1.38%	1.38%	1.38%	1.76%	1.76%	1.76%	
Electricity Demand	Macerating grass elec. demand	(kWh t_{wwt}^{-1})	2	2	2	2	2	2	(Smyth et al., 2009)
	Grass	(t_{wwt} Grass $t_{wwt\ mix}^{-1}$)	0.17	0.17	0.17	0.37	0.37	0.37	
	Macerating elec. demand	(kWh $t_{wwt\ mix}^{-1}$)	0.33	0.33	0.33	0.73	0.73	0.73	
	Mixing 10 - 15 % DS	(kWh $t_{wwt\ mix}^{-1}$)	10	10	10	10	10	10	(Murphy et al., 2004)
	Total elec demand	(kWh $t_{wwt\ mix}^{-1}$)	10.33	10.33	10.33	10.73	10.73	10.73	

Biogas Upgrading % Compressing	Energy Available for Upgrading	(MJ_{biogas} $t_{wwt\ mix}^{-1}$)	862.46	862.46	862.46	1559.35	1559.35	1559.35	
	Biogas CH_4 Concentration	(%)	54.44%	54.44%	54.44%	53.00%	53.00%	53.00%	
	Biogas Available for Upgrading	(m^3 biogas $t_{wwt\ mix}^{-1}$)	44.15	44.15	44.15	81.99	81.99	81.99	
	Energy Required for Upgrading	(kWh_{th} Nm^{-3}_{biogas})	0.58	0.58	0.58	0.58	0.58	0.58	(Beil and Beyrich, 2013)
	Upgrading Parasitic Demand	(MJ $t_{wwt\ mix}^{-1}$)	92.19	92.19	92.19	171.20	171.20	171.20	
	Methane Available for Upgrading	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	21.47	21.47	21.47	38.68	38.68	38.68	
	Energy Required for Compression	(kWh_e $m^{-3}_{biomethane}$)	0.11	0.11	0.11	0.11	0.11	0.11	(Beil and Beyrich, 2013)
	CH_4 Concentration	(%)	99%	99%	99%	99%	99%	99%	
	Elec. Required from Grid	(kWh_e $t_{wwt\ mix}^{-1}$)	2.39	2.39	2.39	4.30	4.30	4.30	
	Biomethane Yield	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	21.68	21.68	21.68	39.08	39.08	39.08	
System methane Losses	Methane Loss %	(%)	1.00%	2.00%	3.55%	1.00%	2.00%	3.55%	
	System Methane Loss	(m^3 CH_4 t_{wwt}^{-1})	0.21	0.43	0.76	0.39	0.77	1.37	
	System Methane Loss	**($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)**	**7.70**	**15.41**	**27.34**	**13.88**	**27.76**	**49.28**	
	System Methane	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	778.13	770.35	758.29	1402.31	1388.29	1366.55	
Carbon Sequestration	Soil Carbon Sequestration	(t C ha^{-1} y^{-1})	0.6	0.6	0.6	0.6	0.6	0.6	(McGeever et al., 2019)
	Soil Carbon Sequestration	(t CO_2 ha^{-1} y^{-1})	2.2	2.2	2.2	2.2	2.2	2.2	
	Soil Carbon Sequestration	(g $CO_{2\text{-eq}}$ t_{wwt}-1 Grass)	64,394	64,394	64,394	64,394	64,394	64,394	
Emissions from Biogas Generation	Electricity Emissions Factor	(kg CO_2 kWh^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	(Long et al., 2021)
	Electricity Demand	(kWh $t_{wwt\ mix}^{-1}$)	10.33	10.33	10.33	10.73	10.73	10.73	
	Emissions	(kg CO_2 $t_{wwt\ mix}^{-1}$)	2.07	2.07	2.07	2.15	2.15	2.15	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**2.66**	**2.69**	**2.73**	**1.53**	**1.55**	**1.57**	
Emissions from upgrading	Electricity Demand	(kWh $t_{wwt\ mix}^{-1}$)	2.39	2.39	2.39	4.30	4.30	4.30	
	Emissions	(kg CO_2 $t_{wwt\ mix}^{-1}$)	0.48	0.48	0.48	0.86	0.86	0.86	
	Emissions	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0.61	0.62	0.63	0.61	0.62	0.63	
	Methane Loss	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	0.21	0.43	0.76	0.39	0.77	1.37	
	Methane Density	(kg CH_4 m^{-3})	0.7177	0.7177	0.7177	0.7177	0.7177	0.7177	
	CH_4 Global Warming Potential		25	25	25	25	25	25	

	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	3.85	7.70	13.67	6.94	13.88	24.64	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**4.95**	**10.00**	**18.03**	**4.95**	**10.00**	**18.03**	
Total emissions from processing	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	6.40	10.25	16.22	9.95	16.89	27.65	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.22**	**13.31**	**21.39**	**7.09**	**12.17**	**20.23**	
Emissions from grid transportation	Emissions factor	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	1.22	1.22	1.22	1.22	1.22	1.22	(Long et al., 2021)
	Methane Yield	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	778.13	770.35	758.29	1402.31	1388.29	1366.55	
	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	0.95	0.94	0.93	1.71	1.69	1.67	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.23**	**1.22**	**1.22**	**1.22**	
Parameters for Slurry	VS in Mix	(g kg^{-1})	556	556	556	302	302	302	
	DS	(g kg^{-1})	87.50	87.50	87.50	87.50	87.50	87.50	
	VS	(g kg^{-1})	66.90	66.90	66.90	66.90	66.90	66.90	
	Water Content	(g kg^{-1})	912.50	912.50	912.50	912.50	912.50	912.50	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	9.57	9.57	9.57	9.57	9.57	9.57	
	P_n - Energy Yield	(MJ kg_{wwt}^{-1})	0.34	0.34	0.34	0.34	0.34	0.34	
	I_n - Input to Digester	($t_{wwt\ n}$ $t_{wwt\ mix}^{-1}$)	0.83	0.83	0.83	0.63	0.63	0.63	
	W_n - Weighting Factor		0.83	0.83	0.83	0.63	0.63	0.63	
	S_n - Share of Energy Content		0.30	0.30	0.30	0.13	0.13	0.13	
Parameters for Grass	VS in Mix	(g kg^{-1})	444	444	444	698	698	698	
	DS	(g kg^{-1})	292.70	292.70	292.70	292.70	292.70	292.70	
	VS	(g kg^{-1})	268.40	268.40	268.40	268.40	268.40	268.40	
	Water Content	(g kg^{-1})	707.30	707.30	707.30	707.30	707.30	707.30	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	106.82	106.82	106.82	106.82	106.82	106.82	
	P_n - Energy Yield	(MJ kg_{wwt}^{-1})	3.83	3.83	3.83	3.83	3.83	3.83	
	I_n - Input to Digester	($t_{wwt\ n}$ $t_{wwt\ mix}^{-1}$)	0.17	0.17	0.17	0.37	0.37	0.37	
	W_n - Weighting Factor		0.17	0.17	0.17	0.37	0.37	0.37	
	S_n - Share of Energy Content		0.70	0.70	0.70	0.87	0.87	0.87	
Emissions Slurry	Cultivation (incl N_2O)	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0	0	0	0	0	0	
	Transport to Digester	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0	0	0	0	0	0	
	Emissions Savings	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**-54**	**-54**	**-54**	**-54**	**-54**	**-54**	
Emissions Grass	**Cultivation (incl N_2O)**	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	
	Transport to Digester	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0.00	0.00	0.00	0.00	0.00	0.00	

	Emissions Savings	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**
Emissions	**Processing**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.22**	**13.31**	**21.39**	**7.09**	**12.17**	**20.23**
	Transportation and Distribution	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.23**	**1.22**	**1.22**	**1.22**
	Fuel in Use	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
REDII Recast Calculations								
Slurry	**Sn**		**0.30**	**0.30**	**0.30**	**0.13**	**0.13**	**0.13**
	e_{ec}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0.00	0.00	0.00	0.00	0.00	0.00
	e_{td}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{l}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{sca}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-54.00**	**-54.00**	**-54.00**	**-54.00**	**-54.00**	**-54.00**
	Sn*SUM		-16.43	-16.43	-16.43	-7.14	-7.14	-7.14
Silage	Sn		0.70	0.70	0.70	0.87	0.87	0.87
	e_{ec}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**
	e_{td}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{l}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{sca}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**
	Sn*SUM		4.58	4.58	4.58	5.71	5.71	5.71
Product	**e_{p}**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.22**	**13.31**	**21.39**	**7.09**	**12.17**	**20.23**
	$e_{td,product}$	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.23**	**1.22**	**1.22**	**1.22**
Other	e_{u}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{ccs}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{ccr}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	Energy Yield	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	961.70	961.70	961.70	1653.98	1653.98	1653.98
	Emissions Pre-processing	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-12.32**	**-12.32**	**-12.32**	**-0.86**	**-0.86**	**-0.86**
	from Processing	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.22**	**13.31**	**21.39**	**7.09**	**12.17**	**20.23**
	from Tansport & Distribution	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.23**	**1.22**	**1.22**	**1.22**
	from Fuel in Use	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Sustainability Check for Heat	**Total Emissions**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-2.88**	**2.21**	**10.30**	**7.45**	**12.53**	**20.59**
	Conv. to heat @ 90% η	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	-3.20	2.46	11.45	8.27	13.92	22.87
	Heat Fossil Fuel Comparator	(g $CO_{2\text{-eq}}$ MJ^{-1})	80	80	80	80	80	80
	Emissions Saved	(%)	104%	97%	86%	90%	83%	71%

	Criteria	(%)	80%	80%	80%	80%	80%	80%
	Sustainable?		***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***No***
Sustainability Check for Transport	**Total Emissions**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-2.88**	**2.21**	**10.30**	**7.45**	**12.53**	**20.59**
	Transport Fossil Fuel Comparator	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	94	94	94	94	94	94
	Emissions Saved	(%)	103%	98%	89%	92%	87%	78%
	Criteria	(%)	65%	65%	65%	65%	65%	65%
	Sustainable?		***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***

	Scenario		ZG-S			PB-S			Source
	Methane Loss	(%)	1%	2%	3.55%	1%	2%	3.55%	
	Slurry VS%	(% of total annual mix)	56	56	56	30	30	30	
	Silage VS%	(% of total annual mix)	44	44	44	70	70	70	
Parameters on basis of kg t_{wwt}^{-1}	DS	(kg t_{wwt}^{-1})	122	122	122	162	162	162	
	VS	(kg t_{wwt}^{-1})	100	100	100	140	140	140	
	Water Content	(kg t_{wwt}^{-1})	878	878	878	838	838	838	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	26	26	26	45	45	45	
	CH_4 Energy	(MJ Nm^{-3})	36	36	36	36	36	36	
	C_p H_20	(kJ kg^{-1} °C^{-1})	4	4	4	4	4	4	
	Total Energy	(MJ CH_4 t_{wwt}^{-1})	945	945	945	1621	1621	1621	
Slurry Parasitic Demand	T_{final}	(°C)	37	37	37	37	37	37	
	T_0	(°C)	10	10	10	10	10	10	
	Δ T	(°C)	27	27	27	27	27	27	
	Feedstock Water Content	(kg t_{wwt}^{-1})	761	761	761	579	579	579	
	Feedstock Thermal Demand	(kJ kg t_{wwt}^{-1} °C)	3.18	3.18	3.18	2.42	2.42	2.42	
	Thermal demand	(kJ kg t_{wwt}^{-1})	85.97	85.97	85.97	65.45	65.45	65.45	
	Parasitic Thermal Demand	(m^3 CH_4 t_{wwt}^{-1})	2.40	2.40	2.40	1.82	1.82	1.82	
	% of Total Energy in CH4	(%)	9.10%	9.10%	9.10%	4.04%	4.04%	4.04%	
Grass Parasitic Demand	T_{final}	(°C)	37	37	37	37	37	37	
	T_0	(°C)	10	10	10	10	10	10	
	Δ T	(°C)	27	27	27	27	27	27	
	Feedstock Water Content	(kg t_{wwt}^{-1})	117	117	117	258	258	258	
	Feedstock Thermal Demand	(kJ kg t_{wwt}^{-1} °C)	0.49	0.49	0.49	1.08	1.08	1.08	
	Thermal demand	(kJ kg t_{wwt}^{-1})	13.27	13.27	13.27	29.19	29.19	29.19	
	Parasitic Thermal Demand	(m^3 CH_4 t_{wwt}^{-1})	0.37	0.37	0.37	0.81	0.81	0.81	
	% of Total Energy in CH4	(%)	1.40%	1.40%	1.40%	1.80%	1.80%	1.80%	
Electricity Demand	Macerating grass elec. demand	(kWh t_{wwt}^{-1})	2	2	2	2	2	2	(Smyth et al., 2009)
	Grass	(t_{wwt} Grass $t_{wwt\ mix}^{-1}$)	0.17	0.17	0.17	0.37	0.37	0.37	
	Macerating elec. demand	(kWh $t_{wwt\ mix}^{-1}$)	0.33	0.33	0.33	0.73	0.73	0.73	
	Mixing 10 - 15 % DS	(kWh $t_{wwt\ mix}^{-1}$)	10	10	10	10	10	10	(Murphy et al., 2004)
	Total elec demand	(kWh $t_{wwt\ mix}^{-1}$)	10.33	10.33	10.33	10.73	10.73	10.73	

Biogas Upgrading % Compressing	Energy Available for Upgrading	(MJ_{biogas} $t_{wwt\ mix}^{-1}$)	845.51	845.51	845.51	1525.91	1525.91	1525.91	
	Biogas CH_4 Concentration	(%)	54.57%	54.57%	54.57%	52.12%	52.12%	52.12%	
	Biogas Available for Upgrading	(m^3 biogas $t_{wwt\ mix}^{-1}$)	43.18	43.18	43.18	81.59	81.59	81.59	
	Energy Required for Upgrading	(kWh_{th} Nm^{-3}_{biogas})	0.58	0.58	0.58	0.58	0.58	0.58	(Beil and Beyrich, 2013)
	Upgrading Parasitic Demand	(MJ $t_{wwt\ mix}^{-1}$)	90.16	90.16	90.16	170.35	170.35	170.35	
	Methane Available for Upgrading	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	21.05	21.05	21.05	37.78	37.78	37.78	
	Energy Required for Compression	(kWh_e $m^{-3}_{biomethane}$)	0.11	0.11	0.11	0.11	0.11	0.11	(Beil and Beyrich, 2013)
	CH_4 Concentration	(%)	99%	99%	99%	99%	99%	99%	
	Elec. Required from Grid	(kWh_e $t_{wwt\ mix}^{-1}$)	2.34	2.34	2.34	4.20	4.20	4.20	
	Biomethane Yield	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	21.26	21.26	21.26	38.16	38.16	38.16	
System methane Losses	Methane Loss %	(%)	1.00%	2.00%	3.55%	1.00%	2.00%	3.55%	
	System Methane Loss	(m^3 CH_4 t_{wwt}^{-1})	0.21	0.42	0.75	0.38	0.76	1.34	
	System Methane Loss	**($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)**	**7.55**	**15.11**	**26.81**	**13.56**	**27.11**	**48.12**	
	System Methane	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	763.06	755.43	743.60	1369.39	1355.69	1334.47	
Carbon Sequestration	Soil Carbon Sequestration	(t C ha^{-1} y^{-1})	0.6	0.6	0.6	0.6	0.6	0.6	(McGeever et al., 2019)
	Soil Carbon Sequestration	(t CO_2 ha^{-1} y^{-1})	2.2	2.2	2.2	2.2	2.2	2.2	
	Soil Carbon Sequestration	(g $CO_{2\text{-eq}}$ t_{wwt}-1 Grass)	64,394	64,394	64,394	64,394	64,394	64,394	
Emissions from Biogas Generation	Electricity Emissions Factor	(kg CO_2 kWh^{-1})	0.2	0.2	0.2	0.2	0.2	0.2	(Long et al., 2021)
	Electricity Demand	(kWh $t_{wwt\ mix}^{-1}$)	10.33	10.33	10.33	10.73	10.73	10.73	
	Emissions	(kg CO_2 $t_{wwt\ mix}^{-1}$)	2.07	2.07	2.07	2.15	2.15	2.15	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**2.71**	**2.74**	**2.78**	**1.57**	**1.59**	**1.61**	
Emissions from upgrading	Electricity Demand	(kWh $t_{wwt\ mix}^{-1}$)	2.34	2.34	2.34	4.20	4.20	4.20	
	Emissions	(kg CO_2 $t_{wwt\ mix}^{-1}$)	0.47	0.47	0.47	0.84	0.84	0.84	
	Emissions	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0.61	0.62	0.63	0.61	0.62	0.63	
	Methane Loss	(m^3 CH_4 $t_{wwt\ mix}^{-1}$)	0.21	0.42	0.75	0.38	0.76	1.34	
	Methane Density	(kg CH_4 m^{-3})	0.7177	0.7177	0.7177	0.7177	0.7177	0.7177	
	CH_4 Global Warming Potential		25	25	25	25	25	25	

	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	3.78	7.55	13.41	6.78	13.56	24.06	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**4.95**	**10.00**	**18.03**	**4.95**	**10.00**	**18.03**	
Total emissions from processing	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	6.31	10.09	15.95	9.77	16.55	27.05	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.27**	**13.36**	**21.44**	**7.13**	**12.21**	**20.27**	
Emissions from grid transportation	Emissions factor	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	1.22	1.22	1.22	1.22	1.22	1.22	(Long et al., 2021)
	Methane Yield	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	763.06	755.43	743.60	1369.39	1355.69	1334.47	
	Emissions	(kg $CO_{2\text{-eq}}$ $t_{wwt\ mix}^{-1}$)	0.93	0.92	0.91	1.67	1.65	1.63	
	Emissions	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	
Parameters for Slurry	VS in Mix	(g kg^{-1})	556	556	556	302	302	302	
	DS	(g kg^{-1})	87.50	87.50	87.50	87.50	87.50	87.50	
	VS	(g kg^{-1})	66.90	66.90	66.90	66.90	66.90	66.90	
	Water Content	(g kg^{-1})	912.50	912.50	912.50	912.50	912.50	912.50	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	9.57	9.57	9.57	9.57	9.57	9.57	
	P_n - Energy Yield	(MJ kg_{wwt}^{-1})	0.34	0.34	0.34	0.34	0.34	0.34	
	I_n - Input to Digester	($t_{wwt\ n}$ $t_{wwt\ mix}^{-1}$)	0.83	0.83	0.83	0.63	0.63	0.63	
	W_n - Weighting Factor		0.83	0.83	0.83	0.63	0.63	0.63	
	S_n - Share of Energy Content		0.30	0.30	0.30	0.13	0.13	0.13	
Parameters for Grass	VS in Mix	(g kg^{-1})	444	444	444	698	698	698	
	DS	(g kg^{-1})	292.70	292.70	292.70	292.70	292.70	292.70	
	VS	(g kg^{-1})	268.40	268.40	268.40	268.40	268.40	268.40	
	Water Content	(g kg^{-1})	707.30	707.30	707.30	707.30	707.30	707.30	
	CH_4 Output	(m^3 CH_4 t_{wwt}^{-1})	106.82	106.82	106.82	106.82	106.82	106.82	
	P_n - Energy Yield	(MJ kg_{wwt}^{-1})	3.83	3.83	3.83	3.83	3.83	3.83	
	I_n - Input to Digester	($t_{wwt\ n}$ $t_{wwt\ mix}^{-1}$)	0.17	0.17	0.17	0.37	0.37	0.37	
	W_n - Weighting Factor		0.17	0.17	0.17	0.37	0.37	0.37	
	S_n - Share of Energy Content		0.70	0.70	0.70	0.87	0.87	0.87	
Emissions Slurry	Cultivation (incl N_2O)	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0	0	0	0	0	0	
	Transport to Digester	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0	0	0	0	0	0	
	Emissions Savings	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**-54**	**-54**	**-54**	**-54**	**-54**	**-54**	
Emissions Grass	**Cultivation (incl N_2O)**	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	
	Transport to Digester	(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})	0.00	0.00	0.00	0.00	0.00	0.00	

	Emissions Savings	**(kg $CO_{2\text{-eq}}$ t_{wwt}^{-1})**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**
Emissions	**Processing**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.27**	**13.36**	**21.44**	**7.13**	**12.21**	**20.27**
	Transportation and Distribution	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**
	Fuel in Use	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
REDII Recast Calculations								
Slurry	**Sn**		**0.30**	**0.30**	**0.30**	**0.13**	**0.13**	**0.13**
	e_{ec}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0.00	0.00	0.00	0.00	0.00	0.00
	e_{td}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{l}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{sca}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-54.00**	**-54.00**	**-54.00**	**-54.00**	**-54.00**	**-54.00**
	Sn*SUM		-16.43	-16.43	-16.43	-7.14	-7.14	-7.14
Silage	Sn		0.70	0.70	0.70	0.87	0.87	0.87
	e_{ec}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**	**70.98**
	e_{td}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{l}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{sca}	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**	**-64.39**
	Sn*SUM		4.58	4.58	4.58	5.71	5.71	5.71
Product	**e_{p}**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.27**	**13.36**	**21.44**	**7.13**	**12.21**	**20.27**
	$e_{td,product}$	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**
Other	e_{u}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{ccs}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	e_{ccr}	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	0	0	0	0	0	0
	Energy Yield	($MJ_{biomethane}$ $t_{wwt\ mix}^{-1}$)	944.75	944.75	944.75	1620.55	1620.55	1620.55
	Emissions Pre-processing	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-12.54**	**-12.54**	**-12.54**	**-0.88**	**-0.88**	**-0.88**
	from Processing	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**8.27**	**13.36**	**21.44**	**7.13**	**12.21**	**20.27**
	from Tansport & Distribution	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**	**1.22**
	from Fuel in Use	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Sustainability Check for Heat	**Total Emissions**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-3.05**	**2.04**	**10.12**	**7.47**	**12.55**	**20.61**
	Conv. to heat @ 90% η	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	-3.39	2.27	11.25	8.30	13.94	22.90
	Heat Fossil Fuel Comparator	(g $CO_{2\text{-eq}}$ MJ^{-1})	80	80	80	80	80	80
	Emissions Saved	(%)	104%	97%	86%	90%	83%	71%

	Criteria	(%)	80%	80%	80%	80%	80%	80%
	Sustainable?		***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***No***
Sustainability Check for Transport	**Total Emissions**	**(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)**	**-3.05**	**2.04**	**10.12**	**7.47**	**12.55**	**20.61**
	Transport Fossil Fuel Comparator	(g $CO_{2\text{-eq}}$ $MJ^{-1}_{biomethane}$)	94	94	94	94	94	94
	Emissions Saved	(%)	103%	98%	89%	92%	87%	78%
	Criteria	(%)	65%	65%	65%	65%	65%	65%
	Sustainable?		***Yes***	***Yes***	***Yes***	***Yes***	***Yes***	***Yes***

Appendix B.2

Some rounding errors are present in the calculations in this appendix. These rounding errors are not present in the calculation results provided in Appendix B.3.

Constant gas demand

To keep the weekly biomethane output constant throughout the year, the left-hand side (LHS) of Eq. (B.1) (weekly biomethane output when livestock are outdoors) must equal the right-hand side (RHS) (weekly biomethane output when livestock are indoors). Of the annual silage harvest, 75.1% is used during weeks 12-45 whilst cows have pasture access (slurry not available) in order to keep the biomethane output close to constant throughout all 52 weeks of the year for PB-C. Alteration of the grass silage feeding regime was chosen as it can be stored in a silage pit year-round and has higher gas production potential. Furthermore, it is not subject to the same availability constraints as slurry.

$$\frac{m_{t_{wwt}}^{silage\ reserve} * VS\%^{silage} * SMY^{silage}}{(52 - N_{weeks})} = \frac{\left(\left(m_{t_{wwt}}^{silage\ harvest} - m_{t_{wwt}}^{silage\ reserve}\right) * VS\%^{silage}\right) + \left(m_{t_{wwt}}^{slurry\ winter} * VS\%^{slurry}\right)\right) * SMY_{G:S\ VS}}{N_{weeks}} \quad \text{(B.1)}$$

where,

$m_{t_{wwt}}^{silage\ reserve}$ = Silage reserved for summer (t_{wwt})

$m_{t_{wwt}}^{silage\ harvest}$ = Total annual silage harvest (t_{wwt})

$VS\%^{silage}$ = VS % of grass silage

SMY^{silage} = BMP of grass silage

N_{weeks} = Number of weeks that cows are indoors

$m_{t_{wwt}}^{slurry\ winter}$ = Dairy slurry collected while cows are indoors

$VS\%^{slurry}$ = VS % of dairy slurry

$SMY_{G:S\ VS}$ = SMY of the ratio of grass VS to slurry VS

In this work, it is assumed that 594 t_{wwt} dairy slurry are collected in scenarios where cows are housed indoors for 18 weeks, and the annual silage harvest was calculated to be 341.65 t_{wwt}. By the input of the feedstock characteristic values from Table 3-3 into Eq. (B.1):

$$\frac{m_{t_{wwt}}^{silage\ reserve} * 0.2684 * 398}{52 - 18} = \frac{\left(\left((341.65 - m_{t_{wwt}}^{silage\ reserve}) * 0.2684\right) + (594 * 0.0669)\right) * SMY_{S:G\ VS}}{18} \quad \text{(B.2)}$$

$m_{t_{wwt}}^{silage\ reserve}$ cannot be found without knowing $SMY_{G:S\ VS}$, and vice versa. The relationship between them is non-linear. The values which result in the LHS and RHS of the equations being equal are:

$$m_{t_{wwt}}^{silage\ reserve} = 256.54\ t_{wwt}\ (75.1\%\ \text{of annual harvest})$$

Resulting in a G:S VS ratio of 36.5:63.5 during the weeks which slurry is available;

$$SMY_{G:S\ VS} = 231.83\ m^3\ CH_4\ t^{-1}\ VS$$

These values were found by using the Solver data analysis tool within Excel, using GRG Nonlinear solving. Inputting these values into Eq. (B.2):

$$\frac{256.54 * 0.2684 * 398}{52 - 18} = \frac{\left(\left((341.65 - 256.54) * 0.2684\right) + (594 * 0.0669)\right) * 231.83}{18} \quad \text{(B.3)}$$

$$806.01 \approx 806.02$$

Winter gas demand

The winter gas demand scenarios are linked to the heating demand of residential buildings, based on heating degree days (HDDs). HDDs quantify the demand for heating energy in a building, derived from outdoor air temperature. The winter peak demand period was modelled on the HDDs at Cork Airport, Ireland, and was calculated by taking the average monthly HDDs from a base temperature of 15.5 ° C from May 2018 to April 2021 (BizEE Software, 2021).

Monthly HDDs	2018	2019	2020	2021	*Average*
January		279.3	287.4	335.4	***300.7***
February		224.8	272.0	265.2	***254.0***
March		255.0	288.5	256.1	***266.5***
April		208.2	184.3	240.8	***211.1***
May	129.0	145.4	135.3		***136.6***
June	38.1	100.4	76.2		***71.6***
July	20.5	26.1	47.6		***31.4***
August	42.3	37.0	34.8		***38.0***
September	100.1	63.9	76.1		***80.0***
October	176.5	176.3	181.6		***178.1***
November	222.3	262.6	206.2		***230.4***
December	214.9	279.0	306.2		***266.7***
			12-Month Average		***172.1***

Table B-2: Average monthly HDDs at Cork Airport, Ireland.

The average monthly HDDs over this period was 172.1 HDDs. Any month that had a monthly HDD higher than this was considered to be a peak winter demand month. The peak winter demand period was considered to be from weeks 1 to 16 and 40 to 52 and includes 83% of the annual average of monthly degree days. Therefore, for the winter demand scenarios, 83% of the grass silage was reserved for these months (relevant to Scenarios ZG-W and PB-W). Alteration to the feeding of grass silage was implemented for the same reasons as PB-C.

In scenario ZG-W, biomethane output is stable during the peak demand period, as the feedstock input is stable during this period. Biomethane output is also stable during the off-peak demand period in scenario ZG-W. However, in scenario PB-W, as livestock are on pasture land during some weeks of the peak-demand period, biomethane output would fall whilst the animals are outdoors (weeks 12 to 15, and 41 to 45) as slurry would no longer be available. A stable biomethane flow could be

achieved throughout the peak demand season through silage allocation in a methodology similar to that used for the constant gas demand scenario (PB-C).

In scenario PB-W, 283.57 t_{wwt} of grass silage (83% of the annual silage harvest) is used during the peak demand period (weeks 1-16 and 41-52). Cows are housed indoors during weeks 1-11 and 46-52. To avoid a dip in biomethane output during weeks 12-15 and 41-45, the silage reserved for the peak demand period is allocated throughout the peak demand period to achieve a stable biomethane output – i.e., the average weekly gas output during the peak demand period must be the same for when cows have pasture access as when cows are housed indoors. In the following equation, which is adapted from Eq. (B.1), the LHS represents the weekly biomethane output in weeks 12-15 and 41-45, and the RHS the weekly biomethane output in weeks 46-52 and 1-11:

$$\frac{m_{t_{wwt}}^{silage\ allocation} * VS\%^{silage} * SMY^{silage}}{N_{weeks}^{pasture}} = \frac{\left(\left(\left(m_{t_{wwt}}^{silage\ reserve} - m_{t_{wwt}}^{silage\ allocation}\right) * VS\%^{silage}\right) + \left(m_{t_{wwt}}^{slurry} * VS\%^{slurry}\right)\right) * SMY_{G:S\ VS}}{N_{weeks}^{indoors}} \quad \text{(B.4)}$$

$$\frac{m_{t_{wwt}}^{silage\ allocation} * 0.2684 * 398}{9} = \frac{\left(\left((283.57 - m_{t_{wwt}}^{silage\ allocation}) * 0.2684\right) + (594 * 0.0669)\right) * SMY_{G:S\ VS}}{18}$$

$m_{t_{wwt}}^{silage\ allocation}$ cannot be found without knowing $SMY_{G:S\ VS}$, and vice versa. The relationship between them is non-linear. The values which result in the LHS and RHS of the equations being equal are:

$$m_{t_{wwt}}^{silage\ allocation} = 115.21\ t_{wwt}$$

Resulting in a G:S VS ratio of 53.2:46.8 during weeks which slurry is available;

$$SMY_{G:S\ VS} = 289.847\ m^3\ CH_4\ t^{-1}\ VS$$

These values were found by using the Solver data analysis tool within Excel, using GRG Nonlinear solving. Inputting these values into Eq. (B.4):

$$\frac{115.21 * 0.2684 * 398}{9} = \frac{\left(\left((283.57 - 115.21) * 0.2684\right) + (594 * 0.0669)\right) * 289.847}{18} \quad \text{(B.5)}$$

$$1367.45 \approx 1367.54$$

Therefore, for the 9 weeks during the peak demand period in which cows are outdoors (weeks 12-16 and 40-45), 112.17 t_{wwt} of silage are input to the digester, or 12.46 $t_{wwt}\ week^{-1}$. For the 18 weeks during the peak demand period in which cows

are indoors (weeks 1-11 and 46-52), 168.35 t_{wwt} of silage are input to the digester, or 9.35 t_{wwt} $week^{-1}$.

Summer gas demand

The summer demand scenario period was modelled on Ireland's domestic milk intake from milk processors using data from the Central Statistics Office (CSO) from 2017 to 2020 (CSO, 2021). Table H-2 shows the monthly milk produced in Irish milk processors for the period 2017 to 2020.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Average*
2017	148.7	272.9	620.9	866.3	999.6	917.9	875.3	786.6	654.0	534.3	380.8	205.5	***605.2***
2018	161.8	294.2	627.5	823.1	993.1	924.7	853.4	823.8	721.8	642.0	461.2	258.5	***632.1***
2019	175.3	303.6	708.7	953.3	1072.2	1001.0	943.2	842.8	721.9	604.7	418.1	241.4	***665.5***
2020	176.2	331.7	725.7	982.7	1115.3	1031.0	985.0	867.6	725.4	645.6	450.8	255.8	***691.1***
Average	***165.5***	***300.6***	***670.7***	***906.4***	***1045.1***	***968.6***	***914.2***	***830.2***	***705.8***	***606.7***	***427.7***	***240.3***	***648.5***

Table B-3: Monthly milk production in Ireland (millions of litres).

The energy and gas demand of milk processors is strongly correlated with milk production (Geraghty, 2011; Shine *et al.*, 2020). The average milk production in Ireland is 648.5 million litres per month. Any month that had, on average, a monthly milk production higher than this was considered to be a peak summer demand month. Hence, the peak summer demand period was considered to be from weeks 10 to 39. This peak summer demand period includes 78% of the annual milk production, i.e., 78% of the total gas demand. Therefore, for the summer peak demand scenarios, 78% of the silage was reserved for these months (relevant to Scenarios ZG-S and PB-S).

In scenario ZG-S, biomethane output is stable during the peak demand period, as the feedstock input is stable during this period. Biomethane output is also stable during the off-peak demand period in scenario ZG-S. However, in scenario PB-S, due to the livestock being housed indoors during certain weeks of the peak-demand period (weeks 10 and 11), biomethane output would increase as slurry would be available for use in the AD plant. Livestock are also still outdoors during weeks 40 to 45, which would result in a reduction in biomethane output during this period. A stable biomethane flow can be achieved throughout the peak and off-peak demand periods through silage allocation, in a methodology similar to that used for the constant and winter gas demand scenarios.

Summer – Peak demand period

In scenario PB-S, 266.48 t_{wwt} of grass silage (78% of the annual silage harvest) is used during the peak demand period (weeks 10-39). Cows are housed indoors during weeks 1-11 and 46-52. To avoid a peak in biomethane output during weeks 10-11, the silage reserved for the peak demand period is allocated throughout the peak demand period to achieve a stable biomethane output – i.e., the average weekly gas output during the peak demand period must be the same for when cows have pasture access as when cows are housed indoors. In the following equation, which is adapted from Eq. (B.1), the LHS represents the weekly biomethane output in weeks 12-39 and the RHS the weekly biomethane output in weeks 10-11:

$$\frac{(m_{t_{wwt}}^{silage\ reserve} - m_{t_{wwt}}^{silage\ allocation}) * VS\%^{silage} * SMY^{silage}}{N_{weeks}^{pasture}} = \frac{\left((m_{t_{wwt}}^{silage\ allocation} * VS\%^{silage}) + (m_{t_{wwt}}^{slurry} * VS\%^{slurry})\right) * SMY_{G:S\,VS}}{N_{weeks}^{indoors}} \quad \text{(B.6)}$$

$$\frac{(266.48 - m_{t_{wwt}}^{silage\ allocation}) * 0.2684 * 398}{28} = \frac{\left((m_{t_{wwt}}^{silage\ allocation} * 0.2684) + (66 * 0.0669)\right) * SMY_{G:S\,VS}}{2}$$

$m_{t_{wwt}}^{silage\ allocation}$ cannot be found without knowing $SMY_{G:S\,VS}$, and vice versa. The relationship between them is non-linear. The values which result in the LHS and RHS of the equations being equal are:

$$m_{t_{wwt}}^{silage\ allocation} = 12.39\ t_{wwt}$$

Resulting in a G:S VS ratio of 43:57 during weeks which slurry is available;

$$SMY_{G:S\,VS} = 250.425\ m^3\ CH_4\ t^{-1}\ VS$$

These values were found by using the Solver data analysis tool within Excel, using GRG Nonlinear solving. Inputting these values into Eq. (B.6):

$$\frac{(266.48 - 12.39) * 0.2684 * 398}{28} = \frac{\left((12.39 * 0.2684) + (66 * 0.0669)\right) * 250.425}{2} \quad \text{(B.7)}$$

$$969.38 \approx 969.25$$

Therefore, for the 2 weeks during the peak demand period in which cows are outdoors (weeks 10-11), 12.39 t_{wwt} of silage are input to the digester, or 6.2 t_{wwt} $week^{-1}$. For the 28 weeks in which cows are indoors during the peak demand period (weeks 12-39), 254.1 t_{wwt} of silage are input to the digester, or 9.07 t_{wwt} $week^{-1}$.

Summer – Off-peak demand period

In scenario PB-S, 75.17 t_{wwt} of grass silage (22% of the annual silage harvest) is used during the off-peak demand period (weeks 1-9 and 40-52). Cows are housed indoors

during weeks 1-11 and 46-52. To avoid a dip in biomethane output during weeks 40-45, the silage for the off-peak demand period is allocated throughout the off-peak demand period to achieve a stable biomethane output – i.e., the average weekly gas output during the peak demand period must be the same for when cows have pasture access as when cows are housed indoors. In the following equation, which is adapted from Eq. (B.1), the LHS represents the weekly biomethane output in weeks 40-45 and the RHS the weekly biomethane output in weeks 46-52 and 1-9:

$$\frac{m_{t_{wwt}}^{silage\ allocation} * VS\%^{silage} * SMY^{silage}}{N_{weeks}^{pasture}} = \frac{\left(\left(m_{t_{wwt}}^{silage\ reserve} - m_{t_{wwt}}^{silage\ allocation} * VS\%^{silage}\right) + \left(m_{t_{wwt}}^{slurry} * VS\%^{slurry}\right)\right) * SMY_{G:S\ VS}}{N_{weeks}^{indoors}} \quad \text{(B.8)}$$

$$\frac{(m_{t_{wwt}}^{silage\ allocation}) * 0.2684 * 398}{6} = \frac{\left(\left(75.17 - m_{t_{wwt}}^{silage\ allocation} * 0.2684\right) + (528 * 0.0669)\right) * SMY_{G:S\ VS}}{16}$$

$m_{t_{wwt}}^{silage\ allocation}$ cannot be found without knowing $SMY_{G:S\ VS}$, and vice versa. The relationship between them is non-linear. The values which result in the LHS and RHS of the equations being equal are:

$$m_{t_{wwt}}^{silage\ allocation} = 33.63\ t_{wwt}$$

Resulting in a G:S VS ratio of 24:76 during weeks which slurry is available;

$$SMY_{G:S\ VS} = 206.17\ m^3\ CH_4\ t^{-1}\ VS$$

These values were found by using the Solver data analysis tool within Excel, using GRG Nonlinear solving. Inputting these values into Eq. (B.8):

$$\frac{(33.63) * 0.2684 * 398}{6} = \frac{(((75.17 - 33.63) * 0.2684) + (528 * 0.0669)) * 206.17}{16} \quad \text{(B.9)}$$

$$598.74 \approx 598.82$$

Appendix B.3

Scenario ZG-C

Week	Slurry fed to digester (twwt)	Slurry water content in digester (t)	Slurry VS fed to digester (tVS)	Silage fed to digester (twwt)
1	33.00	30.11	2.21	6.57
2	33.00	30.11	2.21	6.57
3	33.00	30.11	2.21	6.57
4	33.00	30.11	2.21	6.57
5	33.00	30.11	2.21	6.57
6	33.00	30.11	2.21	6.57
7	33.00	30.11	2.21	6.57
8	33.00	30.11	2.21	6.57
9	33.00	30.11	2.21	6.57
10	33.00	30.11	2.21	6.57
11	33.00	30.11	2.21	6.57
12	33.00	30.11	2.21	6.57
13	33.00	30.11	2.21	6.57
14	33.00	30.11	2.21	6.57
15	33.00	30.11	2.21	6.57
16	33.00	30.11	2.21	6.57
17	33.00	30.11	2.21	6.57
18	33.00	30.11	2.21	6.57
19	33.00	30.11	2.21	6.57
20	33.00	30.11	2.21	6.57
21	33.00	30.11	2.21	6.57
22	33.00	30.11	2.21	6.57
23	33.00	30.11	2.21	6.57
24	33.00	30.11	2.21	6.57
25	33.00	30.11	2.21	6.57
26	33.00	30.11	2.21	6.57
27	33.00	30.11	2.21	6.57
28	33.00	30.11	2.21	6.57
29	33.00	30.11	2.21	6.57
30	33.00	30.11	2.21	6.57
31	33.00	30.11	2.21	6.57
32	33.00	30.11	2.21	6.57
33	33.00	30.11	2.21	6.57
34	33.00	30.11	2.21	6.57
35	33.00	30.11	2.21	6.57
36	33.00	30.11	2.21	6.57
37	33.00	30.11	2.21	6.57
38	33.00	30.11	2.21	6.57
39	33.00	30.11	2.21	6.57
40	33.00	30.11	2.21	6.57
41	33.00	30.11	2.21	6.57
42	33.00	30.11	2.21	6.57
43	33.00	30.11	2.21	6.57
44	33.00	30.11	2.21	6.57
45	33.00	30.11	2.21	6.57
46	33.00	30.11	2.21	6.57
47	33.00	30.11	2.21	6.57
48	33.00	30.11	2.21	6.57
49	33.00	30.11	2.21	6.57
50	33.00	30.11	2.21	6.57
51	33.00	30.11	2.21	6.57
52	33.00	30.11	2.21	6.57
Total	1716.00	1565.85	114.80	341.65

Week	Silage water content in digester (t)	Grass VS fed to digester (tVS)	G:S VS% (%)	SMY (m3 CH4 t-1 VS)	CH4 output (m3)	CH4 v/v (%)
1	4.65	1.76	44%	255.96	1016.46	55%
2	4.65	1.76	44%	255.96	1016.46	55%
3	4.65	1.76	44%	255.96	1016.46	55%
4	4.65	1.76	44%	255.96	1016.46	55%
5	4.65	1.76	44%	255.96	1016.46	55%
6	4.65	1.76	44%	255.96	1016.46	55%
7	4.65	1.76	44%	255.96	1016.46	55%
8	4.65	1.76	44%	255.96	1016.46	55%
9	4.65	1.76	44%	255.96	1016.46	55%
10	4.65	1.76	44%	255.96	1016.46	55%
11	4.65	1.76	44%	255.96	1016.46	55%
12	4.65	1.76	44%	255.96	1016.46	55%
13	4.65	1.76	44%	255.96	1016.46	55%
14	4.65	1.76	44%	255.96	1016.46	55%
15	4.65	1.76	44%	255.96	1016.46	55%
16	4.65	1.76	44%	255.96	1016.46	55%
17	4.65	1.76	44%	255.96	1016.46	55%
18	4.65	1.76	44%	255.96	1016.46	55%
19	4.65	1.76	44%	255.96	1016.46	55%
20	4.65	1.76	44%	255.96	1016.46	55%
21	4.65	1.76	44%	255.96	1016.46	55%
22	4.65	1.76	44%	255.96	1016.46	55%
23	4.65	1.76	44%	255.96	1016.46	55%
24	4.65	1.76	44%	255.96	1016.46	55%
25	4.65	1.76	44%	255.96	1016.46	55%
26	4.65	1.76	44%	255.96	1016.46	55%
27	4.65	1.76	44%	255.96	1016.46	55%
28	4.65	1.76	44%	255.96	1016.46	55%
29	4.65	1.76	44%	255.96	1016.46	55%
30	4.65	1.76	44%	255.96	1016.46	55%
31	4.65	1.76	44%	255.96	1016.46	55%
32	4.65	1.76	44%	255.96	1016.46	55%
33	4.65	1.76	44%	255.96	1016.46	55%
34	4.65	1.76	44%	255.96	1016.46	55%
35	4.65	1.76	44%	255.96	1016.46	55%
36	4.65	1.76	44%	255.96	1016.46	55%
37	4.65	1.76	44%	255.96	1016.46	55%
38	4.65	1.76	44%	255.96	1016.46	55%
39	4.65	1.76	44%	255.96	1016.46	55%
40	4.65	1.76	44%	255.96	1016.46	55%
41	4.65	1.76	44%	255.96	1016.46	55%
42	4.65	1.76	44%	255.96	1016.46	55%
43	4.65	1.76	44%	255.96	1016.46	55%
44	4.65	1.76	44%	255.96	1016.46	55%
45	4.65	1.76	44%	255.96	1016.46	55%
46	4.65	1.76	44%	255.96	1016.46	55%
47	4.65	1.76	44%	255.96	1016.46	55%
48	4.65	1.76	44%	255.96	1016.46	55%
49	4.65	1.76	44%	255.96	1016.46	55%
50	4.65	1.76	44%	255.96	1016.46	55%
51	4.65	1.76	44%	255.96	1016.46	55%
52	4.65	1.76	44%	255.96	1016.46	55%
Total	241.65	91.70			52856.09	

Week	Biogas Output (m3)	Hourly Biogas Output (m3/hr)	CO2 output (m3)	CH4 Weight (t)	CO2 Weight (t)	Biogas Weight (t)	Digestate Weight (t)
1	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
2	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
3	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
4	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
5	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
6	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
7	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
8	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
9	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
10	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
11	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
12	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
13	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
14	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
15	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
16	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
17	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
18	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
19	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
20	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
21	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
22	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
23	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
24	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
25	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
26	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
27	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
28	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
29	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
30	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
31	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
32	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
33	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
34	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
35	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
36	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
37	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
38	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
39	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
40	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
41	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
42	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
43	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
44	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
45	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
46	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
47	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
48	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
49	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
50	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
51	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
52	1856.70	11.05	840.23	0.73	1.66	2.39	37.18
Total	96548.23		43692.14	37.93	86.41	124.35	1933.30

Week	Solid Digestate TS (t)	Solid Digestate TS (%)	Liquid digestate bank (t)	Liquid Digestate Bank Solids (t)
1	1.16	31%	792.67	29.74
2	1.16	31%	826.13	31.00
3	1.16	31%	859.59	32.26
4	1.16	31%	893.05	33.51
5	1.16	31%	926.51	34.77
6	1.16	31%	379.98	14.26
7	1.16	31%	413.44	15.51
8	1.16	31%	446.91	16.77
9	1.16	31%	480.37	18.03
10	1.16	31%	513.83	19.28
11	1.16	31%	547.29	20.54
12	1.16	31%	0.76	0.03
13	1.16	31%	34.22	1.28
14	1.16	31%	67.68	2.54
15	1.16	31%	101.14	3.80
16	1.16	31%	134.60	5.05
17	1.16	31%	168.06	6.31
18	1.16	31%	201.52	7.56
19	1.16	31%	234.99	8.82
20	1.16	31%	268.45	10.07
21	1.16	31%	301.91	11.33
22	1.16	31%	335.37	12.58
23	1.16	31%	368.83	13.84
24	1.16	31%	402.29	15.10
25	1.16	31%	435.75	16.35
26	1.16	31%	469.21	17.61
27	1.16	31%	502.67	18.86
28	1.16	31%	536.13	20.12
29	1.16	31%	569.60	21.37
30	1.16	31%	603.06	22.63
31	1.16	31%	636.52	23.89
32	1.16	31%	669.98	25.14
33	1.16	31%	703.44	26.40
34	1.16	31%	736.90	27.65
35	1.16	31%	770.36	28.91
36	1.16	31%	803.82	30.16
37	1.16	31%	837.28	31.42
38	1.16	31%	290.75	10.91
39	1.16	31%	324.22	12.17
40	1.16	31%	357.68	13.42
41	1.16	31%	391.14	14.68
42	1.16	31%	424.60	15.93
43	1.16	31%	458.06	17.19
44	1.16	31%	491.52	18.44
45	1.16	31%	524.98	19.70
46	1.16	31%	558.44	20.96
47	1.16	31%	591.90	22.21
48	1.16	31%	625.36	23.47
49	1.16	31%	658.82	24.72
50	1.16	31%	692.29	25.98
51	1.16	31%	725.75	27.23
52	1.16	31%	759.21	28.49
Total	60.51			

Week	Digestate Water (t)	Digestate Solids (t)	Liquid Digestate (t)	Liquid Digestate TS (t)	Liquid Digestate TS (%)	Solid Digestate (t)
1	34.76	2.42	33.46	1.26	4%	3.72
2	34.76	2.42	33.46	1.26	4%	3.72
3	34.76	2.42	33.46	1.26	4%	3.72
4	34.76	2.42	33.46	1.26	4%	3.72
5	34.76	2.42	33.46	1.26	4%	3.72
6	34.76	2.42	33.46	1.26	4%	3.72
7	34.76	2.42	33.46	1.26	4%	3.72
8	34.76	2.42	33.46	1.26	4%	3.72
9	34.76	2.42	33.46	1.26	4%	3.72
10	34.76	2.42	33.46	1.26	4%	3.72
11	34.76	2.42	33.46	1.26	4%	3.72
12	34.76	2.42	33.46	1.26	4%	3.72
13	34.76	2.42	33.46	1.26	4%	3.72
14	34.76	2.42	33.46	1.26	4%	3.72
15	34.76	2.42	33.46	1.26	4%	3.72
16	34.76	2.42	33.46	1.26	4%	3.72
17	34.76	2.42	33.46	1.26	4%	3.72
18	34.76	2.42	33.46	1.26	4%	3.72
19	34.76	2.42	33.46	1.26	4%	3.72
20	34.76	2.42	33.46	1.26	4%	3.72
21	34.76	2.42	33.46	1.26	4%	3.72
22	34.76	2.42	33.46	1.26	4%	3.72
23	34.76	2.42	33.46	1.26	4%	3.72
24	34.76	2.42	33.46	1.26	4%	3.72
25	34.76	2.42	33.46	1.26	4%	3.72
26	34.76	2.42	33.46	1.26	4%	3.72
27	34.76	2.42	33.46	1.26	4%	3.72
28	34.76	2.42	33.46	1.26	4%	3.72
29	34.76	2.42	33.46	1.26	4%	3.72
30	34.76	2.42	33.46	1.26	4%	3.72
31	34.76	2.42	33.46	1.26	4%	3.72
32	34.76	2.42	33.46	1.26	4%	3.72
33	34.76	2.42	33.46	1.26	4%	3.72
34	34.76	2.42	33.46	1.26	4%	3.72
35	34.76	2.42	33.46	1.26	4%	3.72
36	34.76	2.42	33.46	1.26	4%	3.72
37	34.76	2.42	33.46	1.26	4%	3.72
38	34.76	2.42	33.46	1.26	4%	3.72
39	34.76	2.42	33.46	1.26	4%	3.72
40	34.76	2.42	33.46	1.26	4%	3.72
41	34.76	2.42	33.46	1.26	4%	3.72
42	34.76	2.42	33.46	1.26	4%	3.72
43	34.76	2.42	33.46	1.26	4%	3.72
44	34.76	2.42	33.46	1.26	4%	3.72
45	34.76	2.42	33.46	1.26	4%	3.72
46	34.76	2.42	33.46	1.26	4%	3.72
47	34.76	2.42	33.46	1.26	4%	3.72
48	34.76	2.42	33.46	1.26	4%	3.72
49	34.76	2.42	33.46	1.26	4%	3.72
50	34.76	2.42	33.46	1.26	4%	3.72
51	34.76	2.42	33.46	1.26	4%	3.72
52	34.76	2.42	33.46	1.26	4%	3.72
Total			1739.97	65.29		193.33

Week	Liquid Digestate Bank TS (%)	Solid digestate bank (t)	Solid Digestate Bank Solids (t)	Solid Digestate Bank TS (%)
1	4%	87.99	27.54	31%
2	4%	91.71	28.70	31%
3	4%	95.43	29.87	31%
4	4%	99.14	31.03	31%
5	4%	102.86	32.20	31%
6	4%	42.14	13.19	31%
7	4%	45.85	14.35	31%
8	4%	49.57	15.52	31%
9	4%	53.29	16.68	31%
10	4%	57.01	17.84	31%
11	4%	60.73	19.01	31%
12	4%	0.00	0.00	#N/A
13	4%	3.72	1.16	31%
14	4%	7.44	2.33	31%
15	4%	11.15	3.49	31%
16	4%	14.87	4.65	31%
17	4%	18.59	5.82	31%
18	4%	22.31	6.98	31%
19	4%	26.03	8.15	31%
20	4%	29.74	9.31	31%
21	4%	33.46	10.47	31%
22	4%	37.18	11.64	31%
23	4%	40.90	12.80	31%
24	4%	44.61	13.96	31%
25	4%	48.33	15.13	31%
26	4%	52.05	16.29	31%
27	4%	55.77	17.46	31%
28	4%	59.49	18.62	31%
29	4%	63.20	19.78	31%
30	4%	66.92	20.95	31%
31	4%	70.64	22.11	31%
32	4%	74.36	23.27	31%
33	4%	78.08	24.44	31%
34	4%	81.79	25.60	31%
35	4%	85.51	26.76	31%
36	4%	89.23	27.93	31%
37	4%	92.95	29.09	31%
38	4%	32.22	10.09	31%
39	4%	35.94	11.25	31%
40	4%	39.66	12.41	31%
41	4%	43.38	13.58	31%
42	4%	47.09	14.74	31%
43	4%	50.81	15.90	31%
44	4%	54.53	17.07	31%
45	4%	58.25	18.23	31%
46	4%	61.96	19.39	31%
47	4%	65.68	20.56	31%
48	4%	69.40	21.72	31%
49	4%	73.12	22.89	31%
50	4%	76.84	24.05	31%
51	4%	80.55	25.21	31%
52	4%	84.27	26.38	31%
Total				

Week	TS content of digester input (%)	Liquid digestate recirculated (t)	Liquid digestate TS recirculated (t)	Flow Rate (m3/day)
1	12%	0.75	0.03	5.76
2	12%	0.75	0.03	5.76
3	12%	0.75	0.03	5.76
4	12%	0.75	0.03	5.76
5	12%	0.75	0.03	5.76
6	12%	0.75	0.03	5.76
7	12%	0.75	0.03	5.76
8	12%	0.75	0.03	5.76
9	12%	0.75	0.03	5.76
10	12%	0.75	0.03	5.76
11	12%	0.75	0.03	5.76
12	12%	0.75	0.03	5.76
13	12%	0.75	0.03	5.76
14	12%	0.75	0.03	5.76
15	12%	0.75	0.03	5.76
16	12%	0.75	0.03	5.76
17	12%	0.75	0.03	5.76
18	12%	0.75	0.03	5.76
19	12%	0.75	0.03	5.76
20	12%	0.75	0.03	5.76
21	12%	0.75	0.03	5.76
22	12%	0.75	0.03	5.76
23	12%	0.75	0.03	5.76
24	12%	0.75	0.03	5.76
25	12%	0.75	0.03	5.76
26	12%	0.75	0.03	5.76
27	12%	0.75	0.03	5.76
28	12%	0.75	0.03	5.76
29	12%	0.75	0.03	5.76
30	12%	0.75	0.03	5.76
31	12%	0.75	0.03	5.76
32	12%	0.75	0.03	5.76
33	12%	0.75	0.03	5.76
34	12%	0.75	0.03	5.76
35	12%	0.75	0.03	5.76
36	12%	0.75	0.03	5.76
37	12%	0.75	0.03	5.76
38	12%	0.75	0.03	5.76
39	12%	0.75	0.03	5.76
40	12%	0.75	0.03	5.76
41	12%	0.75	0.03	5.76
42	12%	0.75	0.03	5.76
43	12%	0.75	0.03	5.76
44	12%	0.75	0.03	5.76
45	12%	0.75	0.03	5.76
46	12%	0.75	0.03	5.76
47	12%	0.75	0.03	5.76
48	12%	0.75	0.03	5.76
49	12%	0.75	0.03	5.76
50	12%	0.75	0.03	5.76
51	12%	0.75	0.03	5.76
52	12%	0.75	0.03	5.76
Total		39.19		

Week	Digester Volume Calculation (m3)	Substrate Conentration (kg VS/m3)	OLR for Max Dig Vol (kg VS/m3 day)	HRT (days)	TS content (with recirc.) (%)
1	230.42	98.48	2.46	40	12%
2	230.42	98.48	2.46	40	12%
3	230.42	98.48	2.46	40	12%
4	230.42	98.48	2.46	40	12%
5	230.42	98.48	2.46	40	12%
6	230.42	98.48	2.46	40	12%
7	230.42	98.48	2.46	40	12%
8	230.42	98.48	2.46	40	12%
9	230.42	98.48	2.46	40	12%
10	230.42	98.48	2.46	40	12%
11	230.42	98.48	2.46	40	12%
12	230.42	98.48	2.46	40	12%
13	230.42	98.48	2.46	40	12%
14	230.42	98.48	2.46	40	12%
15	230.42	98.48	2.46	40	12%
16	230.42	98.48	2.46	40	12%
17	230.42	98.48	2.46	40	12%
18	230.42	98.48	2.46	40	12%
19	230.42	98.48	2.46	40	12%
20	230.42	98.48	2.46	40	12%
21	230.42	98.48	2.46	40	12%
22	230.42	98.48	2.46	40	12%
23	230.42	98.48	2.46	40	12%
24	230.42	98.48	2.46	40	12%
25	230.42	98.48	2.46	40	12%
26	230.42	98.48	2.46	40	12%
27	230.42	98.48	2.46	40	12%
28	230.42	98.48	2.46	40	12%
29	230.42	98.48	2.46	40	12%
30	230.42	98.48	2.46	40	12%
31	230.42	98.48	2.46	40	12%
32	230.42	98.48	2.46	40	12%
33	230.42	98.48	2.46	40	12%
34	230.42	98.48	2.46	40	12%
35	230.42	98.48	2.46	40	12%
36	230.42	98.48	2.46	40	12%
37	230.42	98.48	2.46	40	12%
38	230.42	98.48	2.46	40	12%
39	230.42	98.48	2.46	40	12%
40	230.42	98.48	2.46	40	12%
41	230.42	98.48	2.46	40	12%
42	230.42	98.48	2.46	40	12%
43	230.42	98.48	2.46	40	12%
44	230.42	98.48	2.46	40	12%
45	230.42	98.48	2.46	40	12%
46	230.42	98.48	2.46	40	12%
47	230.42	98.48	2.46	40	12%
48	230.42	98.48	2.46	40	12%
49	230.42	98.48	2.46	40	12%
50	230.42	98.48	2.46	40	12%
51	230.42	98.48	2.46	40	12%
52	230.42	98.48	2.46	40	12%
Total					

Scenario PB-C

Week	Slurry fed to digester (twwt)	Slurry water content in digester (t)	Slurry VS fed to digester (tVS)	Silage fed to digester (twwt)
1	33.00	30.11	2.21	4.73
2	33.00	30.11	2.21	4.73
3	33.00	30.11	2.21	4.73
4	33.00	30.11	2.21	4.73
5	33.00	30.11	2.21	4.73
6	33.00	30.11	2.21	4.73
7	33.00	30.11	2.21	4.73
8	33.00	30.11	2.21	4.73
9	33.00	30.11	2.21	4.73
10	33.00	30.11	2.21	4.73
11	33.00	30.11	2.21	4.73
12	0.00	0.00	0.00	7.55
13	0.00	0.00	0.00	7.55
14	0.00	0.00	0.00	7.55
15	0.00	0.00	0.00	7.55
16	0.00	0.00	0.00	7.55
17	0.00	0.00	0.00	7.55
18	0.00	0.00	0.00	7.55
19	0.00	0.00	0.00	7.55
20	0.00	0.00	0.00	7.55
21	0.00	0.00	0.00	7.55
22	0.00	0.00	0.00	7.55
23	0.00	0.00	0.00	7.55
24	0.00	0.00	0.00	7.55
25	0.00	0.00	0.00	7.55
26	0.00	0.00	0.00	7.55
27	0.00	0.00	0.00	7.55
28	0.00	0.00	0.00	7.55
29	0.00	0.00	0.00	7.55
30	0.00	0.00	0.00	7.55
31	0.00	0.00	0.00	7.55
32	0.00	0.00	0.00	7.55
33	0.00	0.00	0.00	7.55
34	0.00	0.00	0.00	7.55
35	0.00	0.00	0.00	7.55
36	0.00	0.00	0.00	7.55
37	0.00	0.00	0.00	7.55
38	0.00	0.00	0.00	7.55
39	0.00	0.00	0.00	7.55
40	0.00	0.00	0.00	7.55
41	0.00	0.00	0.00	7.55
42	0.00	0.00	0.00	7.55
43	0.00	0.00	0.00	7.55
44	0.00	0.00	0.00	7.55
45	0.00	0.00	0.00	7.55
46	33.00	30.11	2.21	4.73
47	33.00	30.11	2.21	4.73
48	33.00	30.11	2.21	4.73
49	33.00	30.11	2.21	4.73
50	33.00	30.11	2.21	4.73
51	33.00	30.11	2.21	4.73
52	33.00	30.11	2.21	4.73
Total	594.00	542.03	39.74	341.65

Week	Biogas Output (m3)	Hourly Biogas Output (m3/hr)	CO2 output (m3)	CH4 Weight (t)	CO2 Weight (t)	Biogas Weight (t)	Digestate Weight (t)
1	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
2	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
3	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
4	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
5	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
6	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
7	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
8	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
9	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
10	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
11	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
12	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
13	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
14	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
15	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
16	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
17	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
18	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
19	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
20	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
21	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
22	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
23	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
24	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
25	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
26	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
27	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
28	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
29	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
30	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
31	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
32	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
33	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
34	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
35	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
36	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
37	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
38	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
39	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
40	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
41	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
42	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
43	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
44	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
45	1574.23	9.37	768.23	0.58	1.52	2.10	5.45
46	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
47	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
48	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
49	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
50	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
51	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
52	1469.07	8.74	663.07	0.58	1.31	1.89	35.84
Total	79967.30		38054.89	30.08	75.26	105.34	830.30

Week	Silage water content in digester (t)	Grass VS fed to digester (tVS)	G:S VS% (%)	SMY (m3 CH4 t-1 VS)	CH4 output (m3)	CH4 v/v (%)
1	3.34	1.27	37%	231.83	806.01	55%
2	3.34	1.27	37%	231.83	806.01	55%
3	3.34	1.27	37%	231.83	806.01	55%
4	3.34	1.27	37%	231.83	806.01	55%
5	3.34	1.27	37%	231.83	806.01	55%
6	3.34	1.27	37%	231.83	806.01	55%
7	3.34	1.27	37%	231.83	806.01	55%
8	3.34	1.27	37%	231.83	806.01	55%
9	3.34	1.27	37%	231.83	806.01	55%
10	3.34	1.27	37%	231.83	806.01	55%
11	3.34	1.27	37%	231.83	806.01	55%
12	5.34	2.03	100%	398.00	806.01	51%
13	5.34	2.03	100%	398.00	806.01	51%
14	5.34	2.03	100%	398.00	806.01	51%
15	5.34	2.03	100%	398.00	806.01	51%
16	5.34	2.03	100%	398.00	806.01	51%
17	5.34	2.03	100%	398.00	806.01	51%
18	5.34	2.03	100%	398.00	806.01	51%
19	5.34	2.03	100%	398.00	806.01	51%
20	5.34	2.03	100%	398.00	806.01	51%
21	5.34	2.03	100%	398.00	806.01	51%
22	5.34	2.03	100%	398.00	806.01	51%
23	5.34	2.03	100%	398.00	806.01	51%
24	5.34	2.03	100%	398.00	806.01	51%
25	5.34	2.03	100%	398.00	806.01	51%
26	5.34	2.03	100%	398.00	806.01	51%
27	5.34	2.03	100%	398.00	806.01	51%
28	5.34	2.03	100%	398.00	806.01	51%
29	5.34	2.03	100%	398.00	806.01	51%
30	5.34	2.03	100%	398.00	806.01	51%
31	5.34	2.03	100%	398.00	806.01	51%
32	5.34	2.03	100%	398.00	806.01	51%
33	5.34	2.03	100%	398.00	806.01	51%
34	5.34	2.03	100%	398.00	806.01	51%
35	5.34	2.03	100%	398.00	806.01	51%
36	5.34	2.03	100%	398.00	806.01	51%
37	5.34	2.03	100%	398.00	806.01	51%
38	5.34	2.03	100%	398.00	806.01	51%
39	5.34	2.03	100%	398.00	806.01	51%
40	5.34	2.03	100%	398.00	806.01	51%
41	5.34	2.03	100%	398.00	806.01	51%
42	5.34	2.03	100%	398.00	806.01	51%
43	5.34	2.03	100%	398.00	806.01	51%
44	5.34	2.03	100%	398.00	806.01	51%
45	5.34	2.03	100%	398.00	806.01	51%
46	3.34	1.27	37%	231.83	806.01	55%
47	3.34	1.27	37%	231.83	806.01	55%
48	3.34	1.27	37%	231.83	806.01	55%
49	3.34	1.27	37%	231.83	806.01	55%
50	3.34	1.27	37%	231.83	806.01	55%
51	3.34	1.27	37%	231.83	806.01	55%
52	3.34	1.27	37%	231.83	806.01	55%
Total	241.65	91.70			41912.41	

Week	Digestate Water (t)	Digestate Solids (t)	Liquid Digestate (t)	Liquid Digestate TS (t)	Liquid Digestate TS (%)	Solid Digestate (t)
1	33.46	2.38	32.25	1.24	4%	3.58
2	33.46	2.38	32.25	1.24	4%	3.58
3	33.46	2.38	32.25	1.24	4%	3.58
4	33.46	2.38	32.25	1.24	4%	3.58
5	33.46	2.38	32.25	1.24	4%	3.58
6	33.46	2.38	32.25	1.24	4%	3.58
7	33.46	2.38	32.25	1.24	4%	3.58
8	33.46	2.38	32.25	1.24	4%	3.58
9	33.46	2.38	32.25	1.24	4%	3.58
10	33.46	2.38	32.25	1.24	4%	3.58
11	33.46	2.38	32.25	1.24	4%	3.58
12	5.34	0.11	4.90	0.06	1%	0.54
13	5.34	0.11	4.90	0.06	1%	0.54
14	5.34	0.11	4.90	0.06	1%	0.54
15	5.34	0.11	4.90	0.06	1%	0.54
16	5.34	0.11	4.90	0.06	1%	0.54
17	5.34	0.11	4.90	0.06	1%	0.54
18	5.34	0.11	4.90	0.06	1%	0.54
19	5.34	0.11	4.90	0.06	1%	0.54
20	5.34	0.11	4.90	0.06	1%	0.54
21	5.34	0.11	4.90	0.06	1%	0.54
22	5.34	0.11	4.90	0.06	1%	0.54
23	5.34	0.11	4.90	0.06	1%	0.54
24	5.34	0.11	4.90	0.06	1%	0.54
25	5.34	0.11	4.90	0.06	1%	0.54
26	5.34	0.11	4.90	0.06	1%	0.54
27	5.34	0.11	4.90	0.06	1%	0.54
28	5.34	0.11	4.90	0.06	1%	0.54
29	5.34	0.11	4.90	0.06	1%	0.54
30	5.34	0.11	4.90	0.06	1%	0.54
31	5.34	0.11	4.90	0.06	1%	0.54
32	5.34	0.11	4.90	0.06	1%	0.54
33	5.34	0.11	4.90	0.06	1%	0.54
34	5.34	0.11	4.90	0.06	1%	0.54
35	5.34	0.11	4.90	0.06	1%	0.54
36	5.34	0.11	4.90	0.06	1%	0.54
37	5.34	0.11	4.90	0.06	1%	0.54
38	5.34	0.11	4.90	0.06	1%	0.54
39	5.34	0.11	4.90	0.06	1%	0.54
40	5.34	0.11	4.90	0.06	1%	0.54
41	5.34	0.11	4.90	0.06	1%	0.54
42	5.34	0.11	4.90	0.06	1%	0.54
43	5.34	0.11	4.90	0.06	1%	0.54
44	5.34	0.11	4.90	0.06	1%	0.54
45	5.34	0.11	4.90	0.06	1%	0.54
46	33.46	2.38	32.25	1.24	4%	3.58
47	33.46	2.38	32.25	1.24	4%	3.58
48	33.46	2.38	32.25	1.24	4%	3.58
49	33.46	2.38	32.25	1.24	4%	3.58
50	33.46	2.38	32.25	1.24	4%	3.58
51	33.46	2.38	32.25	1.24	4%	3.58
52	33.46	2.38	32.25	1.24	4%	3.58
Total			747.27	24.20		83.03

Week	Solid Digestate TS (t)	Solid Digestate TS (%)	Liquid digestate bank (t)	Liquid Digestate Bank Solids (t)
1	1.15	32%	304.87	10.44
2	1.15	32%	337.12	11.67
3	1.15	32%	369.37	12.91
4	1.15	32%	401.63	14.15
5	1.15	32%	433.88	15.38
6	1.15	32%	217.05	7.74
7	1.15	32%	249.30	8.97
8	1.15	32%	281.56	10.21
9	1.15	32%	313.81	11.45
10	1.15	32%	346.07	12.68
11	1.15	32%	378.32	13.92
12	0.05	10%	134.13	4.78
13	0.05	10%	139.03	4.84
14	0.05	10%	143.94	4.90
15	0.05	10%	148.84	4.95
16	0.05	10%	153.74	5.01
17	0.05	10%	158.64	5.07
18	0.05	10%	163.55	5.13
19	0.05	10%	168.45	5.18
20	0.05	10%	173.35	5.24
21	0.05	10%	178.26	5.30
22	0.05	10%	183.16	5.36
23	0.05	10%	188.06	5.41
24	0.05	10%	192.96	5.47
25	0.05	10%	197.87	5.53
26	0.05	10%	202.77	5.59
27	0.05	10%	207.67	5.64
28	0.05	10%	212.57	5.70
29	0.05	10%	217.48	5.76
30	0.05	10%	222.38	5.82
31	0.05	10%	227.28	5.87
32	0.05	10%	232.19	5.93
33	0.05	10%	237.09	5.99
34	0.05	10%	241.99	6.05
35	0.05	10%	246.89	6.10
36	0.05	10%	251.80	6.16
37	0.05	10%	256.70	6.22
38	0.05	10%	12.51	0.15
39	0.05	10%	17.41	0.20
40	0.05	10%	22.32	0.26
41	0.05	10%	27.22	0.32
42	0.05	10%	32.12	0.38
43	0.05	10%	37.02	0.43
44	0.05	10%	41.93	0.49
45	0.05	10%	46.83	0.55
46	1.15	32%	79.08	1.78
47	1.15	32%	111.34	3.02
48	1.15	32%	143.59	4.26
49	1.15	32%	175.85	5.49
50	1.15	32%	208.10	6.73
51	1.15	32%	240.36	7.97
52	1.15	32%	272.61	9.20
Total	22.43			

Week	Liquid Digestate Bank TS (%)	Solid digestate bank (t)	Solid Digestate Bank Solids (t)	Solid Digestate Bank TS (%)
1	3%	32.48	9.54	29%
2	3%	36.07	10.68	30%
3	3%	39.65	11.83	30%
4	4%	43.24	12.97	30%
5	4%	46.82	14.12	30%
6	4%	22.73	6.88	30%
7	4%	26.31	8.03	31%
8	4%	29.89	9.17	31%
9	4%	33.48	10.32	31%
10	4%	37.06	11.47	31%
11	4%	40.65	12.61	31%
12	4%	13.51	4.06	30%
13	3%	14.06	4.11	29%
14	3%	14.60	4.16	29%
15	3%	15.15	4.22	28%
16	3%	15.69	4.27	27%
17	3%	16.24	4.32	27%
18	3%	16.78	4.38	26%
19	3%	17.33	4.43	26%
20	3%	17.87	4.48	25%
21	3%	18.42	4.53	25%
22	3%	18.96	4.59	24%
23	3%	19.51	4.64	24%
24	3%	20.05	4.69	23%
25	3%	20.60	4.75	23%
26	3%	21.14	4.80	23%
27	3%	21.68	4.85	22%
28	3%	22.23	4.91	22%
29	3%	22.77	4.96	22%
30	3%	23.32	5.01	22%
31	3%	23.86	5.07	21%
32	3%	24.41	5.12	21%
33	3%	24.95	5.17	21%
34	2%	25.50	5.23	20%
35	2%	26.04	5.28	20%
36	2%	26.59	5.33	20%
37	2%	27.13	5.39	20%
38	1%	0.00	0.00	#N/A
39	1%	0.54	0.05	10%
40	1%	1.09	0.11	10%
41	1%	1.63	0.16	10%
42	1%	2.18	0.21	10%
43	1%	2.72	0.27	10%
44	1%	3.27	0.32	10%
45	1%	3.81	0.37	10%
46	2%	7.40	1.52	21%
47	3%	10.98	2.66	24%
48	3%	14.56	3.81	26%
49	3%	18.15	4.95	27%
50	3%	21.73	6.10	28%
51	3%	25.32	7.25	29%
52	3%	28.90	8.39	29%
Total				

Week	Digester Volume Calculation (m3)	Substrate Conentration (kg VS/m3)	OLR for Max Dig Vol (kg VS/m3 day)	HRT (days)	TS content (with recirc.) (%)
1	215.59	92.15	2.30	40	#N/A
2	215.59	92.15	2.30	40	#N/A
3	215.59	92.15	2.30	40	#N/A
4	215.59	92.15	2.30	40	#N/A
5	215.59	92.15	2.30	40	#N/A
6	215.59	92.15	2.30	40	#N/A
7	215.59	92.15	2.30	40	#N/A
8	215.59	92.15	2.30	40	#N/A
9	215.59	92.15	2.30	40	#N/A
10	215.59	92.15	2.30	40	#N/A
11	215.59	92.15	2.30	40	#N/A
12	131.39	88.08	1.34	66	12%
13	130.52	88.67	1.34	66	12%
14	129.72	89.21	1.34	66	12%
15	128.98	89.72	1.34	67	12%
16	128.31	90.19	1.34	67	12%
17	127.68	90.63	1.34	68	12%
18	127.10	91.05	1.34	68	12%
19	126.57	91.43	1.34	68	12%
20	126.07	91.80	1.34	68	12%
21	125.60	92.14	1.34	69	12%
22	125.16	92.46	1.34	69	12%
23	124.75	92.76	1.34	69	12%
24	124.36	93.05	1.34	69	12%
25	124.00	93.33	1.34	70	12%
26	123.66	93.58	1.34	70	12%
27	123.33	93.83	1.34	70	12%
28	123.02	94.06	1.34	70	12%
29	122.73	94.29	1.34	70	12%
30	122.46	94.50	1.34	70	12%
31	122.19	94.70	1.34	71	12%
32	121.95	94.90	1.34	71	12%
33	121.71	95.08	1.34	71	12%
34	121.48	95.26	1.34	71	12%
35	121.26	95.43	1.34	71	12%
36	121.06	95.59	1.34	71	12%
37	120.86	95.75	1.34	71	12%
38	111.88	103.43	1.34	77	12%
39	111.88	103.43	1.34	77	12%
40	111.88	103.43	1.34	77	12%
41	111.88	103.43	1.34	77	12%
42	111.88	103.43	1.34	77	12%
43	111.88	103.43	1.34	77	12%
44	111.88	103.43	1.34	77	12%
45	111.88	103.43	1.34	77	12%
46	215.59	92.15	2.30	40	#N/A
47	215.59	92.15	2.30	40	#N/A
48	215.59	92.15	2.30	40	#N/A
49	215.59	92.15	2.30	40	#N/A
50	215.59	92.15	2.30	40	#N/A
51	215.59	92.15	2.30	40	#N/A
52	215.59	92.15	2.30	40	#N/A
Total					

Week	TS content of digester input (%)	Liquid digestate recirculated (t)	Liquid digestate TS recirculated (t)	Flow Rate (m3/day)
1	11%	0.00	0.00	5.39
2	11%	0.00	0.00	5.39
3	11%	0.00	0.00	5.39
4	11%	0.00	0.00	5.39
5	11%	0.00	0.00	5.39
6	11%	0.00	0.00	5.39
7	11%	0.00	0.00	5.39
8	11%	0.00	0.00	5.39
9	11%	0.00	0.00	5.39
10	11%	0.00	0.00	5.39
11	11%	0.00	0.00	5.39
12	29%	15.45	0.55	3.28
13	29%	15.30	0.53	3.26
14	29%	15.16	0.52	3.24
15	29%	15.03	0.50	3.22
16	29%	14.91	0.49	3.21
17	29%	14.80	0.47	3.19
18	29%	14.70	0.46	3.18
19	29%	14.60	0.45	3.16
20	29%	14.52	0.44	3.15
21	29%	14.43	0.43	3.14
22	29%	14.36	0.42	3.13
23	29%	14.29	0.41	3.12
24	29%	14.22	0.40	3.11
25	29%	14.15	0.40	3.10
26	29%	14.09	0.39	3.09
27	29%	14.04	0.38	3.08
28	29%	13.98	0.38	3.08
29	29%	13.93	0.37	3.07
30	29%	13.88	0.36	3.06
31	29%	13.84	0.36	3.05
32	29%	13.80	0.35	3.05
33	29%	13.75	0.35	3.04
34	29%	13.71	0.34	3.04
35	29%	13.68	0.34	3.03
36	29%	13.64	0.33	3.03
37	29%	13.60	0.33	3.02
38	29%	12.03	0.14	2.80
39	29%	12.03	0.14	2.80
40	29%	12.03	0.14	2.80
41	29%	12.03	0.14	2.80
42	29%	12.03	0.14	2.80
43	29%	12.03	0.14	2.80
44	29%	12.03	0.14	2.80
45	29%	12.03	0.14	2.80
46	11%	0.00	0.00	5.39
47	11%	0.00	0.00	5.39
48	11%	0.00	0.00	5.39
49	11%	0.00	0.00	5.39
50	11%	0.00	0.00	5.39
51	11%	0.00	0.00	5.39
52	11%	0.00	0.00	5.39
Total		468.13		

Scenario ZG-W

Week	Slurry fed to digester (twwt)	Slurry water content in digester (t)	Slurry VS fed to digester (tVS)	Silage fed to digester (twwt)
1	33.00	30.11	2.21	10.50
2	33.00	30.11	2.21	10.50
3	33.00	30.11	2.21	10.50
4	33.00	30.11	2.21	10.50
5	33.00	30.11	2.21	10.50
6	33.00	30.11	2.21	10.50
7	33.00	30.11	2.21	10.50
8	33.00	30.11	2.21	10.50
9	33.00	30.11	2.21	10.50
10	33.00	30.11	2.21	10.50
11	33.00	30.11	2.21	10.50
12	33.00	30.11	2.21	10.50
13	33.00	30.11	2.21	10.50
14	33.00	30.11	2.21	10.50
15	33.00	30.11	2.21	10.50
16	33.00	30.11	2.21	2.32
17	33.00	30.11	2.21	2.32
18	33.00	30.11	2.21	2.32
19	33.00	30.11	2.21	2.32
20	33.00	30.11	2.21	2.32
21	33.00	30.11	2.21	2.32
22	33.00	30.11	2.21	2.32
23	33.00	30.11	2.21	2.32
24	33.00	30.11	2.21	2.32
25	33.00	30.11	2.21	2.32
26	33.00	30.11	2.21	2.32
27	33.00	30.11	2.21	2.32
28	33.00	30.11	2.21	2.32
29	33.00	30.11	2.21	2.32
30	33.00	30.11	2.21	2.32
31	33.00	30.11	2.21	2.32
32	33.00	30.11	2.21	2.32
33	33.00	30.11	2.21	2.32
34	33.00	30.11	2.21	2.32
35	33.00	30.11	2.21	2.32
36	33.00	30.11	2.21	2.32
37	33.00	30.11	2.21	2.32
38	33.00	30.11	2.21	2.32
39	33.00	30.11	2.21	2.32
40	33.00	30.11	2.21	2.32
41	33.00	30.11	2.21	10.50
42	33.00	30.11	2.21	10.50
43	33.00	30.11	2.21	10.50
44	33.00	30.11	2.21	10.50
45	33.00	30.11	2.21	10.50
46	33.00	30.11	2.21	10.50
47	33.00	30.11	2.21	10.50
48	33.00	30.11	2.21	10.50
49	33.00	30.11	2.21	10.50
50	33.00	30.11	2.21	10.50
51	33.00	30.11	2.21	10.50
52	33.00	30.11	2.21	10.50
Total	1716.00	1565.85	114.80	341.65

Week	Biogas Output (m3)	Hourly Biogas Output (m3/hr)	CO2 output (m3)	CH4 Weight (t)	CO2 Weight (t)	Biogas Weight (t)	Digestate Weight (t)
1	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
2	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
3	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
4	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
5	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
6	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
7	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
8	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
9	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
10	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
11	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
12	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
13	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
14	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
15	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
16	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
17	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
18	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
19	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
20	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
21	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
22	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
23	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
24	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
25	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
26	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
27	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
28	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
29	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
30	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
31	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
32	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
33	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
34	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
35	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
36	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
37	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
38	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
39	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
40	1045.93	6.23	473.59	0.41	0.94	1.35	33.98
41	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
42	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
43	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
44	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
45	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
46	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
47	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
48	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
49	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
50	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
51	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
52	2783.58	16.57	1271.06	1.09	2.51	3.60	39.90
Total	101304.81		46158.44	39.58	91.29	130.87	1926.78

Week	Silage water content in digester (t)	Grass VS fed to digester (tVS)	G:S VS% (%)	SMY (m3 CH4 t-1 VS)	CH4 output (m3)	CH4 v/v (%)
1	7.43	2.82	56%	300.91	1512.52	54%
2	7.43	2.82	56%	300.91	1512.52	54%
3	7.43	2.82	56%	300.91	1512.52	54%
4	7.43	2.82	56%	300.91	1512.52	54%
5	7.43	2.82	56%	300.91	1512.52	54%
6	7.43	2.82	56%	300.91	1512.52	54%
7	7.43	2.82	56%	300.91	1512.52	54%
8	7.43	2.82	56%	300.91	1512.52	54%
9	7.43	2.82	56%	300.91	1512.52	54%
10	7.43	2.82	56%	300.91	1512.52	54%
11	7.43	2.82	56%	300.91	1512.52	54%
12	7.43	2.82	56%	300.91	1512.52	54%
13	7.43	2.82	56%	300.91	1512.52	54%
14	7.43	2.82	56%	300.91	1512.52	54%
15	7.43	2.82	56%	300.91	1512.52	54%
16	1.64	0.62	22%	202.15	572.33	55%
17	1.64	0.62	22%	202.15	572.33	55%
18	1.64	0.62	22%	202.15	572.33	55%
19	1.64	0.62	22%	202.15	572.33	55%
20	1.64	0.62	22%	202.15	572.33	55%
21	1.64	0.62	22%	202.15	572.33	55%
22	1.64	0.62	22%	202.15	572.33	55%
23	1.64	0.62	22%	202.15	572.33	55%
24	1.64	0.62	22%	202.15	572.33	55%
25	1.64	0.62	22%	202.15	572.33	55%
26	1.64	0.62	22%	202.15	572.33	55%
27	1.64	0.62	22%	202.15	572.33	55%
28	1.64	0.62	22%	202.15	572.33	55%
29	1.64	0.62	22%	202.15	572.33	55%
30	1.64	0.62	22%	202.15	572.33	55%
31	1.64	0.62	22%	202.15	572.33	55%
32	1.64	0.62	22%	202.15	572.33	55%
33	1.64	0.62	22%	202.15	572.33	55%
34	1.64	0.62	22%	202.15	572.33	55%
35	1.64	0.62	22%	202.15	572.33	55%
36	1.64	0.62	22%	202.15	572.33	55%
37	1.64	0.62	22%	202.15	572.33	55%
38	1.64	0.62	22%	202.15	572.33	55%
39	1.64	0.62	22%	202.15	572.33	55%
40	1.64	0.62	22%	202.15	572.33	55%
41	7.43	2.82	56%	300.91	1512.52	54%
42	7.43	2.82	56%	300.91	1512.52	54%
43	7.43	2.82	56%	300.91	1512.52	54%
44	7.43	2.82	56%	300.91	1512.52	54%
45	7.43	2.82	56%	300.91	1512.52	54%
46	7.43	2.82	56%	300.91	1512.52	54%
47	7.43	2.82	56%	300.91	1512.52	54%
48	7.43	2.82	56%	300.91	1512.52	54%
49	7.43	2.82	56%	300.91	1512.52	54%
50	7.43	2.82	56%	300.91	1512.52	54%
51	7.43	2.82	56%	300.91	1512.52	54%
52	7.43	2.82	56%	300.91	1512.52	54%
Total	241.65	91.70			55146.37	

Week	Digestate Water (t)	Digestate Solids (t)	Liquid Digestate (t)	Liquid Digestate TS (t)	Liquid Digestate TS (%)	Solid Digestate (t)
1	37.54	2.36	35.91	1.23	3%	3.99
2	37.54	2.36	35.91	1.23	3%	3.99
3	37.54	2.36	35.91	1.23	3%	3.99
4	37.54	2.36	35.91	1.23	3%	3.99
5	37.54	2.36	35.91	1.23	3%	3.99
6	37.54	2.36	35.91	1.23	3%	3.99
7	37.54	2.36	35.91	1.23	3%	3.99
8	37.54	2.36	35.91	1.23	3%	3.99
9	37.54	2.36	35.91	1.23	3%	3.99
10	37.54	2.36	35.91	1.23	3%	3.99
11	37.54	2.36	35.91	1.23	3%	3.99
12	37.54	2.36	35.91	1.23	3%	3.99
13	37.54	2.36	35.91	1.23	3%	3.99
14	37.54	2.36	35.91	1.23	3%	3.99
15	37.54	2.36	35.91	1.23	3%	3.99
16	31.76	2.22	30.58	1.15	4%	3.40
17	31.76	2.22	30.58	1.15	4%	3.40
18	31.76	2.22	30.58	1.15	4%	3.40
19	31.76	2.22	30.58	1.15	4%	3.40
20	31.76	2.22	30.58	1.15	4%	3.40
21	31.76	2.22	30.58	1.15	4%	3.40
22	31.76	2.22	30.58	1.15	4%	3.40
23	31.76	2.22	30.58	1.15	4%	3.40
24	31.76	2.22	30.58	1.15	4%	3.40
25	31.76	2.22	30.58	1.15	4%	3.40
26	31.76	2.22	30.58	1.15	4%	3.40
27	31.76	2.22	30.58	1.15	4%	3.40
28	31.76	2.22	30.58	1.15	4%	3.40
29	31.76	2.22	30.58	1.15	4%	3.40
30	31.76	2.22	30.58	1.15	4%	3.40
31	31.76	2.22	30.58	1.15	4%	3.40
32	31.76	2.22	30.58	1.15	4%	3.40
33	31.76	2.22	30.58	1.15	4%	3.40
34	31.76	2.22	30.58	1.15	4%	3.40
35	31.76	2.22	30.58	1.15	4%	3.40
36	31.76	2.22	30.58	1.15	4%	3.40
37	31.76	2.22	30.58	1.15	4%	3.40
38	31.76	2.22	30.58	1.15	4%	3.40
39	31.76	2.22	30.58	1.15	4%	3.40
40	31.76	2.22	30.58	1.15	4%	3.40
41	37.54	2.36	35.91	1.23	3%	3.99
42	37.54	2.36	35.91	1.23	3%	3.99
43	37.54	2.36	35.91	1.23	3%	3.99
44	37.54	2.36	35.91	1.23	3%	3.99
45	37.54	2.36	35.91	1.23	3%	3.99
46	37.54	2.36	35.91	1.23	3%	3.99
47	37.54	2.36	35.91	1.23	3%	3.99
48	37.54	2.36	35.91	1.23	3%	3.99
49	37.54	2.36	35.91	1.23	3%	3.99
50	37.54	2.36	35.91	1.23	3%	3.99
51	37.54	2.36	35.91	1.23	3%	3.99
52	37.54	2.36	35.91	1.23	3%	3.99
Total			1734.10	61.91		192.68

Week	Solid Digestate TS (t)	Solid Digestate TS (%)	Liquid digestate bank (t)	Liquid Digestate Bank Solids (t)
1	1.14	28%	769.73	27.23
2	1.14	28%	805.64	28.45
3	1.14	28%	841.55	29.68
4	1.14	28%	877.47	30.91
5	1.14	28%	913.38	32.13
6	1.14	28%	371.26	13.05
7	1.14	28%	407.17	14.27
8	1.14	28%	443.08	15.50
9	1.14	28%	479.00	16.72
10	1.14	28%	514.91	17.95
11	1.14	28%	550.82	19.18
12	1.14	28%	8.70	0.30
13	1.14	28%	44.61	1.52
14	1.14	28%	80.53	2.75
15	1.14	28%	116.44	3.97
16	1.07	31%	147.02	5.13
17	1.07	31%	177.59	6.28
18	1.07	31%	208.17	7.43
19	1.07	31%	238.75	8.58
20	1.07	31%	269.33	9.74
21	1.07	31%	299.91	10.89
22	1.07	31%	330.49	12.04
23	1.07	31%	361.06	13.19
24	1.07	31%	391.64	14.35
25	1.07	31%	422.22	15.50
26	1.07	31%	452.80	16.65
27	1.07	31%	483.38	17.80
28	1.07	31%	513.96	18.95
29	1.07	31%	544.53	20.11
30	1.07	31%	575.11	21.26
31	1.07	31%	605.69	22.41
32	1.07	31%	636.27	23.56
33	1.07	31%	666.85	24.72
34	1.07	31%	697.42	25.87
35	1.07	31%	728.00	27.02
36	1.07	31%	758.58	28.17
37	1.07	31%	789.16	29.32
38	1.07	31%	241.70	8.99
39	1.07	31%	272.28	10.14
40	1.07	31%	302.86	11.29
41	1.14	28%	338.77	12.52
42	1.14	28%	374.69	13.74
43	1.14	28%	410.60	14.97
44	1.14	28%	446.51	16.19
45	1.14	28%	482.42	17.42
46	1.14	28%	518.34	18.65
47	1.14	28%	554.25	19.87
48	1.14	28%	590.16	21.10
49	1.14	28%	626.08	22.32
50	1.14	28%	661.99	23.55
51	1.14	28%	697.90	24.78
52	1.14	28%	733.81	26.00
Total	57.38			

Week	Liquid Digestate Bank TS (%)	Solid digestate bank (t)	Solid Digestate Bank Solids (t)	Solid Digestate Bank TS (%)
1	4%	84.56	24.94	29%
2	4%	88.55	26.08	29%
3	4%	92.54	27.21	29%
4	4%	96.53	28.35	29%
5	4%	100.52	29.49	29%
6	4%	40.28	11.80	29%
7	4%	44.27	12.94	29%
8	3%	48.26	14.08	29%
9	3%	52.26	15.21	29%
10	3%	56.25	16.35	29%
11	3%	60.24	17.49	29%
12	3%	0.00	0.00	#N/A
13	3%	3.99	1.14	28%
14	3%	7.98	2.27	28%
15	3%	11.97	3.41	28%
16	3%	15.37	4.48	29%
17	4%	18.77	5.54	30%
18	4%	22.16	6.61	30%
19	4%	25.56	7.68	30%
20	4%	28.96	8.75	30%
21	4%	32.36	9.82	30%
22	4%	35.75	10.88	30%
23	4%	39.15	11.95	31%
24	4%	42.55	13.02	31%
25	4%	45.95	14.09	31%
26	4%	49.34	15.16	31%
27	4%	52.74	16.22	31%
28	4%	56.14	17.29	31%
29	4%	59.54	18.36	31%
30	4%	62.93	19.43	31%
31	4%	66.33	20.49	31%
32	4%	69.73	21.56	31%
33	4%	73.13	22.63	31%
34	4%	76.52	23.70	31%
35	4%	79.92	24.77	31%
36	4%	83.32	25.83	31%
37	4%	86.72	26.90	31%
38	4%	25.89	8.04	31%
39	4%	29.29	9.10	31%
40	4%	32.68	10.17	31%
41	4%	36.67	11.31	31%
42	4%	40.67	12.44	31%
43	4%	44.66	13.58	30%
44	4%	48.65	14.72	30%
45	4%	52.64	15.85	30%
46	4%	56.63	16.99	30%
47	4%	60.62	18.12	30%
48	4%	64.61	19.26	30%
49	4%	68.60	20.40	30%
50	4%	72.59	21.53	30%
51	4%	76.58	22.67	30%
52	4%	80.57	23.81	30%
Total				

Week	TS content of digester input (%)	Liquid digestate recirculated (t)	Liquid digestate TS recirculated (t)	Flow Rate (m3/day)
1	14%	8.76	0.31	7.47
2	14%	8.75	0.31	7.47
3	14%	8.75	0.31	7.46
4	14%	8.74	0.31	7.46
5	14%	8.74	0.31	7.46
6	14%	8.74	0.31	7.46
7	14%	8.73	0.31	7.46
8	14%	8.72	0.30	7.46
9	14%	8.71	0.30	7.46
10	14%	8.71	0.30	7.46
11	14%	8.70	0.30	7.46
12	14%	8.63	0.29	7.45
13	14%	8.63	0.29	7.45
14	14%	8.63	0.29	7.45
15	14%	8.63	0.29	7.45
16	10%	0.00	0.00	5.05
17	10%	0.00	0.00	5.05
18	10%	0.00	0.00	5.05
19	10%	0.00	0.00	5.05
20	10%	0.00	0.00	5.05
21	10%	0.00	0.00	5.05
22	10%	0.00	0.00	5.05
23	10%	0.00	0.00	5.05
24	10%	0.00	0.00	5.05
25	10%	0.00	0.00	5.05
26	10%	0.00	0.00	5.05
27	10%	0.00	0.00	5.05
28	10%	0.00	0.00	5.05
29	10%	0.00	0.00	5.05
30	10%	0.00	0.00	5.05
31	10%	0.00	0.00	5.05
32	10%	0.00	0.00	5.05
33	10%	0.00	0.00	5.05
34	10%	0.00	0.00	5.05
35	10%	0.00	0.00	5.05
36	10%	0.00	0.00	5.05
37	10%	0.00	0.00	5.05
38	10%	0.00	0.00	5.05
39	10%	0.00	0.00	5.05
40	10%	0.00	0.00	5.05
41	14%	8.93	0.33	7.49
42	14%	8.90	0.33	7.49
43	14%	8.87	0.32	7.48
44	14%	8.85	0.32	7.48
45	14%	8.84	0.32	7.48
46	14%	8.82	0.32	7.47
47	14%	8.81	0.32	7.47
48	14%	8.80	0.31	7.47
49	14%	8.79	0.31	7.47
50	14%	8.78	0.31	7.47
51	14%	8.77	0.31	7.47
52	14%	8.77	0.31	7.47
Total		236.50		

Week	Digester Volume Calculation (m3)	Substrate Conentration (kg VS/m3)	OLR for Max Dig Vol (kg VS/m3 day)	HRT (days)	TS content (with recirc.) (%)
1	298.64	96.18	2.40	40	12%
2	298.61	96.19	2.40	40	12%
3	298.58	96.20	2.40	40	12%
4	298.55	96.21	2.40	40	12%
5	298.53	96.22	2.40	40	12%
6	298.50	96.22	2.40	40	12%
7	298.45	96.24	2.40	40	12%
8	298.41	96.26	2.40	40	12%
9	298.37	96.27	2.40	40	12%
10	298.34	96.28	2.40	40	12%
11	298.31	96.29	2.40	40	12%
12	297.92	96.41	2.40	40	12%
13	297.92	96.41	2.40	40	12%
14	297.92	96.41	2.40	40	12%
15	297.92	96.41	2.40	40	12%
16	201.85	80.15	1.35	59	#N/A
17	201.85	80.15	1.35	59	#N/A
18	201.85	80.15	1.35	59	#N/A
19	201.85	80.15	1.35	59	#N/A
20	201.85	80.15	1.35	59	#N/A
21	201.85	80.15	1.35	59	#N/A
22	201.85	80.15	1.35	59	#N/A
23	201.85	80.15	1.35	59	#N/A
24	201.85	80.15	1.35	59	#N/A
25	201.85	80.15	1.35	59	#N/A
26	201.85	80.15	1.35	59	#N/A
27	201.85	80.15	1.35	59	#N/A
28	201.85	80.15	1.35	59	#N/A
29	201.85	80.15	1.35	59	#N/A
30	201.85	80.15	1.35	59	#N/A
31	201.85	80.15	1.35	59	#N/A
32	201.85	80.15	1.35	59	#N/A
33	201.85	80.15	1.35	59	#N/A
34	201.85	80.15	1.35	59	#N/A
35	201.85	80.15	1.35	59	#N/A
36	201.85	80.15	1.35	59	#N/A
37	201.85	80.15	1.35	59	#N/A
38	201.85	80.15	1.35	59	#N/A
39	201.85	80.15	1.35	59	#N/A
40	201.85	80.15	1.35	59	#N/A
41	299.59	95.88	2.40	40	12%
42	299.42	95.93	2.40	40	12%
43	299.29	95.97	2.40	40	12%
44	299.17	96.01	2.40	40	12%
45	299.08	96.04	2.40	40	12%
46	299.00	96.07	2.40	40	12%
47	298.93	96.09	2.40	40	12%
48	298.86	96.11	2.40	40	12%
49	298.81	96.13	2.40	40	12%
50	298.76	96.14	2.40	40	12%
51	298.72	96.16	2.40	40	12%
52	298.68	96.17	2.40	40	12%
Total					

Scenario PB-W

Week	Slurry fed to digester (twwt)	Slurry water content in digester (t)	Slurry VS fed to digester (tVS)	Silage fed to digester (twwt)
1	33.00	30.11	2.21	9.35
2	33.00	30.11	2.21	9.35
3	33.00	30.11	2.21	9.35
4	33.00	30.11	2.21	9.35
5	33.00	30.11	2.21	9.35
6	33.00	30.11	2.21	9.35
7	33.00	30.11	2.21	9.35
8	33.00	30.11	2.21	9.35
9	33.00	30.11	2.21	9.35
10	33.00	30.11	2.21	9.35
11	33.00	30.11	2.21	9.35
12	0.00	0.00	0.00	12.80
13	0.00	0.00	0.00	12.80
14	0.00	0.00	0.00	12.80
15	0.00	0.00	0.00	12.80
16	0.00	0.00	0.00	2.32
17	0.00	0.00	0.00	2.32
18	0.00	0.00	0.00	2.32
19	0.00	0.00	0.00	2.32
20	0.00	0.00	0.00	2.32
21	0.00	0.00	0.00	2.32
22	0.00	0.00	0.00	2.32
23	0.00	0.00	0.00	2.32
24	0.00	0.00	0.00	2.32
25	0.00	0.00	0.00	2.32
26	0.00	0.00	0.00	2.32
27	0.00	0.00	0.00	2.32
28	0.00	0.00	0.00	2.32
29	0.00	0.00	0.00	2.32
30	0.00	0.00	0.00	2.32
31	0.00	0.00	0.00	2.32
32	0.00	0.00	0.00	2.32
33	0.00	0.00	0.00	2.32
34	0.00	0.00	0.00	2.32
35	0.00	0.00	0.00	2.32
36	0.00	0.00	0.00	2.32
37	0.00	0.00	0.00	2.32
38	0.00	0.00	0.00	2.32
39	0.00	0.00	0.00	2.32
40	0.00	0.00	0.00	2.32
41	0.00	0.00	0.00	12.80
42	0.00	0.00	0.00	12.80
43	0.00	0.00	0.00	12.80
44	0.00	0.00	0.00	12.80
45	0.00	0.00	0.00	12.80
46	33.00	30.11	2.21	9.35
47	33.00	30.11	2.21	9.35
48	33.00	30.11	2.21	9.35
49	33.00	30.11	2.21	9.35
50	33.00	30.11	2.21	9.35
51	33.00	30.11	2.21	9.35
52	33.00	30.11	2.21	9.35
Total	594.00	542.03	39.74	341.65

Week	Silage water content in digester (t)	Grass VS fed to digester (tVS)	G:S VS% (%)	SMY (m3 CH4 t-1 VS)	CH4 output (m3)	CH4 v/v (%)
1	6.62	2.51	53%	289.85	1367.51	54%
2	6.62	2.51	53%	289.85	1367.51	54%
3	6.62	2.51	53%	289.85	1367.51	54%
4	6.62	2.51	53%	289.85	1367.51	54%
5	6.62	2.51	53%	289.85	1367.51	54%
6	6.62	2.51	53%	289.85	1367.51	54%
7	6.62	2.51	53%	289.85	1367.51	54%
8	6.62	2.51	53%	289.85	1367.51	54%
9	6.62	2.51	53%	289.85	1367.51	54%
10	6.62	2.51	53%	289.85	1367.51	54%
11	6.62	2.51	53%	289.85	1367.51	54%
12	9.05	3.44	100%	398.00	1367.51	51%
13	9.05	3.44	100%	398.00	1367.51	51%
14	9.05	3.44	100%	398.00	1367.51	51%
15	9.05	3.44	100%	398.00	1367.51	51%
16	1.64	0.62	100%	398.00	248.17	51%
17	1.64	0.62	100%	398.00	248.17	51%
18	1.64	0.62	100%	398.00	248.17	51%
19	1.64	0.62	100%	398.00	248.17	51%
20	1.64	0.62	100%	398.00	248.17	51%
21	1.64	0.62	100%	398.00	248.17	51%
22	1.64	0.62	100%	398.00	248.17	51%
23	1.64	0.62	100%	398.00	248.17	51%
24	1.64	0.62	100%	398.00	248.17	51%
25	1.64	0.62	100%	398.00	248.17	51%
26	1.64	0.62	100%	398.00	248.17	51%
27	1.64	0.62	100%	398.00	248.17	51%
28	1.64	0.62	100%	398.00	248.17	51%
29	1.64	0.62	100%	398.00	248.17	51%
30	1.64	0.62	100%	398.00	248.17	51%
31	1.64	0.62	100%	398.00	248.17	51%
32	1.64	0.62	100%	398.00	248.17	51%
33	1.64	0.62	100%	398.00	248.17	51%
34	1.64	0.62	100%	398.00	248.17	51%
35	1.64	0.62	100%	398.00	248.17	51%
36	1.64	0.62	100%	398.00	248.17	51%
37	1.64	0.62	100%	398.00	248.17	51%
38	1.64	0.62	100%	398.00	248.17	51%
39	1.64	0.62	100%	398.00	248.17	51%
40	1.64	0.62	100%	398.00	248.17	51%
41	9.05	3.44	100%	398.00	1367.51	51%
42	9.05	3.44	100%	398.00	1367.51	51%
43	9.05	3.44	100%	398.00	1367.51	51%
44	9.05	3.44	100%	398.00	1367.51	51%
45	9.05	3.44	100%	398.00	1367.51	51%
46	6.62	2.51	53%	289.85	1367.51	54%
47	6.62	2.51	53%	289.85	1367.51	54%
48	6.62	2.51	53%	289.85	1367.51	54%
49	6.62	2.51	53%	289.85	1367.51	54%
50	6.62	2.51	53%	289.85	1367.51	54%
51	6.62	2.51	53%	289.85	1367.51	54%
52	6.62	2.51	53%	289.85	1367.51	54%
Total	241.65	91.70			43126.96	

Week	Biogas Output (m3)	Hourly Biogas Output (m3/hr)	CO2 output (m3)	CH4 Weight (t)	CO2 Weight (t)	Biogas Weight (t)	Digestate Weight (t)
1	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
2	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
3	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
4	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
5	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
6	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
7	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
8	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
9	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
10	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
11	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
12	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
13	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
14	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
15	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
16	484.71	2.89	236.54	0.18	0.47	0.65	1.68
17	484.71	2.89	236.54	0.18	0.47	0.65	1.68
18	484.71	2.89	236.54	0.18	0.47	0.65	1.68
19	484.71	2.89	236.54	0.18	0.47	0.65	1.68
20	484.71	2.89	236.54	0.18	0.47	0.65	1.68
21	484.71	2.89	236.54	0.18	0.47	0.65	1.68
22	484.71	2.89	236.54	0.18	0.47	0.65	1.68
23	484.71	2.89	236.54	0.18	0.47	0.65	1.68
24	484.71	2.89	236.54	0.18	0.47	0.65	1.68
25	484.71	2.89	236.54	0.18	0.47	0.65	1.68
26	484.71	2.89	236.54	0.18	0.47	0.65	1.68
27	484.71	2.89	236.54	0.18	0.47	0.65	1.68
28	484.71	2.89	236.54	0.18	0.47	0.65	1.68
29	484.71	2.89	236.54	0.18	0.47	0.65	1.68
30	484.71	2.89	236.54	0.18	0.47	0.65	1.68
31	484.71	2.89	236.54	0.18	0.47	0.65	1.68
32	484.71	2.89	236.54	0.18	0.47	0.65	1.68
33	484.71	2.89	236.54	0.18	0.47	0.65	1.68
34	484.71	2.89	236.54	0.18	0.47	0.65	1.68
35	484.71	2.89	236.54	0.18	0.47	0.65	1.68
36	484.71	2.89	236.54	0.18	0.47	0.65	1.68
37	484.71	2.89	236.54	0.18	0.47	0.65	1.68
38	484.71	2.89	236.54	0.18	0.47	0.65	1.68
39	484.71	2.89	236.54	0.18	0.47	0.65	1.68
40	484.71	2.89	236.54	0.18	0.47	0.65	1.68
41	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
42	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
43	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
44	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
45	2670.91	15.90	1303.40	0.98	2.58	3.56	9.24
46	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
47	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
48	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
49	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
50	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
51	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
52	2512.06	14.95	1144.55	0.98	2.26	3.25	39.11
Total	81372.94		38245.98	30.95	75.64	106.59	829.05

Week	Digestate Water (t)	Digestate Solids (t)	Liquid Digestate (t)	Liquid Digestate TS (t)	Liquid Digestate TS (%)	Solid Digestate (t)
1	36.73	2.38	35.20	1.24	4%	3.91
2	36.73	2.38	35.20	1.24	4%	3.91
3	36.73	2.38	35.20	1.24	4%	3.91
4	36.73	2.38	35.20	1.24	4%	3.91
5	36.73	2.38	35.20	1.24	4%	3.91
6	36.73	2.38	35.20	1.24	4%	3.91
7	36.73	2.38	35.20	1.24	4%	3.91
8	36.73	2.38	35.20	1.24	4%	3.91
9	36.73	2.38	35.20	1.24	4%	3.91
10	36.73	2.38	35.20	1.24	4%	3.91
11	36.73	2.38	35.20	1.24	4%	3.91
12	9.05	0.19	8.32	0.10	1%	0.92
13	9.05	0.19	8.32	0.10	1%	0.92
14	9.05	0.19	8.32	0.10	1%	0.92
15	9.05	0.19	8.32	0.10	1%	0.92
16	1.64	0.03	1.51	0.02	1%	0.17
17	1.64	0.03	1.51	0.02	1%	0.17
18	1.64	0.03	1.51	0.02	1%	0.17
19	1.64	0.03	1.51	0.02	1%	0.17
20	1.64	0.03	1.51	0.02	1%	0.17
21	1.64	0.03	1.51	0.02	1%	0.17
22	1.64	0.03	1.51	0.02	1%	0.17
23	1.64	0.03	1.51	0.02	1%	0.17
24	1.64	0.03	1.51	0.02	1%	0.17
25	1.64	0.03	1.51	0.02	1%	0.17
26	1.64	0.03	1.51	0.02	1%	0.17
27	1.64	0.03	1.51	0.02	1%	0.17
28	1.64	0.03	1.51	0.02	1%	0.17
29	1.64	0.03	1.51	0.02	1%	0.17
30	1.64	0.03	1.51	0.02	1%	0.17
31	1.64	0.03	1.51	0.02	1%	0.17
32	1.64	0.03	1.51	0.02	1%	0.17
33	1.64	0.03	1.51	0.02	1%	0.17
34	1.64	0.03	1.51	0.02	1%	0.17
35	1.64	0.03	1.51	0.02	1%	0.17
36	1.64	0.03	1.51	0.02	1%	0.17
37	1.64	0.03	1.51	0.02	1%	0.17
38	1.64	0.03	1.51	0.02	1%	0.17
39	1.64	0.03	1.51	0.02	1%	0.17
40	1.64	0.03	1.51	0.02	1%	0.17
41	9.05	0.19	8.32	0.10	1%	0.92
42	9.05	0.19	8.32	0.10	1%	0.92
43	9.05	0.19	8.32	0.10	1%	0.92
44	9.05	0.19	8.32	0.10	1%	0.92
45	9.05	0.19	8.32	0.10	1%	0.92
46	36.73	2.38	35.20	1.24	4%	3.91
47	36.73	2.38	35.20	1.24	4%	3.91
48	36.73	2.38	35.20	1.24	4%	3.91
49	36.73	2.38	35.20	1.24	4%	3.91
50	36.73	2.38	35.20	1.24	4%	3.91
51	36.73	2.38	35.20	1.24	4%	3.91
52	36.73	2.38	35.20	1.24	4%	3.91
Total			746.15	23.55		82.91

Week	Solid Digestate TS (t)	Solid Digestate TS (%)	Liquid digestate bank (t)	Liquid Digestate Bank Solids (t)
1	1.14	29%	335.59	10.51
2	1.14	29%	370.78	11.75
3	1.14	29%	405.98	12.99
4	1.14	29%	441.18	14.22
5	1.14	29%	476.37	15.46
6	1.14	29%	262.85	8.58
7	1.14	29%	298.05	9.81
8	1.14	29%	333.25	11.05
9	1.14	29%	368.45	12.28
10	1.14	29%	403.64	13.52
11	1.14	29%	438.84	14.75
12	0.09	10%	198.44	6.46
13	0.09	10%	206.76	6.56
14	0.09	10%	215.08	6.66
15	0.09	10%	223.40	6.75
16	0.02	10%	224.91	6.77
17	0.02	10%	226.41	6.79
18	0.02	10%	227.92	6.81
19	0.02	10%	229.43	6.82
20	0.02	10%	230.94	6.84
21	0.02	10%	232.45	6.86
22	0.02	10%	233.96	6.88
23	0.02	10%	235.47	6.90
24	0.02	10%	236.98	6.91
25	0.02	10%	238.49	6.93
26	0.02	10%	240.00	6.95
27	0.02	10%	241.51	6.97
28	0.02	10%	243.02	6.98
29	0.02	10%	244.53	7.00
30	0.02	10%	246.04	7.02
31	0.02	10%	247.55	7.04
32	0.02	10%	249.06	7.05
33	0.02	10%	250.57	7.07
34	0.02	10%	252.08	7.09
35	0.02	10%	253.59	7.11
36	0.02	10%	255.10	7.13
37	0.02	10%	256.61	7.14
38	0.02	10%	9.40	0.11
39	0.02	10%	10.91	0.13
40	0.02	10%	12.42	0.15
41	0.09	10%	20.74	0.24
42	0.09	10%	29.05	0.34
43	0.09	10%	37.37	0.44
44	0.09	10%	45.69	0.54
45	0.09	10%	54.01	0.63
46	1.14	29%	89.21	1.87
47	1.14	29%	124.40	3.10
48	1.14	29%	159.60	4.34
49	1.14	29%	194.80	5.57
50	1.14	29%	229.99	6.81
51	1.14	29%	265.19	8.04
52	1.14	29%	300.39	9.28
Total	21.83			

Week	TS content of digester input (%)	Liquid digestate recirculated (t)	Liquid digestate TS recirculated (t)	Flow Rate (m3/day)
1	13%	6.12	0.19	6.92
2	13%	6.15	0.19	6.93
3	13%	6.17	0.20	6.93
4	13%	6.18	0.20	6.93
5	13%	6.20	0.20	6.94
6	13%	6.21	0.20	6.94
7	13%	6.23	0.21	6.94
8	13%	6.25	0.21	6.94
9	13%	6.26	0.21	6.95
10	13%	6.27	0.21	6.95
11	13%	6.28	0.21	6.95
12	29%	25.28	0.82	5.44
13	29%	25.04	0.79	5.41
14	29%	24.83	0.77	5.38
15	29%	24.63	0.74	5.35
16	29%	4.46	0.13	0.97
17	29%	4.46	0.13	0.97
18	29%	4.45	0.13	0.97
19	29%	4.45	0.13	0.97
20	29%	4.44	0.13	0.97
21	29%	4.43	0.13	0.97
22	29%	4.43	0.13	0.96
23	29%	4.42	0.13	0.96
24	29%	4.42	0.13	0.96
25	29%	4.41	0.13	0.96
26	29%	4.41	0.13	0.96
27	29%	4.40	0.13	0.96
28	29%	4.40	0.13	0.96
29	29%	4.39	0.13	0.96
30	29%	4.39	0.13	0.96
31	29%	4.38	0.12	0.96
32	29%	4.38	0.12	0.96
33	29%	4.37	0.12	0.96
34	29%	4.37	0.12	0.96
35	29%	4.36	0.12	0.96
36	29%	4.36	0.12	0.95
37	29%	4.35	0.12	0.95
38	29%	3.71	0.04	0.86
39	29%	3.71	0.04	0.86
40	29%	3.71	0.04	0.86
41	29%	20.42	0.24	4.75
42	29%	20.42	0.24	4.75
43	29%	20.42	0.24	4.75
44	29%	20.42	0.24	4.75
45	29%	20.42	0.24	4.75
46	13%	5.48	0.11	6.83
47	13%	5.71	0.14	6.87
48	13%	5.85	0.16	6.89
49	13%	5.94	0.17	6.90
50	13%	6.00	0.18	6.91
51	13%	6.05	0.18	6.92
52	13%	6.09	0.19	6.92
Total		419.36		

Week	Liquid Digestate Bank TS (%)	Solid digestate bank (t)	Solid Digestate Bank Solids (t)	Solid Digestate Bank TS (%)
1	3%	36.24	9.64	27%
2	3%	40.15	10.79	27%
3	3%	44.06	11.93	27%
4	3%	47.98	13.08	27%
5	3%	51.89	14.22	27%
6	3%	28.16	7.76	28%
7	3%	32.07	8.90	28%
8	3%	35.98	10.05	28%
9	3%	39.89	11.19	28%
10	3%	43.80	12.34	28%
11	3%	47.72	13.48	28%
12	3%	21.00	5.74	27%
13	3%	21.93	5.83	27%
14	3%	22.85	5.92	26%
15	3%	23.78	6.01	25%
16	3%	23.95	6.03	25%
17	3%	24.11	6.05	25%
18	3%	24.28	6.06	25%
19	3%	24.45	6.08	25%
20	3%	24.62	6.09	25%
21	3%	24.78	6.11	25%
22	3%	24.95	6.13	25%
23	3%	25.12	6.14	24%
24	3%	25.29	6.16	24%
25	3%	25.45	6.18	24%
26	3%	25.62	6.19	24%
27	3%	25.79	6.21	24%
28	3%	25.96	6.23	24%
29	3%	26.13	6.24	24%
30	3%	26.29	6.26	24%
31	3%	26.46	6.27	24%
32	3%	26.63	6.29	24%
33	3%	26.80	6.31	24%
34	3%	26.96	6.32	23%
35	3%	27.13	6.34	23%
36	3%	27.30	6.36	23%
37	3%	27.47	6.37	23%
38	1%	0.00	0.00	#N/A
39	1%	0.17	0.02	10%
40	1%	0.34	0.03	10%
41	1%	1.26	0.12	10%
42	1%	2.18	0.21	10%
43	1%	3.11	0.30	10%
44	1%	4.03	0.39	10%
45	1%	4.96	0.48	10%
46	2%	8.87	1.63	18%
47	2%	12.78	2.77	22%
48	3%	16.69	3.92	23%
49	3%	20.60	5.06	25%
50	3%	24.51	6.21	25%
51	3%	28.42	7.35	26%
52	3%	32.33	8.50	26%
Total				

Week	Digester Volume Calculation (m3)	Substrate Conentration (kg VS/m3)	OLR for Max Dig Vol (kg VS/m3 day)	HRT (days)	TS content (with recirc.) (%)
1	276.99	97.33	2.43	40	12%
2	277.14	97.28	2.43	40	12%
3	277.25	97.24	2.43	40	12%
4	277.35	97.20	2.43	40	12%
5	277.44	97.17	2.43	40	12%
6	277.51	97.15	2.43	40	12%
7	277.63	97.11	2.43	40	12%
8	277.73	97.07	2.43	40	12%
9	277.80	97.05	2.43	40	12%
10	277.87	97.03	2.43	40	12%
11	277.92	97.01	2.43	40	12%
12	217.63	90.22	1.77	51	12%
13	216.26	90.79	1.77	51	12%
14	215.02	91.31	1.77	52	12%
15	213.89	91.80	1.77	52	12%
16	38.78	91.88	0.32	287	12%
17	38.75	91.96	0.32	287	12%
18	38.71	92.04	0.32	287	12%
19	38.68	92.12	0.32	287	12%
20	38.64	92.20	0.32	288	12%
21	38.61	92.28	0.32	288	12%
22	38.58	92.36	0.32	288	12%
23	38.55	92.43	0.32	288	12%
24	38.52	92.51	0.32	289	12%
25	38.49	92.58	0.32	289	12%
26	38.46	92.65	0.32	289	12%
27	38.43	92.73	0.32	289	12%
28	38.40	92.80	0.32	290	12%
29	38.37	92.87	0.32	290	12%
30	38.34	92.94	0.32	290	12%
31	38.31	93.00	0.32	290	12%
32	38.28	93.07	0.32	290	12%
33	38.26	93.14	0.32	291	12%
34	38.23	93.20	0.32	291	12%
35	38.20	93.27	0.32	291	12%
36	38.18	93.33	0.32	291	12%
37	38.15	93.39	0.32	291	12%
38	34.45	103.43	0.32	323	12%
39	34.45	103.43	0.32	323	12%
40	34.45	103.43	0.32	323	12%
41	189.82	103.43	1.77	59	12%
42	189.82	103.43	1.77	59	12%
43	189.82	103.43	1.77	59	12%
44	189.82	103.43	1.77	59	12%
45	189.82	103.43	1.77	59	12%
46	273.33	98.64	2.43	41	12%
47	274.64	98.16	2.43	40	12%
48	275.43	97.88	2.43	40	12%
49	275.95	97.70	2.43	40	12%
50	276.33	97.57	2.43	40	12%
51	276.61	97.47	2.43	40	12%
52	276.82	97.39	2.43	40	12%
Total					

Scenario ZG-S

Week	Slurry fed to digester (twwt)	Slurry water content in digester (t)	Slurry VS fed to digester (tVS)	Silage fed to digester (twwt)
1	33.00	30.11	2.21	3.42
2	33.00	30.11	2.21	3.42
3	33.00	30.11	2.21	3.42
4	33.00	30.11	2.21	3.42
5	33.00	30.11	2.21	3.42
6	33.00	30.11	2.21	3.42
7	33.00	30.11	2.21	3.42
8	33.00	30.11	2.21	3.42
9	33.00	30.11	2.21	3.42
10	33.00	30.11	2.21	8.88
11	33.00	30.11	2.21	8.88
12	33.00	30.11	2.21	8.88
13	33.00	30.11	2.21	8.88
14	33.00	30.11	2.21	8.88
15	33.00	30.11	2.21	8.88
16	33.00	30.11	2.21	8.88
17	33.00	30.11	2.21	8.88
18	33.00	30.11	2.21	8.88
19	33.00	30.11	2.21	8.88
20	33.00	30.11	2.21	8.88
21	33.00	30.11	2.21	8.88
22	33.00	30.11	2.21	8.88
23	33.00	30.11	2.21	8.88
24	33.00	30.11	2.21	8.88
25	33.00	30.11	2.21	8.88
26	33.00	30.11	2.21	8.88
27	33.00	30.11	2.21	8.88
28	33.00	30.11	2.21	8.88
29	33.00	30.11	2.21	8.88
30	33.00	30.11	2.21	8.88
31	33.00	30.11	2.21	8.88
32	33.00	30.11	2.21	8.88
33	33.00	30.11	2.21	8.88
34	33.00	30.11	2.21	8.88
35	33.00	30.11	2.21	8.88
36	33.00	30.11	2.21	8.88
37	33.00	30.11	2.21	8.88
38	33.00	30.11	2.21	8.88
39	33.00	30.11	2.21	8.88
40	33.00	30.11	2.21	3.42
41	33.00	30.11	2.21	3.42
42	33.00	30.11	2.21	3.42
43	33.00	30.11	2.21	3.42
44	33.00	30.11	2.21	3.42
45	33.00	30.11	2.21	3.42
46	33.00	30.11	2.21	3.42
47	33.00	30.11	2.21	3.42
48	33.00	30.11	2.21	3.42
49	33.00	30.11	2.21	3.42
50	33.00	30.11	2.21	3.42
51	33.00	30.11	2.21	3.42
52	33.00	30.11	2.21	3.42
Total	1716.00	1565.85	114.80	341.65

Week	Silage water content in digester (t)	Grass VS fed to digester (tVS)	G:S VS% (%)	SMY (m3 CH4 t-1 VS)	CH4 output (m3)	CH4 v/v (%)
1	2.42	0.92	29%	217.16	678.56	55%
2	2.42	0.92	29%	217.16	678.56	55%
3	2.42	0.92	29%	217.16	678.56	55%
4	2.42	0.92	29%	217.16	678.56	55%
5	2.42	0.92	29%	217.16	678.56	55%
6	2.42	0.92	29%	217.16	678.56	55%
7	2.42	0.92	29%	217.16	678.56	55%
8	2.42	0.92	29%	217.16	678.56	55%
9	2.42	0.92	29%	217.16	678.56	55%
10	6.28	2.38	52%	284.90	1308.20	54%
11	6.28	2.38	52%	284.90	1308.20	54%
12	6.28	2.38	52%	284.90	1308.20	54%
13	6.28	2.38	52%	284.90	1308.20	54%
14	6.28	2.38	52%	284.90	1308.20	54%
15	6.28	2.38	52%	284.90	1308.20	54%
16	6.28	2.38	52%	284.90	1308.20	54%
17	6.28	2.38	52%	284.90	1308.20	54%
18	6.28	2.38	52%	284.90	1308.20	54%
19	6.28	2.38	52%	284.90	1308.20	54%
20	6.28	2.38	52%	284.90	1308.20	54%
21	6.28	2.38	52%	284.90	1308.20	54%
22	6.28	2.38	52%	284.90	1308.20	54%
23	6.28	2.38	52%	284.90	1308.20	54%
24	6.28	2.38	52%	284.90	1308.20	54%
25	6.28	2.38	52%	284.90	1308.20	54%
26	6.28	2.38	52%	284.90	1308.20	54%
27	6.28	2.38	52%	284.90	1308.20	54%
28	6.28	2.38	52%	284.90	1308.20	54%
29	6.28	2.38	52%	284.90	1308.20	54%
30	6.28	2.38	52%	284.90	1308.20	54%
31	6.28	2.38	52%	284.90	1308.20	54%
32	6.28	2.38	52%	284.90	1308.20	54%
33	6.28	2.38	52%	284.90	1308.20	54%
34	6.28	2.38	52%	284.90	1308.20	54%
35	6.28	2.38	52%	284.90	1308.20	54%
36	6.28	2.38	52%	284.90	1308.20	54%
37	6.28	2.38	52%	284.90	1308.20	54%
38	6.28	2.38	52%	284.90	1308.20	54%
39	6.28	2.38	52%	284.90	1308.20	54%
40	2.42	0.92	29%	217.16	678.56	55%
41	2.42	0.92	29%	217.16	678.56	55%
42	2.42	0.92	29%	217.16	678.56	55%
43	2.42	0.92	29%	217.16	678.56	55%
44	2.42	0.92	29%	217.16	678.56	55%
45	2.42	0.92	29%	217.16	678.56	55%
46	2.42	0.92	29%	217.16	678.56	55%
47	2.42	0.92	29%	217.16	678.56	55%
48	2.42	0.92	29%	217.16	678.56	55%
49	2.42	0.92	29%	217.16	678.56	55%
50	2.42	0.92	29%	217.16	678.56	55%
51	2.42	0.92	29%	217.16	678.56	55%
52	2.42	0.92	29%	217.16	678.56	55%
Total	241.65	91.70			54174.34	

Week	Biogas Output (m3)	Hourly Biogas Output (m3/hr)	CO2 output (m3)	CH4 Weight (t)	CO2 Weight (t)	Biogas Weight (t)	Digestate Weight (t)
1	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
2	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
3	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
4	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
5	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
6	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
7	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
8	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
9	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
10	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
11	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
12	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
13	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
14	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
15	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
16	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
17	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
18	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
19	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
20	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
21	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
22	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
23	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
24	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
25	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
26	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
27	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
28	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
29	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
30	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
31	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
32	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
33	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
34	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
35	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
36	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
37	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
38	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
39	2401.13	14.29	1092.93	0.94	2.16	3.10	38.78
40	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
41	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
42	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
43	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
44	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
45	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
46	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
47	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
48	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
49	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
50	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
51	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
52	1238.39	7.37	559.83	0.49	1.11	1.59	34.82
Total	99278.55		45104.21	38.88	89.21	128.08	1929.56

Week	Digestate Water (t)	Digestate Solids (t)	Liquid Digestate (t)	Liquid Digestate TS (t)	Liquid Digestate TS (%)	Solid Digestate (t)
1	32.53	2.29	31.34	1.19	4%	3.48
2	32.53	2.29	31.34	1.19	4%	3.48
3	32.53	2.29	31.34	1.19	4%	3.48
4	32.53	2.29	31.34	1.19	4%	3.48
5	32.53	2.29	31.34	1.19	4%	3.48
6	32.53	2.29	31.34	1.19	4%	3.48
7	32.53	2.29	31.34	1.19	4%	3.48
8	32.53	2.29	31.34	1.19	4%	3.48
9	32.53	2.29	31.34	1.19	4%	3.48
10	36.40	2.39	34.90	1.24	4%	3.88
11	36.40	2.39	34.90	1.24	4%	3.88
12	36.40	2.39	34.90	1.24	4%	3.88
13	36.40	2.39	34.90	1.24	4%	3.88
14	36.40	2.39	34.90	1.24	4%	3.88
15	36.40	2.39	34.90	1.24	4%	3.88
16	36.40	2.39	34.90	1.24	4%	3.88
17	36.40	2.39	34.90	1.24	4%	3.88
18	36.40	2.39	34.90	1.24	4%	3.88
19	36.40	2.39	34.90	1.24	4%	3.88
20	36.40	2.39	34.90	1.24	4%	3.88
21	36.40	2.39	34.90	1.24	4%	3.88
22	36.40	2.39	34.90	1.24	4%	3.88
23	36.40	2.39	34.90	1.24	4%	3.88
24	36.40	2.39	34.90	1.24	4%	3.88
25	36.40	2.39	34.90	1.24	4%	3.88
26	36.40	2.39	34.90	1.24	4%	3.88
27	36.40	2.39	34.90	1.24	4%	3.88
28	36.40	2.39	34.90	1.24	4%	3.88
29	36.40	2.39	34.90	1.24	4%	3.88
30	36.40	2.39	34.90	1.24	4%	3.88
31	36.40	2.39	34.90	1.24	4%	3.88
32	36.40	2.39	34.90	1.24	4%	3.88
33	36.40	2.39	34.90	1.24	4%	3.88
34	36.40	2.39	34.90	1.24	4%	3.88
35	36.40	2.39	34.90	1.24	4%	3.88
36	36.40	2.39	34.90	1.24	4%	3.88
37	36.40	2.39	34.90	1.24	4%	3.88
38	36.40	2.39	34.90	1.24	4%	3.88
39	36.40	2.39	34.90	1.24	4%	3.88
40	32.53	2.29	31.34	1.19	4%	3.48
41	32.53	2.29	31.34	1.19	4%	3.48
42	32.53	2.29	31.34	1.19	4%	3.48
43	32.53	2.29	31.34	1.19	4%	3.48
44	32.53	2.29	31.34	1.19	4%	3.48
45	32.53	2.29	31.34	1.19	4%	3.48
46	32.53	2.29	31.34	1.19	4%	3.48
47	32.53	2.29	31.34	1.19	4%	3.48
48	32.53	2.29	31.34	1.19	4%	3.48
49	32.53	2.29	31.34	1.19	4%	3.48
50	32.53	2.29	31.34	1.19	4%	3.48
51	32.53	2.29	31.34	1.19	4%	3.48
52	32.53	2.29	31.34	1.19	4%	3.48
Total			1736.61	63.35		192.96

Week	Solid Digestate TS (t)	Solid Digestate TS (%)	Liquid digestate bank (t)	Liquid Digestate Bank Solids (t)
1	1.10	32%	807.83	29.76
2	1.10	32%	839.17	30.95
3	1.10	32%	870.51	32.14
4	1.10	32%	901.85	33.33
5	1.10	32%	933.19	34.52
6	1.10	32%	385.66	14.28
7	1.10	32%	417.00	15.47
8	1.10	32%	448.34	16.66
9	1.10	32%	479.68	17.85
10	1.15	30%	514.58	19.09
11	1.15	30%	549.49	20.33
12	1.15	30%	5.52	0.20
13	1.15	30%	40.43	1.43
14	1.15	30%	75.33	2.67
15	1.15	30%	110.23	3.91
16	1.15	30%	145.14	5.15
17	1.15	30%	180.04	6.39
18	1.15	30%	214.95	7.63
19	1.15	30%	249.85	8.87
20	1.15	30%	284.76	10.11
21	1.15	30%	319.66	11.35
22	1.15	30%	354.56	12.58
23	1.15	30%	389.47	13.82
24	1.15	30%	424.37	15.06
25	1.15	30%	459.28	16.30
26	1.15	30%	494.18	17.54
27	1.15	30%	529.08	18.78
28	1.15	30%	563.99	20.02
29	1.15	30%	598.89	21.26
30	1.15	30%	633.80	22.50
31	1.15	30%	668.70	23.74
32	1.15	30%	703.61	24.97
33	1.15	30%	738.51	26.21
34	1.15	30%	773.41	27.45
35	1.15	30%	808.32	28.69
36	1.15	30%	843.22	29.93
37	1.15	30%	878.13	31.17
38	1.15	30%	334.16	11.86
39	1.15	30%	369.07	13.10
40	1.10	32%	400.41	14.29
41	1.10	32%	431.75	15.48
42	1.10	32%	463.09	16.67
43	1.10	32%	494.43	17.86
44	1.10	32%	525.77	19.05
45	1.10	32%	557.11	20.24
46	1.10	32%	588.45	21.43
47	1.10	32%	619.79	22.62
48	1.10	32%	651.13	23.81
49	1.10	32%	682.47	25.00
50	1.10	32%	713.81	26.19
51	1.10	32%	745.15	27.38
52	1.10	32%	776.49	28.57
Total	58.71			

Week	TS content of digester input (%)	Liquid digestate recirculated (t)	Liquid digestate TS recirculated (t)	Flow Rate (m3/day)
1	11%	0.00	0.00	5.20
2	11%	0.00	0.00	5.20
3	11%	0.00	0.00	5.20
4	11%	0.00	0.00	5.20
5	11%	0.00	0.00	5.20
6	11%	0.00	0.00	5.20
7	11%	0.00	0.00	5.20
8	11%	0.00	0.00	5.20
9	11%	0.00	0.00	5.20
10	13%	5.57	0.21	6.78
11	13%	5.56	0.21	6.78
12	13%	5.46	0.19	6.76
13	13%	5.46	0.19	6.76
14	13%	5.46	0.19	6.76
15	13%	5.46	0.19	6.76
16	13%	5.46	0.19	6.76
17	13%	5.46	0.19	6.76
18	13%	5.46	0.19	6.76
19	13%	5.46	0.19	6.76
20	13%	5.46	0.19	6.76
21	13%	5.46	0.19	6.76
22	13%	5.46	0.19	6.76
23	13%	5.46	0.19	6.76
24	13%	5.46	0.19	6.76
25	13%	5.46	0.19	6.76
26	13%	5.46	0.19	6.76
27	13%	5.46	0.19	6.76
28	13%	5.46	0.19	6.76
29	13%	5.46	0.19	6.76
30	13%	5.46	0.19	6.76
31	13%	5.46	0.19	6.76
32	13%	5.46	0.19	6.76
33	13%	5.46	0.19	6.76
34	13%	5.46	0.19	6.76
35	13%	5.46	0.19	6.76
36	13%	5.46	0.19	6.76
37	13%	5.46	0.19	6.76
38	13%	5.46	0.19	6.76
39	13%	5.46	0.19	6.76
40	11%	0.00	0.00	5.20
41	11%	0.00	0.00	5.20
42	11%	0.00	0.00	5.20
43	11%	0.00	0.00	5.20
44	11%	0.00	0.00	5.20
45	11%	0.00	0.00	5.20
46	11%	0.00	0.00	5.20
47	11%	0.00	0.00	5.20
48	11%	0.00	0.00	5.20
49	11%	0.00	0.00	5.20
50	11%	0.00	0.00	5.20
51	11%	0.00	0.00	5.20
52	11%	0.00	0.00	5.20
Total		164.06		

Week	Liquid Digestate Bank TS (%)	Solid digestate bank (t)	Solid Digestate Bank Solids (t)	Solid Digestate Bank TS (%)
1	4%	89.14	27.40	31%
2	4%	92.63	28.51	31%
3	4%	96.11	29.61	31%
4	4%	99.59	30.71	31%
5	4%	103.07	31.81	31%
6	4%	42.24	13.05	31%
7	4%	45.72	14.15	31%
8	4%	49.20	15.25	31%
9	4%	52.68	16.36	31%
10	4%	56.56	17.51	31%
11	4%	60.44	18.65	31%
12	4%	0.00	0.00	#N/A
13	4%	3.88	1.15	30%
14	4%	7.76	2.30	30%
15	4%	11.63	3.44	30%
16	4%	15.51	4.59	30%
17	4%	19.39	5.74	30%
18	4%	23.27	6.89	30%
19	4%	27.15	8.04	30%
20	4%	31.03	9.19	30%
21	4%	34.90	10.33	30%
22	4%	38.78	11.48	30%
23	4%	42.66	12.63	30%
24	4%	46.54	13.78	30%
25	4%	50.42	14.93	30%
26	4%	54.30	16.07	30%
27	4%	58.17	17.22	30%
28	4%	62.05	18.37	30%
29	4%	65.93	19.52	30%
30	4%	69.81	20.67	30%
31	4%	73.69	21.82	30%
32	4%	77.56	22.96	30%
33	4%	81.44	24.11	30%
34	4%	85.32	25.26	30%
35	4%	89.20	26.41	30%
36	4%	93.08	27.56	30%
37	4%	96.96	28.70	30%
38	4%	36.52	10.81	30%
39	4%	40.39	11.96	30%
40	4%	43.88	13.06	30%
41	4%	47.36	14.17	30%
42	4%	50.84	15.27	30%
43	4%	54.32	16.37	30%
44	4%	57.80	17.47	30%
45	4%	61.29	18.58	30%
46	4%	64.77	19.68	30%
47	4%	68.25	20.78	30%
48	4%	71.73	21.89	31%
49	4%	75.22	22.99	31%
50	4%	78.70	24.09	31%
51	4%	82.18	25.20	31%
52	4%	85.66	26.30	31%
Total				

Week	Digester Volume Calculation (m3)	Substrate Conentration (kg VS/m3)	OLR for Max Dig Vol (kg VS/m3 day)	HRT (days)	TS content (with recirc.) (%)
1	208.09	85.80	1.65	52	#N/A
2	208.09	85.80	1.65	52	#N/A
3	208.09	85.80	1.65	52	#N/A
4	208.09	85.80	1.65	52	#N/A
5	208.09	85.80	1.65	52	#N/A
6	208.09	85.80	1.65	52	#N/A
7	208.09	85.80	1.65	52	#N/A
8	208.09	85.80	1.65	52	#N/A
9	208.09	85.80	1.65	52	#N/A
10	271.14	96.77	2.42	40	12%
11	271.11	96.79	2.42	40	12%
12	270.54	96.99	2.42	40	12%
13	270.54	96.99	2.42	40	12%
14	270.54	96.99	2.42	40	12%
15	270.54	96.99	2.42	40	12%
16	270.54	96.99	2.42	40	12%
17	270.54	96.99	2.42	40	12%
18	270.54	96.99	2.42	40	12%
19	270.54	96.99	2.42	40	12%
20	270.54	96.99	2.42	40	12%
21	270.54	96.99	2.42	40	12%
22	270.54	96.99	2.42	40	12%
23	270.54	96.99	2.42	40	12%
24	270.54	96.99	2.42	40	12%
25	270.54	96.99	2.42	40	12%
26	270.54	96.99	2.42	40	12%
27	270.54	96.99	2.42	40	12%
28	270.54	96.99	2.42	40	12%
29	270.54	96.99	2.42	40	12%
30	270.54	96.99	2.42	40	12%
31	270.54	96.99	2.42	40	12%
32	270.54	96.99	2.42	40	12%
33	270.54	96.99	2.42	40	12%
34	270.54	96.99	2.42	40	12%
35	270.54	96.99	2.42	40	12%
36	270.54	96.99	2.42	40	12%
37	270.54	96.99	2.42	40	12%
38	270.54	96.99	2.42	40	12%
39	270.54	96.99	2.42	40	12%
40	208.09	85.80	1.65	52	#N/A
41	208.09	85.80	1.65	52	#N/A
42	208.09	85.80	1.65	52	#N/A
43	208.09	85.80	1.65	52	#N/A
44	208.09	85.80	1.65	52	#N/A
45	208.09	85.80	1.65	52	#N/A
46	208.09	85.80	1.65	52	#N/A
47	208.09	85.80	1.65	52	#N/A
48	208.09	85.80	1.65	52	#N/A
49	208.09	85.80	1.65	52	#N/A
50	208.09	85.80	1.65	52	#N/A
51	208.09	85.80	1.65	52	#N/A
52	208.09	85.80	1.65	52	#N/A
Total					

Scenario PB-S

Week	Slurry fed to digester (twwt)	Slurry water content in digester (t)	Slurry VS fed to digester (tVS)	Silage fed to digester (twwt)
1	33.00	30.11	2.21	2.60
2	33.00	30.11	2.21	2.60
3	33.00	30.11	2.21	2.60
4	33.00	30.11	2.21	2.60
5	33.00	30.11	2.21	2.60
6	33.00	30.11	2.21	2.60
7	33.00	30.11	2.21	2.60
8	33.00	30.11	2.21	2.60
9	33.00	30.11	2.21	2.60
10	33.00	30.11	2.21	6.20
11	33.00	30.11	2.21	6.20
12	0.00	0.00	0.00	9.07
13	0.00	0.00	0.00	9.07
14	0.00	0.00	0.00	9.07
15	0.00	0.00	0.00	9.07
16	0.00	0.00	0.00	9.07
17	0.00	0.00	0.00	9.07
18	0.00	0.00	0.00	9.07
19	0.00	0.00	0.00	9.07
20	0.00	0.00	0.00	9.07
21	0.00	0.00	0.00	9.07
22	0.00	0.00	0.00	9.07
23	0.00	0.00	0.00	9.07
24	0.00	0.00	0.00	9.07
25	0.00	0.00	0.00	9.07
26	0.00	0.00	0.00	9.07
27	0.00	0.00	0.00	9.07
28	0.00	0.00	0.00	9.07
29	0.00	0.00	0.00	9.07
30	0.00	0.00	0.00	9.07
31	0.00	0.00	0.00	9.07
32	0.00	0.00	0.00	9.07
33	0.00	0.00	0.00	9.07
34	0.00	0.00	0.00	9.07
35	0.00	0.00	0.00	9.07
36	0.00	0.00	0.00	9.07
37	0.00	0.00	0.00	9.07
38	0.00	0.00	0.00	9.07
39	0.00	0.00	0.00	9.07
40	0.00	0.00	0.00	5.61
41	0.00	0.00	0.00	5.61
42	0.00	0.00	0.00	5.61
43	0.00	0.00	0.00	5.61
44	0.00	0.00	0.00	5.61
45	0.00	0.00	0.00	5.61
46	33.00	30.11	2.21	2.60
47	33.00	30.11	2.21	2.60
48	33.00	30.11	2.21	2.60
49	33.00	30.11	2.21	2.60
50	33.00	30.11	2.21	2.60
51	33.00	30.11	2.21	2.60
52	33.00	30.11	2.21	2.60
Total	594.00	542.03	39.74	341.65

Week	Silage water content in digester (t)	Grass VS fed to digester (tVS)	G:S VS% (%)	SMY (m3 CH4 t-1 VS)	CH4 output (m3)	CH4 v/v (%)
1	1.84	0.70	24%	206.17	598.80	55%
2	1.84	0.70	24%	206.17	598.80	55%
3	1.84	0.70	24%	206.17	598.80	55%
4	1.84	0.70	24%	206.17	598.80	55%
5	1.84	0.70	24%	206.17	598.80	55%
6	1.84	0.70	24%	206.17	598.80	55%
7	1.84	0.70	24%	206.17	598.80	55%
8	1.84	0.70	24%	206.17	598.80	55%
9	1.84	0.70	24%	206.17	598.80	55%
10	4.38	1.66	43%	250.43	969.38	55%
11	4.38	1.66	43%	250.43	969.38	55%
12	6.42	2.44	100%	398.00	969.38	51%
13	6.42	2.44	100%	398.00	969.38	51%
14	6.42	2.44	100%	398.00	969.38	51%
15	6.42	2.44	100%	398.00	969.38	51%
16	6.42	2.44	100%	398.00	969.38	51%
17	6.42	2.44	100%	398.00	969.38	51%
18	6.42	2.44	100%	398.00	969.38	51%
19	6.42	2.44	100%	398.00	969.38	51%
20	6.42	2.44	100%	398.00	969.38	51%
21	6.42	2.44	100%	398.00	969.38	51%
22	6.42	2.44	100%	398.00	969.38	51%
23	6.42	2.44	100%	398.00	969.38	51%
24	6.42	2.44	100%	398.00	969.38	51%
25	6.42	2.44	100%	398.00	969.38	51%
26	6.42	2.44	100%	398.00	969.38	51%
27	6.42	2.44	100%	398.00	969.38	51%
28	6.42	2.44	100%	398.00	969.38	51%
29	6.42	2.44	100%	398.00	969.38	51%
30	6.42	2.44	100%	398.00	969.38	51%
31	6.42	2.44	100%	398.00	969.38	51%
32	6.42	2.44	100%	398.00	969.38	51%
33	6.42	2.44	100%	398.00	969.38	51%
34	6.42	2.44	100%	398.00	969.38	51%
35	6.42	2.44	100%	398.00	969.38	51%
36	6.42	2.44	100%	398.00	969.38	51%
37	6.42	2.44	100%	398.00	969.38	51%
38	6.42	2.44	100%	398.00	969.38	51%
39	6.42	2.44	100%	398.00	969.38	51%
40	3.96	1.50	100%	398.00	598.80	51%
41	3.96	1.50	100%	398.00	598.80	51%
42	3.96	1.50	100%	398.00	598.80	51%
43	3.96	1.50	100%	398.00	598.80	51%
44	3.96	1.50	100%	398.00	598.80	51%
45	3.96	1.50	100%	398.00	598.80	51%
46	1.84	0.70	24%	206.17	598.80	55%
47	1.84	0.70	24%	206.17	598.80	55%
48	1.84	0.70	24%	206.17	598.80	55%
49	1.84	0.70	24%	206.17	598.80	55%
50	1.84	0.70	24%	206.17	598.80	55%
51	1.84	0.70	24%	206.17	598.80	55%
52	1.84	0.70	24%	206.17	598.80	55%
Total	241.65	91.70			42255.09	

Week	Biogas Output (m3)	Hourly Biogas Output (m3/hr)	CO2 output (m3)	CH4 Weight (t)	CO2 Weight (t)	Biogas Weight (t)	Digestate Weight (t)
1	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
2	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
3	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
4	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
5	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
6	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
7	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
8	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
9	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
10	1769.07	10.53	799.69	0.70	1.58	2.28	36.92
11	1769.07	10.53	799.69	0.70	1.58	2.28	36.92
12	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
13	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
14	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
15	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
16	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
17	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
18	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
19	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
20	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
21	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
22	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
23	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
24	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
25	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
26	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
27	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
28	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
29	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
30	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
31	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
32	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
33	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
34	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
35	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
36	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
37	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
38	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
39	1893.33	11.27	923.94	0.70	1.83	2.52	6.55
40	1169.53	6.96	570.73	0.43	1.13	1.56	4.05
41	1169.53	6.96	570.73	0.43	1.13	1.56	4.05
42	1169.53	6.96	570.73	0.43	1.13	1.56	4.05
43	1169.53	6.96	570.73	0.43	1.13	1.56	4.05
44	1169.53	6.96	570.73	0.43	1.13	1.56	4.05
45	1169.53	6.96	570.73	0.43	1.13	1.56	4.05
46	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
47	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
48	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
49	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
50	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
51	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
52	1093.90	6.51	495.10	0.43	0.98	1.41	34.19
Total	81070.88		38815.79	30.33	76.77	107.09	828.55

Week	Digestate Water (t)	Digestate Solids (t)	Liquid Digestate (t)	Liquid Digestate TS (t)	Liquid Digestate TS (%)	Solid Digestate (t)
1	31.95	2.24	30.77	1.16	4%	3.42
2	31.95	2.24	30.77	1.16	4%	3.42
3	31.95	2.24	30.77	1.16	4%	3.42
4	31.95	2.24	30.77	1.16	4%	3.42
5	31.95	2.24	30.77	1.16	4%	3.42
6	31.95	2.24	30.77	1.16	4%	3.42
7	31.95	2.24	30.77	1.16	4%	3.42
8	31.95	2.24	30.77	1.16	4%	3.42
9	31.95	2.24	30.77	1.16	4%	3.42
10	34.50	2.42	33.23	1.26	4%	3.69
11	34.50	2.42	33.23	1.26	4%	3.69
12	6.42	0.13	5.90	0.07	1%	0.66
13	6.42	0.13	5.90	0.07	1%	0.66
14	6.42	0.13	5.90	0.07	1%	0.66
15	6.42	0.13	5.90	0.07	1%	0.66
16	6.42	0.13	5.90	0.07	1%	0.66
17	6.42	0.13	5.90	0.07	1%	0.66
18	6.42	0.13	5.90	0.07	1%	0.66
19	6.42	0.13	5.90	0.07	1%	0.66
20	6.42	0.13	5.90	0.07	1%	0.66
21	6.42	0.13	5.90	0.07	1%	0.66
22	6.42	0.13	5.90	0.07	1%	0.66
23	6.42	0.13	5.90	0.07	1%	0.66
24	6.42	0.13	5.90	0.07	1%	0.66
25	6.42	0.13	5.90	0.07	1%	0.66
26	6.42	0.13	5.90	0.07	1%	0.66
27	6.42	0.13	5.90	0.07	1%	0.66
28	6.42	0.13	5.90	0.07	1%	0.66
29	6.42	0.13	5.90	0.07	1%	0.66
30	6.42	0.13	5.90	0.07	1%	0.66
31	6.42	0.13	5.90	0.07	1%	0.66
32	6.42	0.13	5.90	0.07	1%	0.66
33	6.42	0.13	5.90	0.07	1%	0.66
34	6.42	0.13	5.90	0.07	1%	0.66
35	6.42	0.13	5.90	0.07	1%	0.66
36	6.42	0.13	5.90	0.07	1%	0.66
37	6.42	0.13	5.90	0.07	1%	0.66
38	6.42	0.13	5.90	0.07	1%	0.66
39	6.42	0.13	5.90	0.07	1%	0.66
40	3.96	0.08	3.64	0.04	1%	0.40
41	3.96	0.08	3.64	0.04	1%	0.40
42	3.96	0.08	3.64	0.04	1%	0.40
43	3.96	0.08	3.64	0.04	1%	0.40
44	3.96	0.08	3.64	0.04	1%	0.40
45	3.96	0.08	3.64	0.04	1%	0.40
46	31.95	2.24	30.77	1.16	4%	3.42
47	31.95	2.24	30.77	1.16	4%	3.42
48	31.95	2.24	30.77	1.16	4%	3.42
49	31.95	2.24	30.77	1.16	4%	3.42
50	31.95	2.24	30.77	1.16	4%	3.42
51	31.95	2.24	30.77	1.16	4%	3.42
52	31.95	2.24	30.77	1.16	4%	3.42
Total			745.70	23.29		82.86

Week	Solid Digestate TS (t)	Solid Digestate TS (%)	Liquid digestate bank (t)	Liquid Digestate Bank Solids (t)
1	1.08	31%	288.60	9.79
2	1.08	31%	319.37	10.95
3	1.08	31%	350.14	12.11
4	1.08	31%	380.91	13.28
5	1.08	31%	411.68	14.44
6	1.08	31%	193.88	6.84
7	1.08	31%	224.65	8.00
8	1.08	31%	255.41	9.16
9	1.08	31%	286.18	10.32
10	1.17	32%	319.41	11.58
11	1.17	32%	352.64	12.84
12	0.06	10%	109.97	3.83
13	0.06	10%	115.86	3.90
14	0.06	10%	121.76	3.96
15	0.06	10%	127.66	4.03
16	0.06	10%	133.55	4.10
17	0.06	10%	139.45	4.17
18	0.06	10%	145.35	4.24
19	0.06	10%	151.24	4.31
20	0.06	10%	157.14	4.38
21	0.06	10%	163.04	4.45
22	0.06	10%	168.93	4.52
23	0.06	10%	174.83	4.59
24	0.06	10%	180.73	4.66
25	0.06	10%	186.62	4.72
26	0.06	10%	192.52	4.79
27	0.06	10%	198.41	4.86
28	0.06	10%	204.31	4.93
29	0.06	10%	210.21	5.00
30	0.06	10%	216.10	5.07
31	0.06	10%	222.00	5.14
32	0.06	10%	227.90	5.21
33	0.06	10%	233.79	5.28
34	0.06	10%	239.69	5.35
35	0.06	10%	245.59	5.42
36	0.06	10%	251.48	5.48
37	0.06	10%	257.38	5.55
38	0.06	10%	14.71	0.17
39	0.06	10%	20.61	0.24
40	0.04	10%	24.25	0.28
41	0.04	10%	27.89	0.33
42	0.04	10%	31.53	0.37
43	0.04	10%	35.18	0.41
44	0.04	10%	38.82	0.45
45	0.04	10%	42.46	0.50
46	1.08	31%	73.23	1.66
47	1.08	31%	104.00	2.82
48	1.08	31%	134.76	3.98
49	1.08	31%	165.53	5.14
50	1.08	31%	196.30	6.31
51	1.08	31%	227.07	7.47
52	1.08	31%	257.84	8.63
Total	21.59			

Week	Liquid Digestate Bank TS (%)	Solid digestate bank (t)	Solid Digestate Bank Solids (t)	Solid Digestate Bank TS (%)
1	3%	30.43	8.91	29%
2	3%	33.85	9.99	30%
3	3%	37.27	11.07	30%
4	3%	40.69	12.14	30%
5	4%	44.11	13.22	30%
6	4%	19.91	5.99	30%
7	4%	23.33	7.07	30%
8	4%	26.74	8.14	30%
9	4%	30.16	9.22	31%
10	4%	33.86	10.38	31%
11	4%	37.55	11.55	31%
12	3%	10.58	3.10	29%
13	3%	11.24	3.16	28%
14	3%	11.89	3.23	27%
15	3%	12.55	3.29	26%
16	3%	13.20	3.35	25%
17	3%	13.86	3.42	25%
18	3%	14.52	3.48	24%
19	3%	15.17	3.55	23%
20	3%	15.83	3.61	23%
21	3%	16.48	3.67	22%
22	3%	17.14	3.74	22%
23	3%	17.79	3.80	21%
24	3%	18.45	3.87	21%
25	3%	19.10	3.93	21%
26	2%	19.76	3.99	20%
27	2%	20.41	4.06	20%
28	2%	21.07	4.12	20%
29	2%	21.72	4.19	19%
30	2%	22.38	4.25	19%
31	2%	23.03	4.31	19%
32	2%	23.69	4.38	18%
33	2%	24.34	4.44	18%
34	2%	25.00	4.51	18%
35	2%	25.65	4.57	18%
36	2%	26.31	4.63	18%
37	2%	26.96	4.70	17%
38	1%	0.00	0.00	#N/A
39	1%	0.66	0.06	10%
40	1%	1.06	0.10	10%
41	1%	1.46	0.14	10%
42	1%	1.87	0.18	10%
43	1%	2.27	0.22	10%
44	1%	2.68	0.26	10%
45	1%	3.08	0.30	10%
46	2%	6.50	1.38	21%
47	3%	9.92	2.45	25%
48	3%	13.34	3.53	26%
49	3%	16.76	4.61	27%
50	3%	20.18	5.68	28%
51	3%	23.60	6.76	29%
52	3%	27.01	7.84	29%
Total				

Week	TS content of digester input (%)	Liquid digestate recirculated (t)	Liquid digestate TS recirculated (t)	Flow Rate (m3/day)
1	10%	0.00	0.00	5.09
2	10%	0.00	0.00	5.09
3	10%	0.00	0.00	5.09
4	10%	0.00	0.00	5.09
5	10%	0.00	0.00	5.09
6	10%	0.00	0.00	5.09
7	10%	0.00	0.00	5.09
8	10%	0.00	0.00	5.09
9	10%	0.00	0.00	5.09
10	12%	0.00	0.00	5.60
11	12%	0.00	0.00	5.60
12	29%	18.39	0.64	3.92
13	29%	18.14	0.61	3.89
14	29%	17.92	0.58	3.86
15	29%	17.73	0.56	3.83
16	29%	17.55	0.54	3.80
17	29%	17.40	0.52	3.78
18	29%	17.26	0.50	3.76
19	29%	17.13	0.49	3.74
20	29%	17.01	0.47	3.73
21	29%	16.90	0.46	3.71
22	29%	16.80	0.45	3.70
23	29%	16.71	0.44	3.68
24	29%	16.63	0.43	3.67
25	29%	16.55	0.42	3.66
26	29%	16.48	0.41	3.65
27	29%	16.41	0.40	3.64
28	29%	16.35	0.39	3.63
29	29%	16.29	0.39	3.62
30	29%	16.23	0.38	3.62
31	29%	16.18	0.37	3.61
32	29%	16.13	0.37	3.60
33	29%	16.09	0.36	3.59
34	29%	16.04	0.36	3.59
35	29%	16.00	0.35	3.58
36	29%	15.96	0.35	3.58
37	29%	15.92	0.34	3.57
38	29%	14.47	0.17	3.36
39	29%	14.47	0.17	3.36
40	29%	8.94	0.10	2.08
41	29%	8.94	0.10	2.08
42	29%	8.94	0.10	2.08
43	29%	8.94	0.10	2.08
44	29%	8.94	0.10	2.08
45	29%	8.94	0.10	2.08
46	10%	0.00	0.00	5.09
47	10%	0.00	0.00	5.09
48	10%	0.00	0.00	5.09
49	10%	0.00	0.00	5.09
50	10%	0.00	0.00	5.09
51	10%	0.00	0.00	5.09
52	10%	0.00	0.00	5.09
Total		518.81		

Week	Digester Volume Calculation (m3)	Substrate Conentration (kg VS/m3)	OLR for Max Dig Vol (kg VS/m3 day)	HRT (days)	TS content (with recirc.) (%)
1	203.40	81.59	1.85	44	#N/A
2	203.40	81.59	1.85	44	#N/A
3	203.40	81.59	1.85	44	#N/A
4	203.40	81.59	1.85	44	#N/A
5	203.40	81.59	1.85	44	#N/A
6	203.40	81.59	1.85	44	#N/A
7	203.40	81.59	1.85	44	#N/A
8	203.40	81.59	1.85	44	#N/A
9	203.40	81.59	1.85	44	#N/A
10	223.98	98.76	2.47	40	#N/A
11	223.98	98.76	2.47	40	#N/A
12	156.96	88.67	1.55	57	12%
13	155.53	89.49	1.55	58	12%
14	154.27	90.22	1.55	58	12%
15	153.16	90.87	1.55	58	12%
16	152.16	91.47	1.55	59	12%
17	151.27	92.01	1.55	59	12%
18	150.46	92.50	1.55	60	12%
19	149.72	92.96	1.55	60	12%
20	149.06	93.37	1.55	60	12%
21	148.44	93.76	1.55	60	12%
22	147.88	94.12	1.55	61	12%
23	147.36	94.45	1.55	61	12%
24	146.88	94.76	1.55	61	12%
25	146.44	95.04	1.55	61	12%
26	146.02	95.31	1.55	61	12%
27	145.64	95.57	1.55	62	12%
28	145.27	95.80	1.55	62	12%
29	144.94	96.03	1.55	62	12%
30	144.62	96.24	1.55	62	12%
31	144.32	96.44	1.55	62	12%
32	144.04	96.63	1.55	62	12%
33	143.77	96.81	1.55	62	12%
34	143.52	96.97	1.55	62	12%
35	143.28	97.14	1.55	63	12%
36	143.06	97.29	1.55	63	12%
37	142.84	97.43	1.55	63	12%
38	134.56	103.43	1.55	67	12%
39	134.56	103.43	1.55	67	12%
40	83.12	103.43	0.96	108	12%
41	83.12	103.43	0.96	108	12%
42	83.12	103.43	0.96	108	12%
43	83.12	103.43	0.96	108	12%
44	83.12	103.43	0.96	108	12%
45	83.12	103.43	0.96	108	12%
46	203.40	81.59	1.85	44	#N/A
47	203.40	81.59	1.85	44	#N/A
48	203.40	81.59	1.85	44	#N/A
49	203.40	81.59	1.85	44	#N/A
50	203.40	81.59	1.85	44	#N/A
51	203.40	81.59	1.85	44	#N/A
52	203.40	81.59	1.85	44	#N/A
Total					

Appendix B.4

For the solid digestate, gaps in the chart lines represent when the solid digestate bank is fully emptied. The seasonality of slurry directly influences when the digestate banks can be emptied (or can approach empty in the case of the liquid digestate bank). There must be sufficient digestate in the banks by weeks 5, 11 and 37, so that a third of the annual digestate produced can be spread. In the ZG scenarios, the digestate bank may not be fully emptied on week 5 or week 37, as there would not be enough digestate available in the tanks to spread one third of the annual digestate amount on week 11 – therefore the digestate banks must be emptied on week 11. Contrary to this, in the PB scenarios, the digestate banks must be emptied on week 37 to ensure sufficient digestate availability in week 5 and week 11, to allow an even 33% spread at each spreading week. This digestate spreading regime only applies if 33% of the total annual digestate produced must be spread on the weeks mentioned – changes in the spreading dates or the amount spread may change this.

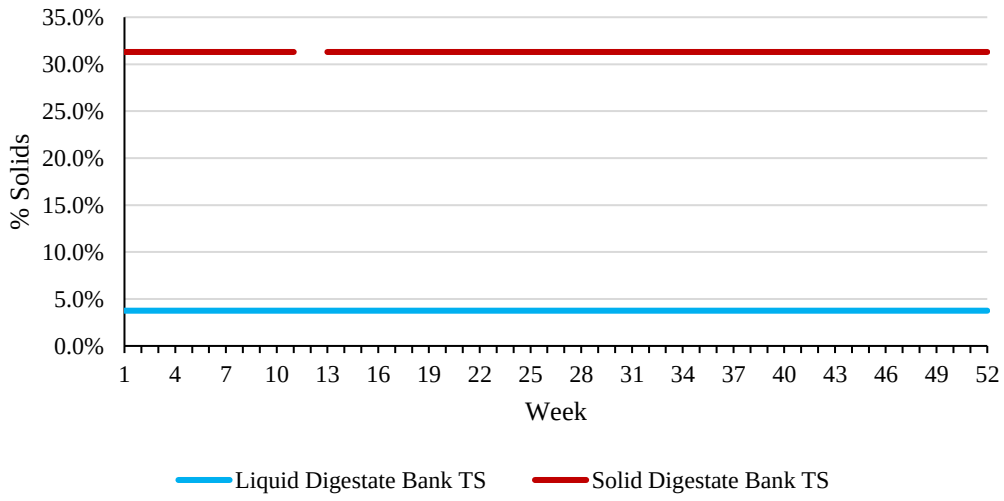


Figure B-1: Scenario ZG-C digestate bank solids content.

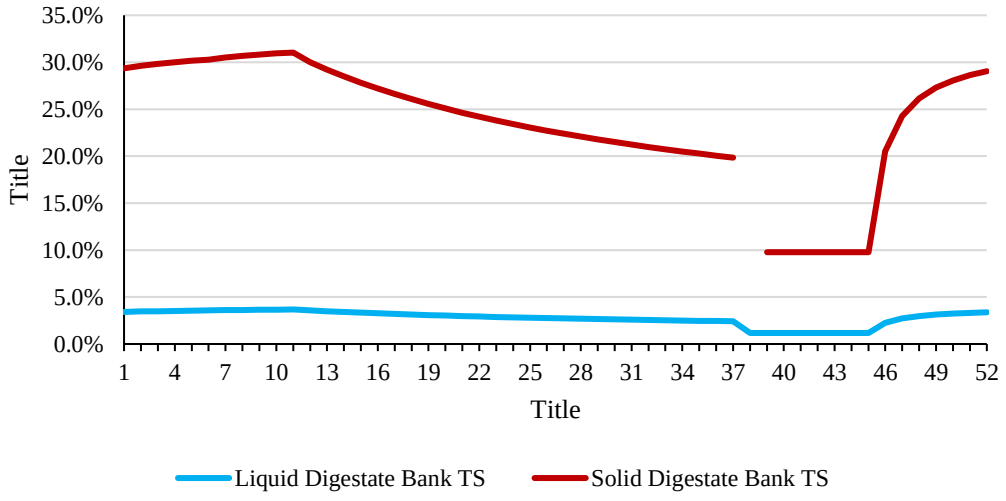


Figure B-2: Scenario PB-C digestate bank solids content.

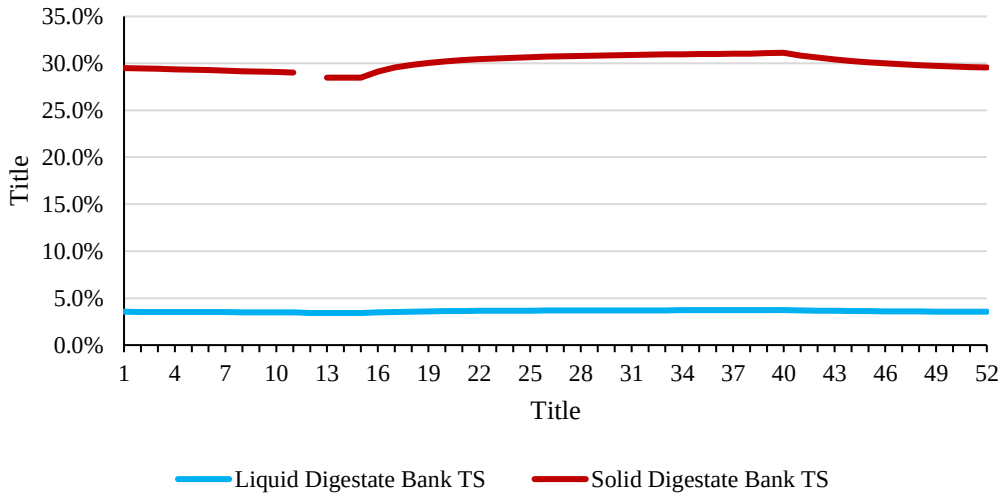


Figure B-3: Scenario ZG-W digestate bank solids content.

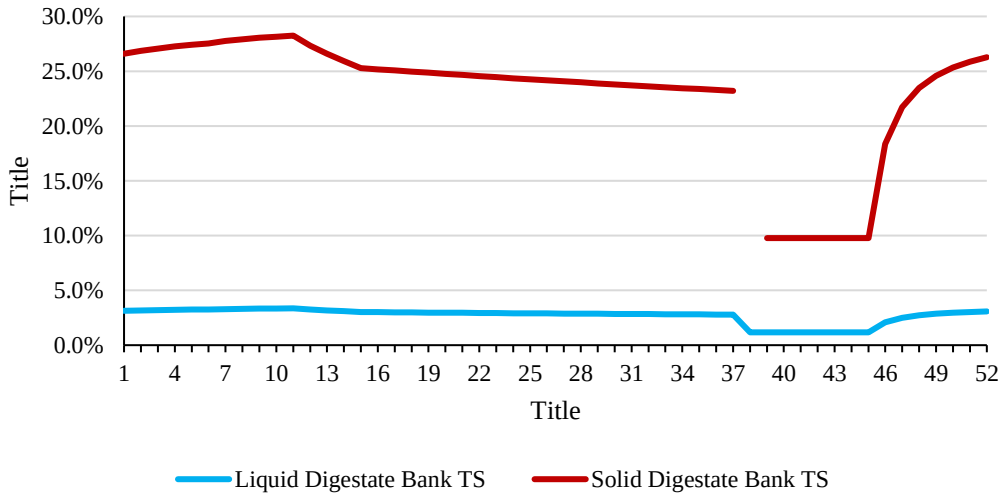


Figure B-4: Scenario PB-W digestate bank solids content.

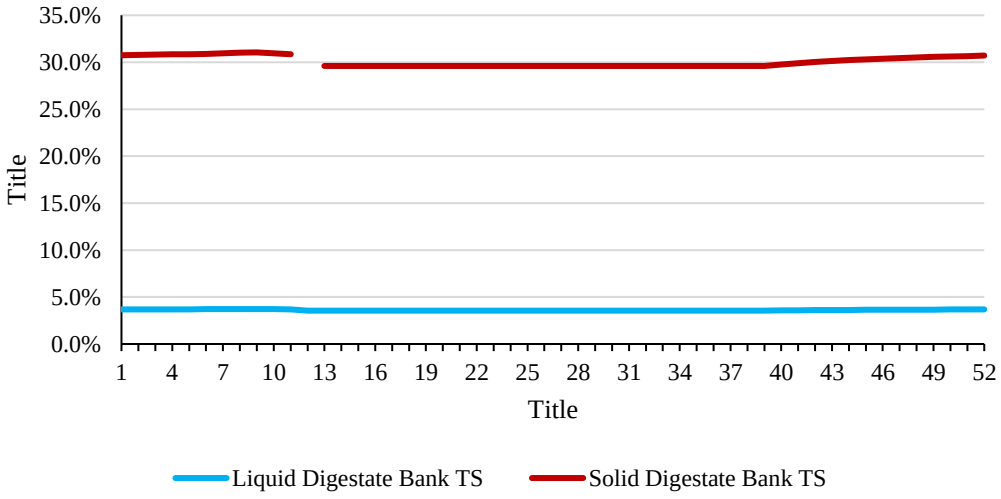


Figure B-5: Scenario ZG-S digestate bank solids content.

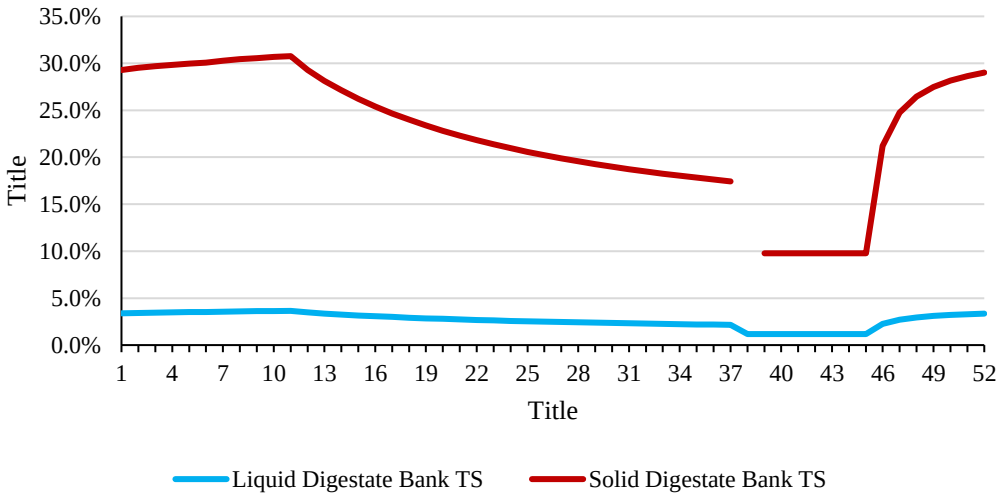


Figure B-6: Scenario PB-S digestate bank solids content.

Appendix B.5

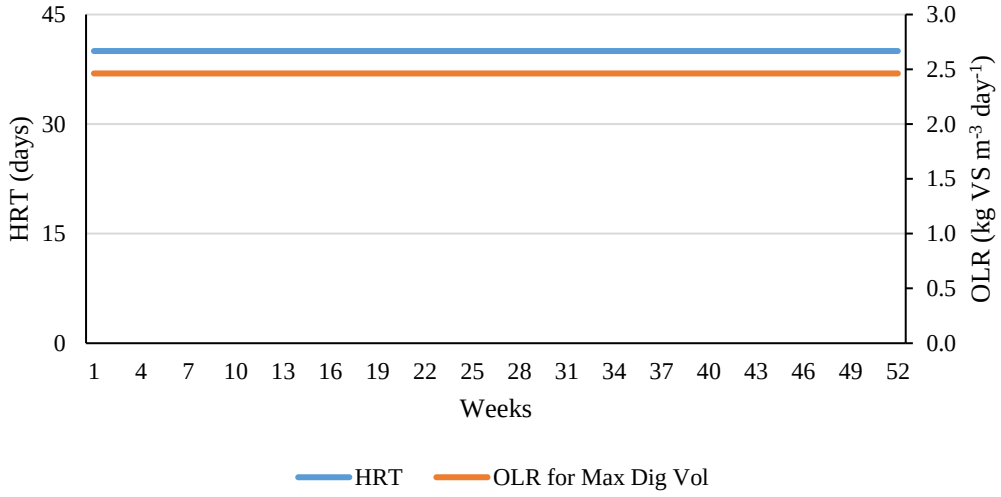


Figure B-7: Scenario ZG-C HRT and OLR.

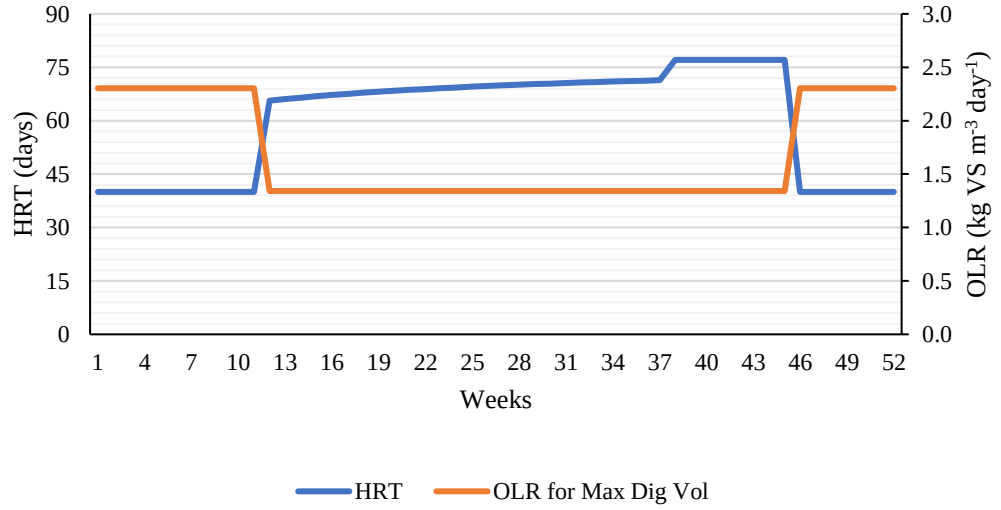


Figure B-8: Scenario PB-C HRT and OLR.

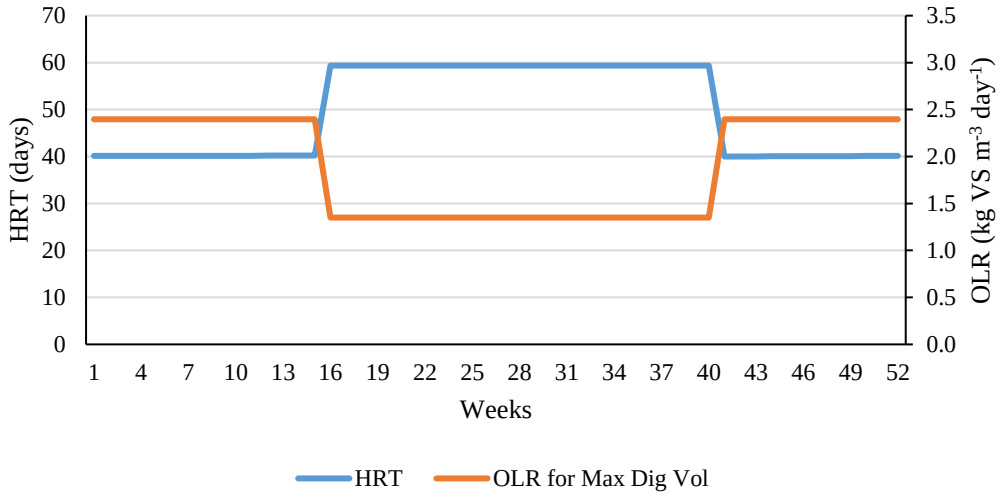


Figure B-9: Scenario ZG-W HRT and OLR.

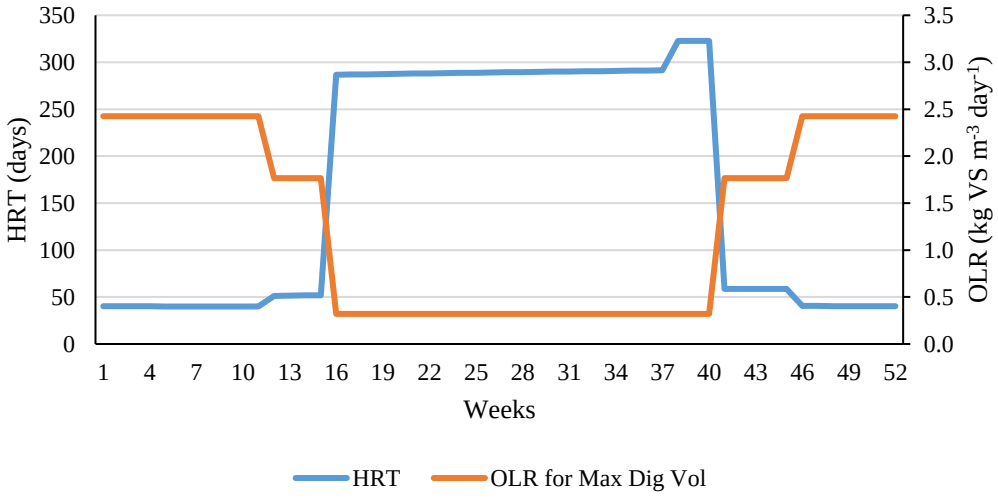


Figure B-10: Scenario PB-W HRT and OLR.

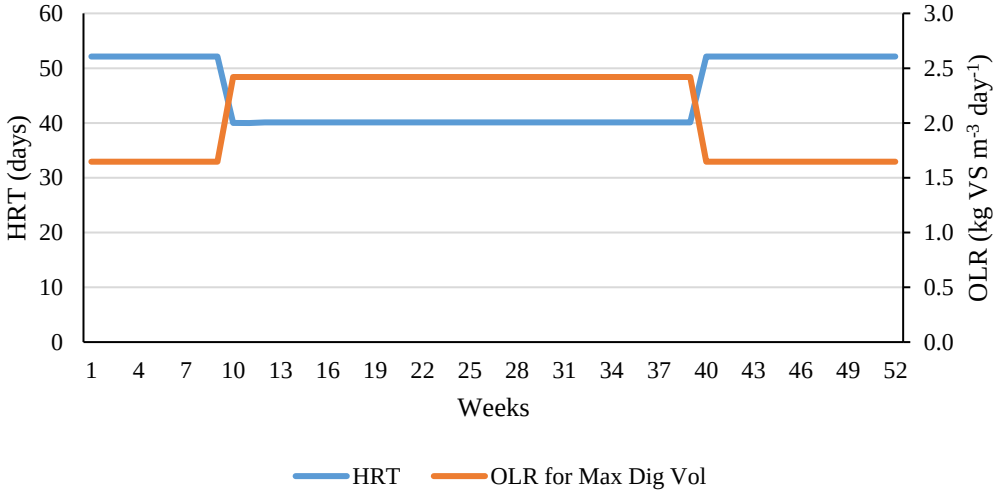


Figure B-11: Scenario ZG-S HRT and OLR.

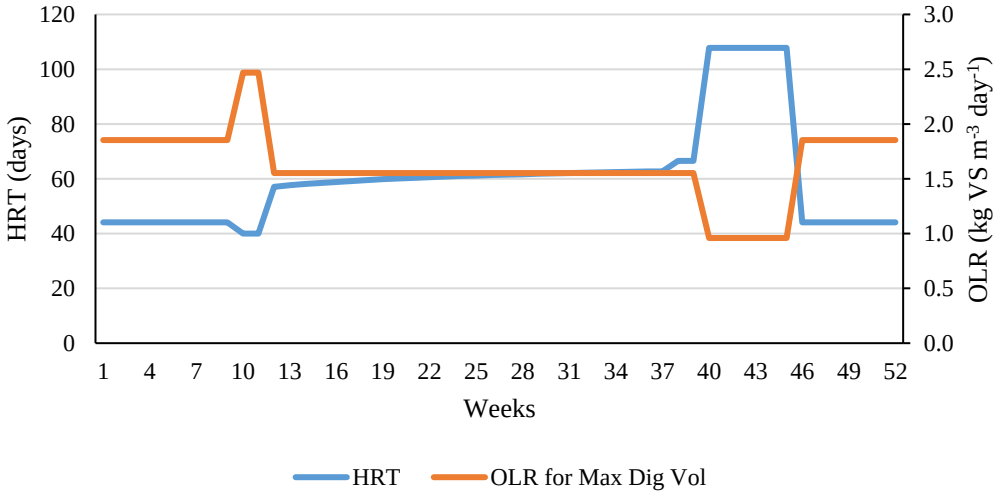


Figure B-12: Scenario PB-S HRT and OLR.

Appendix C

Appendix C.1

Figure C-1 shows an example of two farm locations with corresponding features used to identify them.

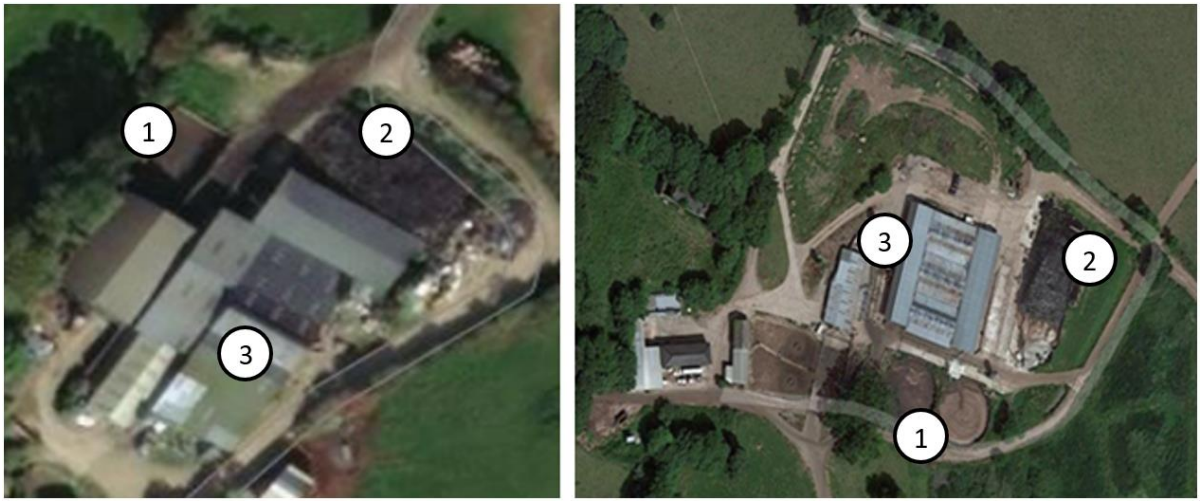


Figure C-1: Farm satellite imagery (1: Slurry storage, 2: Silage storage, 3: Cattle sheds). Images captured from Google Maps.

Tables C-1 and C-2 below show all details associated with each farm site.

Farm	Dairy Herd	Stocking rate (per hectare)	Platform (hectare)	Grass req. (t DM)	Silage req. (t DM)	Pasture land (ha)	Silage land (ha)	Silage land for AD (ha)
Farm 1	120	2	60	440.52	179.4	31.47	16.83	11.71
Farm 2	122	2.56	48	447.86	182.39	31.99	17.11	0
Farm 3	108	2.16	50	396.47	161.46	28.32	15.15	6.53
Farm 4	87	1.91	46	319.38	130.07	22.81	12.2	10.99
Farm 5	112	2.69	42	411.15	167.44	29.37	15.71	0
Farm 6	82	1.97	42	301.02	122.59	21.5	11.5	9
Farm 7	78	1.64	48	286.34	116.61	20.45	10.94	16.61
Farm 8	78	1.56	50	286.34	116.61	20.45	10.94	18.61
Farm 9	83	2.08	40	304.69	124.09	21.76	11.64	6.6
Farm 10	124	2.48	50	455.2	185.38	32.51	17.39	0.1
Farm 11	73	1.83	40	267.98	109.14	19.14	10.24	10.62
Farm 12	104	2.29	45	381.78	155.48	27.27	14.59	3.14
Farm 13	86	2.15	40	315.71	128.57	22.55	12.06	5.39
Farm 14	111	2.22	50	407.48	165.95	29.11	15.57	5.33
Farm 15	55	1.16	47	201.91	82.23	14.42	7.71	24.86
Farm 16	100	2.2	46	367.1	149.5	26.22	14.02	5.75
Farm 17	47	1.94	24	172.54	70.27	12.32	6.59	5.08
Farm 18	106	2.54	42	389.13	158.47	27.79	14.87	0
Farm 19	61	1.22	50	223.93	91.2	16	8.55	25.45

Farm	Dairy Herd	Stocking rate (per hectare)	Platform (hectare)	Grass req. (t DM)	Silage req. (t DM)	Pasture land (ha)	Silage land (ha)	Silage land for AD (ha)
Farm 20	87	1.91	46	319.38	130.07	22.81	12.2	10.99
Farm 21	95	2.28	42	348.75	142.03	24.91	13.32	3.77
Farm 22	129	2.71	48	473.56	192.86	33.83	18.09	0
Farm 23	55	1.32	42	201.91	82.23	14.42	7.71	19.86
Farm 24	125	2.63	48	458.88	186.88	32.78	17.53	0
Farm 25	102	2.45	42	374.44	152.49	26.75	14.3	0.95
Farm 26	105	2.52	42	385.46	156.98	27.53	14.73	0
Farm 27	89	1.78	50	326.72	133.06	23.34	12.48	14.18
Farm 28	117	2.93	40	429.51	174.92	30.68	16.41	0
Farm 29	78	1.95	40	286.34	116.61	20.45	10.94	8.61
Farm 30	76	1.82	42	279	113.62	19.93	10.66	11.41
Farm 31	101	2.02	50	370.77	151	26.48	14.16	9.35
Farm 32	87	1.74	50	319.38	130.07	22.81	12.2	14.99
Farm 33	71	1.7	42	260.64	106.15	18.62	9.96	13.43
Farm 34	119	2.38	50	436.85	177.91	31.2	16.69	2.11
Farm 35	109	2.18	50	400.14	162.96	28.58	15.29	6.13
Farm 36	92	1.84	50	337.73	137.54	24.12	12.9	12.97
Farm 37	116	2.9	40	425.84	173.42	30.42	16.27	0
Farm 38	70	1.75	40	256.97	104.65	18.36	9.82	11.83
Farm 39	128	2.94	44	469.89	191.36	33.56	17.95	0
Farm 40	118	2.71	44	433.18	176.41	30.94	16.55	0
Farm 41	44	1.01	44	161.52	65.78	11.54	6.17	26.29
Farm 42	116	2.55	46	425.84	173.42	30.42	16.27	0
Farm 43	109	2.29	48	400.14	162.96	28.58	15.29	4.13
Farm 44	120	2.64	46	440.52	179.4	31.47	16.83	0
Farm 45	93	1.95	48	341.4	139.04	24.39	13.04	10.57
Farm 46	77	1.77	44	282.67	115.12	20.19	10.8	13.01
Farm 47	71	1.7	42	260.64	106.15	18.62	9.96	13.43
Farm 48	112	2.46	46	411.15	167.44	29.37	15.71	0.92
Farm 49	30	0.75	40	110.13	44.85	7.87	4.21	27.93
Farm 50	87	2.09	42	319.38	130.07	22.81	12.2	6.99
Farm 51	96	2.21	43	352.42	143.52	25.17	13.46	4.36
Farm 52	78	1.79	44	286.34	116.61	20.45	10.94	12.61
Farm 53	113	2.71	42	414.82	168.94	29.63	15.85	0
Farm 54	113	2.49	45	414.82	168.94	29.63	15.85	0
Farm 55	127	2.92	44	466.22	189.87	33.3	17.81	0
Farm 56	96	2.4	40	352.42	143.52	25.17	13.46	1.36
Farm 57	125	3.13	40	458.88	186.88	32.78	17.53	0
Farm 58	85	2.04	42	312.04	127.08	22.29	11.92	7.79
Farm 59	104	2.39	44	381.78	155.48	27.27	14.59	2.14
Farm 60	34	0.78	44	124.81	50.83	8.92	4.77	30.32
Farm 61	73	1.46	50	267.98	109.14	19.14	10.24	20.62
Farm 62	94	2.26	42	345.07	140.53	24.65	13.18	4.17

Farm	Dairy Herd	Stocking rate (per hectare)	Platform (hectare)	Grass req. (t DM)	Silage req. (t DM)	Pasture land (ha)	Silage land (ha)	Silage land for AD (ha)
Farm 63	100	2	50	367.1	149.5	26.22	14.02	9.75
Farm 64	80	1.6	50	293.68	119.6	20.98	11.22	17.8
Farm 65	78	1.64	48	286.34	116.61	20.45	10.94	16.61
Farm 66	124	2.85	44	455.2	185.38	32.51	17.39	0
Farm 67	78	1.64	48	286.34	116.61	20.45	10.94	16.61
Farm 68	110	2.75	40	403.81	164.45	28.84	15.43	0
Farm 69	78	1.64	48	286.34	116.61	20.45	10.94	16.61
Farm 70	109	2.18	50	400.14	162.96	28.58	15.29	6.13
Farm 71	76	1.82	42	279	113.62	19.93	10.66	11.41
Farm 72	105	2.21	48	385.46	156.98	27.53	14.73	5.74
Farm 73	110	2.42	46	403.81	164.45	28.84	15.43	1.73
Farm 74	86	2.06	42	315.71	128.57	22.55	12.06	7.39
Farm 75	122	3.05	40	447.86	182.39	31.99	17.11	0
Farm 76	100	2.5	40	367.1	149.5	26.22	14.02	0
Farm 77	88	1.94	45	323.05	131.56	23.07	12.34	9.58
Farm 78	79	1.98	40	290.01	118.11	20.71	11.08	8.21
Farm 79	112	2.35	48	411.15	167.44	29.37	15.71	2.92
Farm 80	76	1.82	42	279	113.62	19.93	10.66	11.41
Farm 81	112	2.24	50	411.15	167.44	29.37	15.71	4.92
Farm 82	110	2.42	46	403.81	164.45	28.84	15.43	1.73
Farm 83	92	2.21	42	337.73	137.54	24.12	12.9	4.97
Farm 84	36	0.72	50	132.16	53.82	9.44	5.05	35.51
Farm 85	115	2.53	46	422.17	171.93	30.15	16.13	0
Farm 86	71	1.56	46	260.64	106.15	18.62	9.96	17.43
Farm 87	83	1.99	42	304.69	124.09	21.76	11.64	8.6
Farm 88	44	0.97	45	161.52	65.78	11.54	6.17	27.29
Farm 89	107	2.35	46	392.8	159.97	28.06	15.01	2.94
Farm 90	67	1.41	48	245.96	100.17	17.57	9.4	21.04
Farm 91	106	2.44	43	389.13	158.47	27.79	14.87	0.34
Farm 92	97	2.23	44	356.09	145.02	25.43	13.6	4.96
Farm 93	44	0.97	45	161.52	65.78	11.54	6.17	27.29
Farm 94	123	3.08	40	451.53	183.89	32.25	17.25	0
Farm 95	55	1.21	46	201.91	82.23	14.42	7.71	23.86
Farm 96	84	2.1	40	308.36	125.58	22.03	11.78	6.19
Farm 97	45	0.95	47	165.2	67.28	11.8	6.31	28.89
Farm 98	113	2.6	44	414.82	168.94	29.63	15.85	0
Farm 99	85	2.13	40	312.04	127.08	22.29	11.92	5.79
Farm 100	80	1.84	44	293.68	119.6	20.98	11.22	11.8

Table C-1: List of farms' stocking rates, platform size, and land availability.

Farm	Dairy herd	Slurry availability (only 18 of 52 weeks) (t_{wwt} week^{-1})	Surplus silage availability (t DM week^{-1})	Weekly CH_4 output (Nm^3 week^{-1})	Weekly biogas output (Nm^3 week^{-1})	Mobile-upgrading time [Scenario 7] (hr:mm week^{-1})
Farm 1	120	39.60	124.78	809.01	1568.76	6:16
Farm 2	122	40.26	0	106.66	196.79	0:47
Farm 3	108	35.64	69.66	487.50	941.93	3:46
Farm 4	87	28.71	117.11	736.92	1431.07	5:43
Farm 5	112	36.96	0	97.92	180.66	0:43
Farm 6	82	27.06	95.92	612.98	1189.47	4:45
Farm 7	78	25.74	177.04	1067.24	2077.09	8:18
Farm 8	78	25.74	198.36	1187.55	2312.06	9:14
Farm 9	83	27.39	70.31	469.34	908.83	3:38
Farm 10	124	40.92	1.01	114.13	211.20	0:50
Farm 11	73	24.09	113.22	702.69	1365.54	5:27
Farm 12	104	34.32	33.52	280.07	537.18	2:08
Farm 13	86	28.38	57.44	399.33	771.81	3:05
Farm 14	111	36.63	56.79	417.49	804.92	3:13
Farm 15	55	18.15	265.06	1543.80	3010.03	12:02
Farm 16	100	33.00	61.34	433.56	837.35	3:20
Farm 17	47	15.51	54.20	346.94	673.18	2:41
Farm 18	106	34.98	0	92.67	170.98	0:41
Farm 19	61	20.13	271.30	1584.25	3088.47	12:21
Farm 20	87	28.71	117.11	736.92	1431.07	5:43
Farm 21	95	31.35	40.15	309.62	595.75	2:22
Farm 22	129	42.57	0	112.78	208.08	0:49
Farm 23	55	18.15	211.76	1243.03	2422.59	9:41
Farm 24	125	41.25	0	109.28	201.63	0:48
Farm 25	102	33.66	10.12	146.28	276.05	1:06
Farm 26	105	34.65	0	91.80	169.37	0:40
Farm 27	89	29.37	151.17	930.86	1809.68	7:14
Farm 28	117	38.61	0	102.29	188.72	0:45
Farm 29	78	25.74	91.76	586.01	1137.18	4:32
Farm 30	76	25.08	121.66	752.99	1463.50	5:51
Farm 31	101	33.33	99.69	650.84	1261.63	5:02
Farm 32	87	28.71	159.75	977.53	1901.02	7:36
Farm 33	71	23.43	143.12	869.67	1691.86	6:46
Farm 34	119	39.27	22.47	230.81	439.55	1:45
Farm 35	109	35.97	65.37	464.16	896.26	3:35
Farm 36	92	30.36	138.30	860.86	1672.67	6:41
Farm 37	116	38.28	0	101.41	187.11	0:44
Farm 38	70	23.10	126.09	772.69	1502.55	6:00
Farm 39	128	42.24	0	111.90	206.46	0:49
Farm 40	118	38.94	0	103.16	190.33	0:45
Farm 41	44	14.52	280.27	1620.02	3159.95	12:38

Farm	Dairy herd	Slurry availability (only 18 of 52 weeks) (t_{wwt} week^{-1})	Surplus silage availability (t DM week^{-1})	Weekly CH_4 output (Nm^3 week^{-1})	Weekly biogas output (Nm^3 week^{-1})	Mobile-upgrading time [Scenario 7] (hr:mm week^{-1})
Farm 42	116	38.28	0	101.41	187.11	0:44
Farm 43	109	35.97	44.05	343.85	661.28	2:38
Farm 44	120	39.60	0	104.91	193.56	0:46
Farm 45	93	30.69	112.69	717.22	1392.02	5:34
Farm 46	77	25.41	138.69	849.96	1652.81	6:36
Farm 47	71	23.43	143.12	869.67	1691.86	6:46
Farm 48	112	36.96	9.86	153.54	289.30	1:09
Farm 49	30	9.90	297.69	1706.10	3329.39	13:19
Farm 50	87	28.71	74.47	496.30	961.12	3:50
Farm 51	96	31.68	46.52	346.44	667.57	2:40
Farm 52	78	25.74	134.40	826.63	1607.13	6:25
Farm 53	113	37.29	0	98.79	182.27	0:43
Farm 54	113	37.29	0	98.79	182.27	0:43
Farm 55	127	41.91	0	111.03	204.85	0:49
Farm 56	96	31.68	14.54	165.98	315.10	1:15
Farm 57	125	41.25	0	109.28	201.63	0:48
Farm 58	85	28.05	83.05	542.97	1052.46	4:12
Farm 59	104	34.32	22.86	219.91	419.69	1:40
Farm 60	34	11.22	323.17	1853.37	3616.66	14:28
Farm 61	73	24.09	219.82	1304.23	2540.42	10:09
Farm 62	94	31.02	44.44	332.96	641.42	2:33
Farm 63	100	33.00	103.98	674.18	1307.30	5:13
Farm 64	80	26.40	189.78	1140.88	2220.72	8:52
Farm 65	78	25.74	177.04	1067.24	2077.09	8:18
Farm 66	124	40.92	0	108.41	200.01	0:48
Farm 67	78	25.74	177.04	1067.24	2077.09	8:18
Farm 68	110	36.30	0	96.17	177.43	0:42
Farm 69	78	25.74	177.04	1067.24	2077.09	8:18
Farm 70	109	35.97	65.37	464.16	896.26	3:35
Farm 71	76	25.08	121.66	752.99	1463.50	5:51
Farm 72	105	34.65	61.21	437.19	843.97	3:22
Farm 73	110	36.30	18.44	200.21	380.64	1:31
Farm 74	86	28.38	78.76	519.64	1006.79	4:01
Farm 75	122	40.26	0	106.66	196.79	0:47
Farm 76	100	33.00	0	87.42	161.30	0:38
Farm 77	88	29.04	102.16	653.43	1267.91	5:04
Farm 78	79	26.07	87.47	562.68	1091.51	4:21
Farm 79	112	36.96	31.18	273.85	524.27	2:05
Farm 80	76	25.08	121.66	752.99	1463.50	5:51
Farm 81	112	36.96	52.50	394.15	759.25	3:02
Farm 82	110	36.30	18.44	200.21	380.64	1:31

Farm	Dairy herd	Slurry availability (only 18 of 52 weeks) (t_{wwt} week^{-1})	Surplus silage availability (t DM week^{-1})	Weekly CH_4 output (Nm^3 week^{-1})	Weekly biogas output (Nm^3 week^{-1})	Mobile-upgrading time [Scenario 7] (hr:mm week^{-1})
Farm 83	92	30.36	53.02	379.63	732.76	2:55
Farm 84	36	11.88	378.55	2167.63	4230.25	16:55
Farm 85	115	37.95	0	100.54	185.50	0:44
Farm 86	71	23.43	185.76	1110.28	2161.81	8:38
Farm 87	83	27.39	91.63	589.64	1143.80	4:34
Farm 88	44	14.52	290.93	1680.18	3277.44	13:06
Farm 89	107	35.31	31.31	270.22	517.65	2:04
Farm 90	67	22.11	224.24	1323.93	2579.47	10:19
Farm 91	106	34.98	3.62	113.09	210.86	0:50
Farm 92	97	32.01	52.89	383.26	739.39	2:57
Farm 93	44	14.52	290.93	1680.18	3277.44	13:06
Farm 94	123	40.59	0	107.53	198.40	0:47
Farm 95	55	18.15	254.40	1483.64	2892.54	11:34
Farm 96	84	27.72	66.02	446.00	863.16	3:27
Farm 97	45	14.85	307.96	1777.15	3466.74	13:52
Farm 98	113	37.29	0	98.79	182.27	0:43
Farm 99	85	28.05	61.73	422.67	817.49	3:16
Farm 100	80	26.40	125.82	779.96	1515.79	6:03

Table C-2: List of farms' gas output and scenario 7 upgrading time.

Appendix C.2

DEFRA vehicle emissions factors are based on road freight statistics from the UK Department for Transport for Great Britain, from surveys of different rigid and articulated HGVs of different sizes in the UK fleet for the year 2019, and fuel consumption data was estimated from the Department for Transport surveys. The methodology combines these data sets with data from the EU ARTEMIS project, showing the variation in fuel efficiency and CO_2 emissions with vehicle load (Department for Business Energy and Industrial Strategy, 2021).

Appendix C.3

Scenario 1 routing

Total net profit: **-558.99**

Vehicle:	**V1**	**Stops:**	**3**	**Net profit:**	**-11.19**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 85	4.90	0:06	08:06	08:07	0:07	0	0.40
2	Customer 84	5.98	0:08	08:09	08:31	0:31	0	9.07
3	Depot	11.19	0:15	08:38		0:38	0	0.00
4								
5								
6								
7								
8								
9								
10								

	Emissions			
	Distance Travelled (km)		Load %	Emissions (kg CO2e-q)
	4.90		0.00	2.18
	1.08		0.05	0.48
	5.21		0.93	2.69
	0.00		0.00	0.00
	0.00		0.00	0.00
	0.00		0.00	0.00
	0.00		0.00	0.00
	0.00		0.00	0.00
	0.00		0.00	0.00
	0.00		0.00	0.00
	0.00		0.00	0.00
Total	**11.19**		**0.93**	**5.36**
CO2 all Routes	***269.24***			**5.36**

Vehicle:	**V2**	**Stops:**	**4**	**Net profit:**	**-23.05**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 59	8.93	0:10	08:10	08:12	0:12	0	0.88
2	Customer 65	11.22	0:13	08:15	08:26	0:26	0	5.15
3	Customer 64	12.03	0:14	08:27	08:39	0:39	0	9.71
4	Depot	23.05	0:26	08:51		0:51	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.93	0.00	3.98
2.29	0.09	1.03
0.82	0.53	0.40
11.02	1.00	5.75
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
23.05	**1.00**	**11.16**
		11.16

Vehicle:	V3	Stops:	3	Net profit:	-20.19			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 90	8.06	0:08	08:08	08:21	0:21	0	5.30
2	Customer 86	12.33	0:13	08:26	08:38	0:38	0	9.74
3	Depot	20.19	0:23	08:48		0:48	0	0.00
4								
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.06	0.00	3.59
4.27	0.54	2.08
7.87	1.00	4.10
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
20.19	**1.00**	**9.77**
		9.77

Vehicle:	V4	Stops:	3	Net profit:	-19.26			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 58	8.56	0:10	08:10	08:15	0:15	0	2.17
2	Customer 60	10.32	0:12	08:17	08:36	0:36	0	9.59
3	Depot	19.26	0:22	08:46		0:46	0	0.00
4								
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.56	0.00	3.81
1.76	0.23	0.82
8.94	0.98	4.65
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
19.26	**0.98**	**9.28**
		9.28

Vehicle:	V5	Stops:	2	Net profit:	-9.91			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 49	4.96	0:06	08:06	08:23	0:23	0	6.82
2	Depot	9.91	0:12	08:29		0:29	0	0.00
3								
4								
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.96	0.00	2.21
4.96	0.70	2.47
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
9.91	**0.70**	**4.68**
		4.68

Vehicle:	V6	Stops:	5	Net profit:	-20.47			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 89	6.92	0:07	08:07	08:09	0:09	0	1.08
2	Customer 91	9.81	0:10	08:12	08:13	0:13	0	1.53
3	Customer 92	9.92	0:10	08:13	08:17	0:17	0	3.07
4	Customer 93	10.53	0:11	08:18	08:36	0:36	0	9.79
5	Depot	20.47	0:21	08:46		0:46	0	0.00
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.92	0.00	3.08
2.89	0.12	1.32
0.11	0.16	0.05
0.61	0.32	0.29
9.95	1.00	5.19
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
20.47	**1.00**	**9.92**
		9.92

Vehicle:	V7	Stops:	7	Net profit:	-37.17			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 3	17.02	0:18	08:18	08:23	0:23	0	1.95
2	Customer 17	18.31	0:21	08:26	08:29	0:29	0	3.34
3	Customer 6	19.13	0:23	08:31	08:37	0:37	0	5.79
4	Customer 18	21.74	0:28	08:42	08:43	0:43	0	6.16
5	Customer 1	21.80	0:28	08:43	08:52	0:52	0	9.40
6	Customer 5	26.46	0:34	08:58	08:59	0:59	0	9.79
7	Depot	37.17	0:48	09:13		1:13	0	0.00
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
17.02	0.00	7.58
1.29	0.20	0.60
0.82	0.35	0.38
2.62	0.60	1.28
0.05	0.63	0.03
4.67	0.96	2.42
10.71	1.00	5.59
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
37.17	**1.00**	**17.88**
		17.88

Vehicle:	V8	Stops:	4	Net profit:	-15.13			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 82	1.54	0:02	08:02	08:04	0:04	0	0.80
2	Customer 97	6.90	0:09	08:11	08:29	0:29	0	7.91
3	Customer 96	7.56	0:10	08:30	08:34	0:34	0	9.69
4	Depot	15.13	0:19	08:43		0:43	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
1.54	0.00	0.69
5.36	0.09	2.43
0.66	0.81	0.34
7.56	0.99	3.94
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
15.13	**0.99**	**7.39**
		7.39

Vehicle:	V9	Stops:	3	Net profit:	-12.56			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 87	5.83	0:06	08:06	08:12	0:12	0	2.36
2	Customer 88	6.28	0:06	08:12	08:29	0:29	0	9.08
3	Depot	12.56	0:13	08:36		0:36	0	0.00
4								
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.83	0.00	2.60
0.45	0.25	0.21
6.28	0.93	3.24
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
12.56	**0.93**	**6.05**
		6.05

Vehicle:	V10	Stops:	4	Net profit:	-21.45			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 11	7.15	0:10	08:10	08:17	0:17	0	2.81
2	Customer 33	12.55	0:18	08:25	08:34	0:34	0	6.29
3	Customer 30	12.85	0:18	08:34	08:41	0:41	0	9.30
4	Depot	21.45	0:29	08:52		0:52	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.15	0.00	3.19
5.39	0.29	2.52
0.31	0.65	0.15
8.60	0.95	4.45
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
21.45	**0.95**	**10.31**
		10.31

Vehicle:	V11	Stops:	6	Net profit:	-39.78			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 7	12.50	0:16	08:16	08:27	0:27	0	4.27
2	Customer 20	18.64	0:24	08:35	08:42	0:42	0	7.22
3	Customer 2	22.53	0:30	08:48	08:49	0:49	0	7.64
4	Customer 16	27.65	0:39	08:58	09:03	1:03	0	9.38
5	Customer 28	31.38	0:44	09:08	09:09	1:09	0	9.79
6	Depot	39.78	0:55	09:20		1:20	0	0.00
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
12.50	0.00	5.57
6.14	0.44	2.94
3.89	0.74	1.95
5.13	0.78	2.59
3.73	0.96	1.94
8.40	1.00	4.38
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
39.78	**1.00**	**19.37**
		19.37

Vehicle:	V12	Stops:	5	Net profit:	-9.00				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot	0.00	0:00		08:00	0:00	0	0.00	
1	Customer 75	2.50	0:04	08:04	08:05	0:05	0	0.43	
2	Customer 77	3.40	0:05	08:06	08:12	0:12	0	3.04	
3	Customer 76	3.68	0:06	08:13	08:14	0:14	0	3.39	
4	Customer 69	4.68	0:07	08:15	08:26	0:26	0	7.66	
5	Depot	9.00	0:13	08:32		0:32	0	0.00	
6									
7									
8									
9									
10									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
2.50	0.00	1.11
0.90	0.05	0.40
0.28	0.31	0.13
1.00	0.35	0.47
4.33	0.79	2.19
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
9.00	**0.79**	**4.31**
		4.31

Vehicle:	V13	Stops:	6	Net profit:	-22.55				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot	0.00	0:00		08:00	0:00	0	0.00	
1	Customer 98	6.33	0:08	08:08	08:09	0:09	0	0.40	
2	Customer 29	8.08	0:10	08:11	08:17	0:17	0	2.74	
3	Customer 10	10.91	0:14	08:21	08:22	0:22	0	3.20	
4	Customer 31	12.85	0:16	08:24	08:30	0:30	0	5.80	
5	Customer 32	15.05	0:19	08:33	08:44	0:44	0	9.71	
6	Depot	22.55	0:28	08:53		0:53	0	0.00	
7									
8									
9									
10									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.33	0.00	2.82
1.74	0.05	0.78
2.84	0.28	1.32
1.94	0.33	0.91
2.20	0.60	1.08
7.50	0.99	3.91
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
22.55	**0.99**	**10.83**
		10.83

Vehicle:	V14	Stops:	5	Net profit:	-28.67				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot	0.00	0:00		08:00	0:00	0	0.00	
1	Customer 66	8.10	0:10	08:10	08:11	0:11	0	0.43	
2	Customer 63	12.70	0:15	08:16	08:23	0:23	0	3.13	
3	Customer 62	17.40	0:21	08:29	08:32	0:32	0	4.46	
4	Customer 61	18.33	0:22	08:33	08:46	0:46	0	9.68	
5	Depot	28.67	0:34	08:58		0:58	0	0.00	
6									
7									
8									
9									
10									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.10	0.00	3.61
4.60	0.05	2.06
4.71	0.32	2.21
0.93	0.46	0.45
10.34	0.99	5.39
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
28.67	**0.99**	**13.72**
		13.72

Vehicle:	V15	Stops:	6	Net profit:	-23.00			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 34	9.59	0:10	08:10	08:12	0:12	0	0.92
2	Customer 36	11.01	0:13	08:15	08:24	0:24	0	4.37
3	Customer 37	11.45	0:14	08:25	08:26	0:26	0	4.77
4	Customer 35	12.89	0:16	08:28	08:33	0:33	0	6.63
5	Customer 38	15.43	0:20	08:37	08:45	0:45	0	9.72
6	Depot	23.00	0:28	08:53		0:53	0	0.00
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
9.59	0.00	4.27
1.41	0.10	0.64
0.44	0.45	0.21
1.44	0.49	0.70
2.54	0.68	1.26
7.57	1.00	3.95
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
23.00	**1.00**	**11.03**
		11.03

Vehicle:	V16	Stops:	10	Net profit:	-26.84			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 48	5.73	0:08	08:08	08:09	0:09	0	0.61
2	Customer 50	7.65	0:10	08:11	08:16	0:16	0	2.60
3	Customer 57	9.93	0:13	08:19	08:20	0:20	0	3.04
4	Customer 56	11.07	0:14	08:21	08:23	0:23	0	3.70
5	Customer 55	12.38	0:16	08:25	08:26	0:26	0	4.14
6	Customer 54	13.69	0:18	08:28	08:29	0:29	0	4.54
7	Customer 53	14.66	0:19	08:30	08:31	0:31	0	4.93
8	Customer 52	15.31	0:20	08:32	08:41	0:41	0	8.24
9	Customer 51	18.27	0:24	08:45	08:48	0:48	0	9.63
10	Depot	26.84	0:34	08:58		0:58	0	0.00

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.73	0.00	2.55
1.92	0.07	0.86
2.28	0.27	1.06
1.15	0.31	0.54
1.31	0.38	0.62
1.31	0.43	0.63
0.97	0.47	0.47
0.65	0.51	0.32
2.96	0.85	1.51
8.57	0.99	4.47
0.00	0.00	0.00
26.84	**0.99**	**13.02**
		13.02

Vehicle:	V17	Stops:	3	Net profit:	-22.10			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 27	11.05	0:11	08:11	08:20	0:20	0	3.72
2	Customer 95	11.57	0:11	08:20	08:35	0:35	0	9.66
3	Depot	22.10	0:21	08:45		0:45	0	0.00
4								
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
11.05	0.00	4.92
0.52	0.38	0.25
10.53	0.99	5.48
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
22.10	**0.99**	**10.65**
		10.65

Vehicle:	V18	Stops:	4	Net profit:	-17.36			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 13	6.57	0:09	08:09	08:13	0:13	0	1.60
2	Customer 15	8.63	0:12	08:16	08:32	0:32	0	7.77
3	Customer 14	9.51	0:13	08:33	08:37	0:37	0	9.44
4	Depot	17.36	0:23	08:47		0:47	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.57	0.00	2.93
2.06	0.17	0.94
0.88	0.80	0.45
7.85	0.97	4.08
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
17.36	**0.97**	**8.40**
		8.40

Vehicle:	V19	Stops:	4	Net profit:	-25.25			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 46	11.62	0:13	08:13	08:21	0:21	0	3.40
2	Customer 45	12.62	0:14	08:22	08:30	0:30	0	6.27
3	Customer 47	14.88	0:17	08:33	08:42	0:42	0	9.75
4	Depot	25.25	0:28	08:53		0:53	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
11.62	0.00	5.17
1.01	0.35	0.48
2.26	0.64	1.12
10.37	1.00	5.41
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
25.25	**1.00**	**12.18**
		12.18

Vehicle:	V20	Stops:	6	Net profit:	-17.72			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 73	7.05	0:10	08:10	08:12	0:12	0	0.80
2	Customer 74	7.80	0:12	08:14	08:19	0:19	0	2.88
3	Customer 99	9.45	0:14	08:21	08:25	0:25	0	4.57
4	Customer 100	10.20	0:15	08:26	08:34	0:34	0	7.69
5	Customer 72	11.67	0:16	08:35	08:40	0:40	0	9.44
6	Depot	17.72	0:24	08:48		0:48	0	0.00
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.05	0.00	3.14
0.75	0.09	0.34
1.65	0.30	0.77
0.75	0.47	0.36
1.47	0.79	0.74
6.05	0.97	3.14
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
17.72	**0.97**	**8.50**
		8.50

Vehicle:	V21	Stops:	9	Net profit:	-50.92			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0.00		0.33	0.00	0.00	0.00
1	Customer 12	7.82	0.01	0.34	0.34	0.01	0.00	1.12
2	Customer 26	15.74	0.01	0.35	0.35	0.02	0.00	1.49
3	Customer 21	24.59	0.02	0.36	0.36	0.03	0.00	2.73
4	Customer 22	27.68	0.02	0.36	0.36	0.03	0.00	3.18
5	Customer 23	29.72	0.03	0.37	0.37	0.04	0.00	8.15
6	Customer 24	33.19	0.03	0.38	0.38	0.05	0.00	8.59
7	Customer 25	35.96	0.03	0.38	0.38	0.05	0.00	9.17
8	Customer 94	43.28	0.04	0.39	0.39	0.06	0.00	9.60
9	Depot	50.92	0.04	0.39		0.06	0.00	0.00
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.82	0.00	3.48
7.91	0.12	3.60
8.85	0.16	4.05
3.09	0.28	1.44
2.04	0.33	0.96
3.47	0.84	1.77
2.77	0.88	1.42
7.32	0.94	3.79
7.64	0.98	3.97
0.00	0.00	0.00
0.00	0.00	0.00
50.92	**0.98**	**24.49**
		24.49

Vehicle:	V22	Stops:	7	Net profit:	-28.79			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 39	6.85	0:07	08:07	08:08	0:08	0	0.45
2	Customer 42	11.98	0:11	08:12	08:13	0:13	0	0.85
3	Customer 43	13.15	0:12	08:14	08:17	0:17	0	2.23
4	Customer 44	14.86	0:15	08:20	08:21	0:21	0	2.65
5	Customer 41	17.52	0:20	08:26	08:43	0:43	0	9.13
6	Customer 40	21.48	0:26	08:49	08:50	0:50	0	9.54
7	Depot	28.79	0:34	08:58		0:58	0	0.00
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.85	0.00	3.05
5.14	0.05	2.31
1.17	0.09	0.53
1.71	0.23	0.79
2.65	0.28	1.24
3.96	0.94	2.05
7.31	0.98	3.80
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
28.79	**0.98**	**13.77**
		13.77

Vehicle:	V23	Stops:	4	Net profit:	-11.14			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 83	5.16	0:06	08:06	08:09	0:09	0	1.52
2	Customer 19	7.91	0:10	08:13	08:30	0:30	0	7.86
3	Customer 81	10.90	0:14	08:34	08:38	0:38	0	9.43
4	Depot	11.14	0:14	08:38		0:38	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.16	0.00	2.30
2.75	0.16	1.26
2.99	0.81	1.51
0.24	0.97	0.13
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
11.14	**0.97**	**5.20**
		5.20

Vehicle:	V24	Stops:	4	Net profit:	-26.48			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 9	9.61	0:13	08:13	08:17	0:17	0	1.88
2	Customer 8	10.90	0:16	08:20	08:33	0:33	0	6.63
3	Customer 4	15.16	0:21	08:38	08:45	0:45	0	9.58
4	Depot	26.48	0:35	08:59		0:59	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
9.61	0.00	4.28
1.29	0.20	0.59
4.26	0.68	2.12
11.32	0.98	5.89
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
26.48	**0.98**	**12.88**
		12.88

Vehicle:	V25	Stops:	4	Net profit:	-4.31			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 80	0.82	0:02	08:02	08:09	0:09	0	3.01
2	Customer 78	2.16	0:04	08:11	08:17	0:17	0	5.26
3	Customer 79	2.72	0:05	08:18	08:21	0:21	0	6.36
4	Depot	4.31	0:07	08:23		0:23	0	0.00
5								
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.82	0.00	0.37
1.33	0.31	0.62
0.57	0.54	0.28
1.59	0.65	0.79
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
4.31	**0.65**	**2.06**
		2.06

Vehicle:	V26	Stops:	5	Net profit:	-14.69			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 67	5.83	0:08	08:08	08:19	0:19	0	4.27
2	Customer 68	7.54	0:10	08:21	08:22	0:22	0	4.65
3	Customer 71	9.40	0:12	08:24	08:31	0:31	0	7.67
4	Customer 70	11.00	0:14	08:33	08:38	0:38	0	9.52
5	Depot	14.69	0:19	08:43		0:43	0	0.00
6								
7								
8								
9								
10								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.83	0.00	2.60
1.71	0.44	0.82
1.86	0.48	0.90
1.60	0.79	0.81
3.69	0.98	1.92
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
14.69	**0.98**	**7.04**
		7.04

Scenario 2 routing

Total net profit: **-287.03**

Vehicle:	**V1**	**Stops:**	**7**	**Net profit:**	**-12.70**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 81	0.24	0:00	08:00	08:04	0:04	0	1.58
2	Customer 82	1.54	0:02	08:06	08:08	0:08	0	2.38
3	Customer 85	4.90	0:07	08:13	08:14	0:14	0	2.78
4	Customer 83	5.92	0:09	08:16	08:20	0:20	0	4.30
5	Customer 84	6.66	0:10	08:21	08:43	0:43	0	12.97
6	Customer 19	9.47	0:14	08:47	09:03	1:03	0	19.31
7	Depot	12.70	0:18	09:07		1:07	0	0.00
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								

Detected reasons of infeasibility	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
	0.24	0.00	0.13
	1.30	0.07	0.71
	3.36	0.10	1.85
	1.02	0.11	0.56
	0.74	0.17	0.42
	2.81	0.51	1.72
	3.23	0.76	2.10
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
Total	**12.70**	**0.76**	**7.48**
CO2 all Routes	***175.16***		**7.48**

Vehicle:	**V2**	**Stops:**	**14**	**Net profit:**	**-20.85**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 75	2.50	0:04	08:04	08:05	0:05	0	0.43
2	Customer 77	3.40	0:05	08:06	08:12	0:12	0	3.04
3	Customer 76	3.68	0:06	08:13	08:14	0:14	0	3.39
4	Customer 69	4.68	0:07	08:15	08:26	0:26	0	7.66
5	Customer 71	5.64	0:08	08:27	08:35	0:35	0	10.67
6	Customer 72	6.40	0:09	08:36	08:41	0:41	0	12.42
7	Customer 73	7.40	0:10	08:42	08:44	0:44	0	13.22
8	Customer 74	8.15	0:12	08:46	08:51	0:51	0	15.30
9	Customer 99	9.80	0:14	08:53	08:57	0:57	0	16.99
10	Customer 100	10.55	0:15	08:58	09:06	1:06	0	20.11
11	Customer 70	14.38	0:19	09:10	09:15	1:15	0	21.97
12	Customer 79	18.13	0:24	09:20	09:23	1:23	0	23.06
13	Customer 78	18.69	0:25	09:24	09:30	1:30	0	25.31
14	Depot	20.85	0:28	09:33		1:33	0	0.00
15								
16								
17								
18								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
2.50	0.00	1.34
0.90	0.02	0.48
0.28	0.12	0.15
1.00	0.14	0.56
0.97	0.30	0.56
0.76	0.42	0.45
1.00	0.49	0.61
0.75	0.52	0.46
1.65	0.60	1.03
0.75	0.67	0.48
3.83	0.79	2.51
3.75	0.86	2.50
0.57	0.90	0.38
2.16	0.99	1.48
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
20.85	**0.99**	**12.99**
		12.99

Vehicle:	V3	Stops:	12	Net profit:	-30.60				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot	0.00	0:00		08:00	0:00	0	0.00	
1	Customer 49	4.96	0:06	08:06	08:23	0:23	0	6.82	
2	Customer 58	8.56	0:09	08:26	08:32	0:32	0	9.00	
3	Customer 60	10.32	0:11	08:34	08:53	0:53	0	16.41	
4	Customer 57	13.43	0:14	08:56	08:57	0:57	0	16.85	
5	Customer 56	14.58	0:15	08:58	09:00	1:00	0	17.51	
6	Customer 55	15.89	0:17	09:02	09:03	1:03	0	17.95	
7	Customer 54	17.19	0:19	09:05	09:06	1:06	0	18.35	
8	Customer 53	18.17	0:20	09:07	09:08	1:08	0	18.75	
9	Customer 52	18.82	0:21	09:09	09:17	1:17	0	22.05	
10	Customer 51	21.78	0:25	09:21	09:25	1:25	0	23.44	
11	Customer 50	22.95	0:27	09:27	09:32	1:32	0	25.42	
12	Depot	30.60	0:37	09:42		1:42	0	0.00	
13									
14									
15									
16									
17									
18									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.96	0.00	2.65
3.60	0.27	2.07
1.76	0.35	1.04
3.12	0.64	1.97
1.15	0.66	0.73
1.31	0.69	0.84
1.31	0.70	0.84
0.97	0.72	0.63
0.65	0.73	0.42
2.96	0.86	1.97
1.18	0.92	0.79
7.65	0.99	5.24
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
30.60	**0.99**	**19.19**
		19.19

Vehicle:	V4	Stops:	9	Net profit:	-23.68			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 88	6.28	0:06	08:06	08:23	0:23	0	6.72
2	Customer 86	8.76	0:10	08:27	08:38	0:38	0	11.16
3	Customer 87	10.80	0:14	08:42	08:48	0:48	0	13.52
4	Customer 98	12.74	0:18	08:52	08:53	0:53	0	13.92
5	Customer 13	12.98	0:18	08:53	08:57	0:57	0	15.51
6	Customer 12	14.58	0:21	09:00	09:03	1:03	0	16.63
7	Customer 11	15.25	0:22	09:04	09:12	1:12	0	19.44
8	Customer 80	22.86	0:32	09:22	09:29	1:29	0	22.46
9	Depot	23.68	0:33	09:30		1:30	0	0.00
10								
11								
12								
13								
14								
15								
16								
17								
18								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.28	0.00	3.36
2.49	0.27	1.43
2.04	0.44	1.23
1.94	0.53	1.19
0.24	0.55	0.15
1.60	0.61	1.00
0.67	0.65	0.42
7.61	0.76	4.95
0.82	0.88	0.55
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
23.68	**0.88**	**14.29**
		14.29

Vehicle:	V5	Stops:	18	Net profit:	-58.25			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 29	7.92	0:10	08:10	08:16	0:16	0	2.34
2	Customer 28	8.40	0:10	08:16	08:17	0:17	0	2.75
3	Customer 26	12.86	0:15	08:22	08:23	0:23	0	3.12
4	Customer 17	19.42	0:24	08:32	08:35	0:35	0	4.51
5	Customer 6	20.23	0:26	08:37	08:43	0:43	0	6.96
6	Customer 3	22.00	0:30	08:47	08:52	0:52	0	8.91
7	Customer 18	23.03	0:32	08:54	08:55	0:55	0	9.28
8	Customer 1	23.08	0:32	08:55	09:04	1:04	0	12.52
9	Customer 2	25.77	0:36	09:08	09:09	1:09	0	12.94
10	Customer 20	29.66	0:42	09:15	09:22	1:22	0	15.89
11	Customer 21	31.92	0:46	09:26	09:30	1:30	0	17.13
12	Customer 22	35.01	0:51	09:35	09:36	1:36	0	17.58
13	Customer 23	37.05	0:54	09:39	09:52	1:52	0	22.55
14	Customer 24	40.52	0:59	09:57	09:58	1:58	0	22.99
15	Customer 25	43.29	1:03	10:02	10:03	2:03	0	23.58
16	Customer 94	50.61	1:11	10:11	10:12	2:12	0	24.01
17	Customer 89	51.34	1:11	10:12	10:15	2:15	0	25.09
18	Depot	58.25	1:18	10:22		2:22	0	0.00

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.92	0.00	4.24
0.48	0.10	0.26
4.46	0.11	2.47
6.56	0.13	3.64
0.82	0.18	0.46
1.76	0.28	1.02
1.03	0.35	0.61
0.05	0.37	0.03
2.70	0.49	1.64
3.89	0.51	2.38
2.26	0.62	1.42
3.09	0.67	1.97
2.04	0.69	1.31
3.47	0.88	2.32
2.77	0.90	1.86
7.32	0.92	4.94
0.72	0.94	0.49
6.92	0.98	4.73
58.25	**0.98**	**35.78**
		35.78

Vehicle:	V6	Stops:	11	Net profit:	-25.05			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 14	7.85	0:10	08:10	08:14	0:14	0	1.67
2	Customer 15	8.73	0:11	08:15	08:31	0:31	0	7.85
3	Customer 10	10.14	0:13	08:33	08:34	0:34	0	8.30
4	Customer 31	12.08	0:15	08:36	08:43	0:43	0	10.91
5	Customer 32	14.28	0:18	08:46	08:56	0:56	0	14.82
6	Customer 30	15.38	0:20	08:58	09:05	1:05	0	17.83
7	Customer 33	15.68	0:21	09:06	09:15	1:15	0	21.31
8	Customer 38	17.41	0:24	09:18	09:26	1:26	0	24.40
9	Customer 40	17.74	0:24	09:26	09:27	1:27	0	24.81
10	Customer 39	18.21	0:25	09:28	09:30	1:30	0	25.26
11	Depot	25.05	0:32	09:37		1:37	0	0.00
12								
13								
14								
15								
16								
17								
18								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.85	0.00	4.21
0.88	0.07	0.48
1.41	0.31	0.82
1.94	0.33	1.13
2.20	0.43	1.32
1.10	0.58	0.68
0.31	0.70	0.20
1.72	0.83	1.14
0.33	0.95	0.23
0.47	0.97	0.32
6.85	0.99	4.69
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
25.05	**0.99**	**15.21**
		15.21

Vehicle:	V7	Stops:	13	Net profit:	-37.25				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot	0.00	0:00		08:00	0:00	0	0.00	
1	Customer 34	9.59	0:10	08:10	08:12	0:12	0	0.92	
2	Customer 35	10.93	0:12	08:14	08:19	0:19	0	2.78	
3	Customer 37	12.37	0:15	08:22	08:23	0:23	0	3.19	
4	Customer 36	12.81	0:16	08:24	08:33	0:33	0	6.63	
5	Customer 42	15.28	0:20	08:37	08:38	0:38	0	7.03	
6	Customer 43	16.45	0:21	08:39	08:42	0:42	0	8.41	
7	Customer 44	18.15	0:24	08:45	08:46	0:46	0	8.83	
8	Customer 41	20.81	0:29	08:51	09:08	1:08	0	15.31	
9	Customer 47	23.76	0:33	09:12	09:21	1:21	0	18.79	
10	Customer 45	26.02	0:36	09:24	09:31	1:31	0	21.66	
11	Customer 46	27.03	0:37	09:32	09:41	1:41	0	25.06	
12	Customer 48	31.52	0:43	09:47	09:49	1:49	0	25.67	
13	Depot	37.25	0:51	09:57		1:57	0	0.00	
14									
15									
16									
17									
18									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
9.59	0.00	5.14
1.33	0.04	0.72
1.44	0.11	0.80
0.44	0.13	0.24
2.47	0.26	1.42
1.17	0.28	0.68
1.71	0.33	1.00
2.65	0.35	1.56
2.95	0.60	1.85
2.26	0.73	1.46
1.01	0.85	0.67
4.49	0.98	3.07
5.73	1.00	3.93
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
37.25	**1.00**	**22.54**
		22.54

Vehicle:	V8	Stops:	8	Net profit:	-28.27			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 9	9.61	0:13	08:13	08:17	0:17	0	1.88
2	Customer 8	10.90	0:16	08:20	08:33	0:33	0	6.63
3	Customer 7	13.47	0:20	08:37	08:48	0:48	0	10.90
4	Customer 16	16.10	0:24	08:52	08:56	0:56	0	12.63
5	Customer 4	16.90	0:26	08:58	09:06	1:06	0	15.58
6	Customer 5	17.51	0:27	09:07	09:08	1:08	0	15.97
7	Customer 97	21.37	0:32	09:13	09:31	1:31	0	23.08
8	Depot	28.27	0:41	09:40		1:40	0	0.00
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
9.61	0.00	5.15
1.29	0.08	0.71
2.57	0.26	1.48
2.63	0.43	1.58
0.81	0.50	0.49
0.61	0.61	0.38
3.86	0.63	2.43
6.90	0.90	4.63
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
28.27	**0.90**	**16.85**
		16.85

Vehicle:	V9	Stops:	10	Net profit:	-29.92			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 68	5.51	0:08	08:08	08:08	0:08	0	0.38
2	Customer 67	7.22	0:10	08:10	08:22	0:22	0	4.65
3	Customer 66	9.35	0:13	08:25	08:26	0:26	0	5.09
4	Customer 65	11.77	0:16	08:29	08:40	0:40	0	9.36
5	Customer 63	13.94	0:18	08:42	08:49	0:49	0	12.05
6	Customer 64	15.30	0:19	08:50	09:01	1:01	0	16.62
7	Customer 61	17.72	0:23	09:05	09:19	1:19	0	21.83
8	Customer 62	18.65	0:24	09:20	09:23	1:23	0	23.17
9	Customer 59	20.98	0:28	09:27	09:29	1:29	0	24.04
10	Depot	29.92	0:38	09:39		1:39	0	0.00
11								
12								
13								
14								
15								
16								
17								
18								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.51	0.00	2.95
1.71	0.02	0.92
2.13	0.19	1.20
2.42	0.20	1.37
2.17	0.37	1.29
1.36	0.47	0.82
2.42	0.65	1.53
0.93	0.85	0.61
2.34	0.90	1.57
8.93	0.94	6.05
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
29.92	**0.94**	**18.32**
		18.32

Vehicle:	V10	Stops:	8	Net profit:	-20.46			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 96	7.56	0:09	08:09	08:13	0:13	0	1.78
2	Customer 27	8.83	0:11	08:15	08:25	0:25	0	5.51
3	Customer 95	9.35	0:11	08:25	08:40	0:40	0	11.44
4	Customer 93	9.93	0:11	08:40	08:57	0:57	0	18.16
5	Customer 91	10.65	0:12	08:58	08:59	0:59	0	18.62
6	Customer 92	10.75	0:12	08:59	09:03	1:03	0	20.15
7	Customer 90	12.40	0:14	09:05	09:19	1:19	0	25.44
8	Depot	20.46	0:22	09:27		1:27	0	0.00
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.56	0.00	4.05
1.26	0.07	0.69
0.52	0.22	0.30
0.58	0.45	0.35
0.72	0.71	0.46
0.11	0.73	0.07
1.64	0.79	1.08
8.06	0.99	5.52
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
20.46	**0.99**	**12.51**
		12.51

Scenario 3 routing

Total net profit: **-205.49**

Vehicle:	**V1**	**Stops:**	**20**	**Net profit:**	**-33.52**		
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 81	0.24	0:00	08:00	08:04	0:04	1.58
2	Customer 85	4.90	0:06	08:10	08:11	0:11	1.98
3	Customer 83	5.92	0:08	08:13	08:17	0:17	3.50
4	Customer 84	6.67	0:09	08:18	08:40	0:40	12.17
5	Customer 19	9.47	0:13	08:44	09:00	1:00	18.50
6	Customer 86	14.62	0:19	09:06	09:18	1:18	22.95
7	Customer 87	16.66	0:23	09:22	09:28	1:28	25.30
8	Customer 88	17.11	0:23	09:28	09:45	1:45	32.03
9	Customer 89	17.74	0:23	09:45	09:48	1:48	33.11
10	Customer 94	18.46	0:23	09:48	09:49	1:49	33.54
11	Customer 90	18.89	0:23	09:49	10:03	2:03	38.83
12	Customer 92	20.53	0:25	10:05	10:09	2:09	40.36
13	Customer 91	20.63	0:25	10:09	10:10	2:10	40.82
14	Customer 93	21.35	0:26	10:11	10:28	2:28	47.54
15	Customer 95	21.93	0:26	10:28	10:43	2:43	53.47
16	Customer 27	22.45	0:26	10:43	10:53	2:53	57.20
17	Customer 28	24.64	0:29	10:56	10:57	2:57	57.61
18	Customer 29	25.12	0:29	10:57	11:03	3:03	59.95
19	Customer 14	25.67	0:30	11:04	11:08	3:08	61.62
20	Depot	33.52	0:40	11:18		3:18	0.00
21							
22							
23							
24							
25							
26							
27							
28							
29							
30							

	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
	0.24	0.00	0.15
	4.66	0.03	2.95
	1.02	0.04	0.65
	0.74	0.06	0.48
	2.81	0.20	1.92
	5.15	0.30	3.68
	2.04	0.37	1.50
	0.45	0.41	0.34
	0.64	0.52	0.50
	0.72	0.54	0.57
	0.42	0.54	0.33
	1.64	0.63	1.34
	0.11	0.65	0.09
	0.72	0.66	0.59
	0.58	0.77	0.50
	0.52	0.87	0.46
	2.19	0.93	1.98
	0.48	0.93	0.43
	0.55	0.97	0.50
	7.85	1.00	7.29
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
	0.00	0.00	0.00
Total	**33.52**	**1.00**	**26.25**
CO2 all Routes	***160.97***		**26.25**

Vehicle:	V2	Stops:	30	Net profit:	-74.87				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0	Depot	0.00	0:00		08:00	0:00	0.00	6.33	0.00	3.95
1	Customer 98	6.33	0:08	08:08	08:09	0:09	0.40	0.24	0.01	0.15
2	Customer 13	6.57	0:08	08:09	08:13	0:13	1.99	1.60	0.04	1.02
3	Customer 12	8.17	0:11	08:16	08:19	0:19	3.11	0.67	0.06	0.43
4	Customer 11	8.84	0:12	08:20	08:27	0:27	5.92	2.56	0.10	1.67
5	Customer 31	11.40	0:16	08:31	08:37	0:37	8.53	1.94	0.14	1.29
6	Customer 10	13.34	0:18	08:39	08:41	0:41	8.98	1.41	0.15	0.94
7	Customer 15	14.75	0:20	08:43	08:59	0:59	15.16	3.12	0.25	2.18
8	Customer 9	17.87	0:24	09:03	09:07	1:07	17.04	1.29	0.28	0.92
9	Customer 8	19.16	0:27	09:10	09:23	1:23	21.79	2.57	0.36	1.88
10	Customer 7	21.73	0:31	09:27	09:38	1:38	26.06	2.99	0.42	2.25
11	Customer 5	24.73	0:35	09:42	09:43	1:43	26.45	0.61	0.43	0.46
12	Customer 4	25.34	0:36	09:44	09:51	1:51	29.39	0.81	0.48	0.62
13	Customer 16	26.14	0:38	09:53	09:58	1:58	31.13	4.36	0.51	3.39
14	Customer 18	30.50	0:44	10:04	10:05	2:05	31.50	1.03	0.51	0.80
15	Customer 3	31.53	0:46	10:07	10:12	2:12	33.45	1.29	0.54	1.02
16	Customer 17	32.82	0:49	10:15	10:18	2:18	34.84	0.81	0.57	0.65
17	Customer 6	33.63	0:51	10:20	10:27	2:27	37.29	2.67	0.61	2.16
18	Customer 1	36.30	0:56	10:32	10:40	2:40	40.53	2.70	0.66	2.22
19	Customer 2	39.00	1:00	10:44	10:45	2:45	40.95	3.89	0.66	3.21
20	Customer 20	42.89	1:06	10:51	10:59	2:59	43.90	2.26	0.71	1.90
21	Customer 21	45.14	1:10	11:03	11:06	3:06	45.14	3.09	0.73	2.61
22	Customer 22	48.23	1:15	11:11	11:12	3:12	45.59	2.04	0.74	1.74
23	Customer 23	50.28	1:18	11:15	11:28	3:28	50.56	3.47	0.82	3.03
24	Customer 24	53.74	1:23	11:33	11:34	3:34	51.00	2.77	0.83	2.43
25	Customer 25	56.51	1:27	11:38	11:39	3:39	51.58	6.50	0.84	5.72
26	Customer 26	63.02	1:35	11:47	11:48	3:48	51.95	4.29	0.84	3.77
27	Customer 96	67.31	1:41	11:54	11:59	3:59	53.73	0.66	0.87	0.59
28	Customer 97	67.97	1:42	12:00	12:18	4:18	60.84	5.36	0.98	4.94
29	Customer 82	73.33	1:49	12:25	12:27	4:27	61.64	1.54	1.00	1.43
30	Depot	74.87	1:51	12:29		4:29	0.00	**74.87**	**1.00**	**59.36**
										59.36

Vehicle:	V3	Stops:	28	Net profit:	-55.45		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 49	4.96	0:06	08:06	08:23	0:23	6.82
2	Customer 59	8.93	0:10	08:27	08:29	0:29	7.70
3	Customer 62	11.27	0:14	08:33	08:37	0:37	9.04
4	Customer 61	12.19	0:15	08:38	08:51	0:51	14.25
5	Customer 57	16.10	0:20	08:56	08:57	0:57	14.69
6	Customer 56	17.24	0:21	08:58	09:00	1:00	15.35
7	Customer 55	18.55	0:23	09:02	09:03	1:03	15.80
8	Customer 54	19.86	0:25	09:05	09:06	1:06	16.19
9	Customer 53	20.83	0:26	09:07	09:08	1:08	16.59
10	Customer 52	21.48	0:27	09:09	09:18	1:18	19.89
11	Customer 45	26.13	0:33	09:24	09:31	1:31	22.76
12	Customer 46	27.14	0:34	09:32	09:41	1:41	26.16
13	Customer 47	28.38	0:36	09:43	09:52	1:52	29.64
14	Customer 41	31.34	0:40	09:56	10:13	2:13	36.12
15	Customer 44	33.99	0:45	10:18	10:19	2:19	36.54
16	Customer 43	35.70	0:48	10:22	10:25	2:25	37.92
17	Customer 42	36.87	0:49	10:26	10:27	2:27	38.32
18	Customer 36	39.34	0:53	10:31	10:40	2:40	41.77
19	Customer 37	39.78	0:54	10:41	10:42	2:42	42.17
20	Customer 35	41.22	0:56	10:44	10:49	2:49	44.03
21	Customer 34	42.55	0:58	10:51	10:53	2:53	44.95
22	Customer 32	44.68	1:02	10:57	11:07	3:07	48.86
23	Customer 30	45.78	1:04	11:09	11:17	3:17	51.87
24	Customer 33	46.09	1:05	11:18	11:27	3:27	55.35
25	Customer 38	47.81	1:08	11:30	11:38	3:38	58.44
26	Customer 40	48.14	1:08	11:38	11:39	3:39	58.86
27	Customer 39	48.61	1:09	11:40	11:41	3:41	59.30
28	Depot	55.45	1:16	11:48		3:48	0.00
29							
30							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.96	0.00	3.09
3.98	0.11	2.61
2.34	0.13	1.55
0.93	0.15	0.62
3.90	0.23	2.71
1.15	0.24	0.80
1.31	0.25	0.91
1.31	0.26	0.92
0.97	0.27	0.69
0.65	0.27	0.46
4.64	0.33	3.36
1.01	0.37	0.74
1.25	0.43	0.94
2.95	0.48	2.27
2.65	0.59	2.13
1.71	0.59	1.37
1.17	0.62	0.95
2.47	0.62	2.00
0.44	0.68	0.36
1.44	0.68	1.20
1.33	0.71	1.12
2.13	0.73	1.80
1.10	0.79	0.95
0.31	0.84	0.27
1.72	0.90	1.55
0.33	0.95	0.30
0.47	0.95	0.42
6.85	0.96	6.27
0.00	0.00	0.00
0.00	0.00	0.00
55.45	**0.96**	**42.39**
		42.39

Vehicle:	V4	Stops:	26	Net profit:	-41.65		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 80	0.82	0:02	08:02	08:09	0:09	3.01
2	Customer 78	2.16	0:04	08:11	08:17	0:17	5.26
3	Customer 79	2.72	0:05	08:18	08:21	0:21	6.36
4	Customer 75	5.28	0:10	08:26	08:27	0:27	6.78
5	Customer 77	6.18	0:11	08:28	08:35	0:35	9.40
6	Customer 76	6.46	0:12	08:36	08:37	0:37	9.75
7	Customer 70	6.83	0:12	08:37	08:41	0:41	11.60
8	Customer 69	7.46	0:13	08:42	08:53	0:53	15.87
9	Customer 71	8.43	0:14	08:54	09:02	1:02	18.89
10	Customer 72	9.18	0:15	09:03	09:08	1:08	20.63
11	Customer 73	10.18	0:16	09:09	09:11	1:11	21.44
12	Customer 74	10.93	0:18	09:13	09:18	1:18	23.51
13	Customer 99	12.58	0:20	09:20	09:24	1:24	25.20
14	Customer 100	13.33	0:21	09:25	09:34	1:34	28.32
15	Customer 68	17.42	0:25	09:38	09:39	1:39	28.71
16	Customer 67	19.13	0:27	09:41	09:52	1:52	32.98
17	Customer 66	21.25	0:30	09:55	09:56	1:56	33.41
18	Customer 65	23.67	0:33	09:59	10:10	2:10	37.68
19	Customer 63	25.85	0:35	10:12	10:19	2:19	40.38
20	Customer 64	27.20	0:36	10:20	10:31	2:31	44.94
21	Customer 60	29.28	0:38	10:33	10:52	2:52	52.35
22	Customer 58	31.04	0:40	10:54	11:00	3:00	54.53
23	Customer 51	32.82	0:43	11:03	11:07	3:07	55.91
24	Customer 50	34.00	0:45	11:09	11:14	3:14	57.90
25	Customer 48	35.92	0:47	11:16	11:17	3:17	58.51
26	Depot	41.65	0:55	11:25		3:25	0.00
27							
28							
29							
30							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.82	0.00	0.51
1.33	0.05	0.85
0.57	0.09	0.37
2.56	0.11	1.68
0.90	0.11	0.59
0.28	0.16	0.19
0.37	0.16	0.25
0.64	0.19	0.43
0.97	0.26	0.68
0.76	0.31	0.54
1.00	0.34	0.73
0.75	0.35	0.55
1.65	0.38	1.22
0.75	0.41	0.56
4.09	0.46	3.12
1.71	0.47	1.31
2.13	0.54	1.67
2.42	0.54	1.91
2.17	0.61	1.76
1.36	0.65	1.11
2.08	0.73	1.76
1.76	0.85	1.56
1.78	0.88	1.59
1.18	0.90	1.06
1.92	0.94	1.74
5.73	0.95	5.23
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
0.00	0.00	0.00
41.65	**0.95**	**32.97**
		32.97

Scenario 4 routing

Total net profit:	**-263.17**

Vehicle:	**V11 (T2)**	**Stops:**	**11**	**Net profit:**	**-18.07**		
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 75	2.50	0:04	08:04	08:05	0:05	0.43
2	Customer 77	3.40	0:05	08:06	08:12	0:12	3.04
3	Customer 70	4.04	0:06	08:13	08:18	0:18	4.90
4	Customer 71	5.65	0:08	08:20	08:28	0:28	7.91
5	Customer 72	6.40	0:09	08:29	08:33	0:33	9.66
6	Customer 73	7.40	0:10	08:34	08:36	0:36	10.46
7	Customer 74	8.15	0:12	08:38	08:44	0:44	12.54
8	Customer 100	9.05	0:14	08:46	08:54	0:54	15.66
9	Customer 99	9.80	0:15	08:55	08:59	0:59	17.35
10	Customer 69	13.74	0:19	09:03	09:14	1:14	21.62
11	Depot	18.07	0:25	09:20		1:20	0.00
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

		Distance Travelled (km)				Load %	Emissions (kg CO2e-q)
		2.50				0.00%	1.34
		0.90				2.00%	0.48
		0.64				12.00%	0.36
		1.60				20.00%	0.91
		0.76				31.00%	0.44
		1.00				38.00%	0.59
		0.75				41.00%	0.45
		0.90				49.00%	0.55
		0.75				61.00%	0.47
		3.94				68.00%	2.52
		4.33				84.00%	2.87
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		0.00				0.00%	0.00
		18.07				**84.00%**	**10.97**
	CO2 all Routes	***173.37***					**10.97**

Vehicle:	V12 (T2)	Stops:	4	Net profit:	-4.31		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 80	0.82	0:02	08:02	08:09	0:09	3.01
2	Customer 78	2.16	0:04	08:11	08:17	0:17	5.26
3	Customer 79	2.72	0:05	08:18	08:21	0:21	6.36
4	Depot	4.31	0:07	08:23		0:23	0.00
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.82	0.00%	0.44
1.33	12.00%	0.74
0.57	21.00%	0.32
1.59	25.00%	0.91
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
4.31	**25.00%**	**2.41**
		2.41

Vehicle:	V13 (T2)	Stops:	8	Net profit:	-22.49		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 81	0.24	0:00	08:00	08:04	0:04	1.58
2	Customer 85	4.90	0:06	08:10	08:11	0:11	1.98
3	Customer 83	5.92	0:08	08:13	08:17	0:17	3.50
4	Customer 84	6.67	0:09	08:18	08:40	0:40	12.17
5	Customer 19	9.47	0:13	08:44	09:00	1:00	18.50
6	Customer 86	14.62	0:19	09:06	09:18	1:18	22.95
7	Customer 87	16.66	0:23	09:22	09:28	1:28	25.30
8	Depot	22.49	0:29	09:34		1:34	0.00
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.24	0.00%	0.13
4.66	7.00%	2.54
1.02	8.00%	0.56
0.74	14.00%	0.41
2.81	48.00%	1.71
5.15	72.00%	3.32
2.04	90.00%	1.37
5.83	99.00%	3.99
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
22.49	**99.00%**	**14.02**
		14.02

Vehicle:	V14 (T2)	Stops:	12	Net profit:	-24.95		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 98	6.33	0:08	08:08	08:09	0:09	0.40
2	Customer 13	6.57	0:08	08:09	08:13	0:13	1.99
3	Customer 15	8.63	0:11	08:16	08:32	0:32	8.17
4	Customer 10	10.04	0:13	08:34	08:35	0:35	8.62
5	Customer 31	11.97	0:15	08:37	08:43	0:43	11.23
6	Customer 32	14.17	0:18	08:46	08:57	0:57	15.14
7	Customer 30	15.27	0:20	08:59	09:06	1:06	18.15
8	Customer 33	15.58	0:21	09:07	09:16	1:16	21.63
9	Customer 38	17.30	0:24	09:19	09:27	1:27	24.72
10	Customer 40	17.64	0:24	09:27	09:28	1:28	25.13
11	Customer 39	18.10	0:25	09:29	09:30	1:30	25.58
12	Depot	24.95	0:32	09:37		1:37	0.00
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.33	0.00%	3.39
0.24	2.00%	0.13
2.06	8.00%	1.13
1.41	32.00%	0.82
1.94	34.00%	1.14
2.20	44.00%	1.32
1.10	59.00%	0.69
0.31	71.00%	0.20
1.72	85.00%	1.14
0.33	97.00%	0.23
0.47	98.00%	0.32
6.85	100.00%	4.70
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
24.95	**100.00%**	**15.20**
		15.20

Vehicle:	V15 (T2)	Stops:	12	Net profit:	-30.75		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 49	4.96	0:06	08:06	08:23	0:23	6.82
2	Customer 60	8.94	0:10	08:27	08:46	0:46	14.24
3	Customer 58	10.70	0:12	08:48	08:54	0:54	16.41
4	Customer 51	12.48	0:15	08:57	09:00	1:00	17.80
5	Customer 52	15.44	0:19	09:04	09:13	1:13	21.10
6	Customer 53	16.09	0:20	09:14	09:15	1:15	21.50
7	Customer 54	17.06	0:21	09:16	09:17	1:17	21.89
8	Customer 55	18.37	0:23	09:19	09:20	1:20	22.34
9	Customer 56	19.68	0:25	09:22	09:24	1:24	23.00
10	Customer 57	20.82	0:27	09:26	09:27	1:27	23.44
11	Customer 50	23.10	0:29	09:29	09:34	1:34	25.42
12	Depot	30.75	0:39	09:44		1:44	0.00
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.96	0.00%	2.65
3.98	27.00%	2.30
1.76	56.00%	1.09
1.78	64.00%	1.12
2.96	70.00%	1.90
0.65	82.00%	0.43
0.97	84.00%	0.64
1.31	86.00%	0.87
1.31	87.00%	0.87
1.15	90.00%	0.77
2.28	92.00%	1.54
7.65	99.00%	5.24
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
30.75	**99.00%**	**19.42**
		19.42

Vehicle:	V16 (T2)	Stops:	11	Net profit:	-29.92		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 59	8.93	0:10	08:10	08:12	0:12	0.88
2	Customer 61	10.34	0:13	08:15	08:28	0:28	6.10
3	Customer 62	11.27	0:14	08:29	08:33	0:33	7.43
4	Customer 65	13.80	0:18	08:37	08:48	0:48	11.70
5	Customer 63	15.97	0:20	08:50	08:57	0:57	14.39
6	Customer 64	17.33	0:21	08:58	09:09	1:09	18.96
7	Customer 66	20.57	0:25	09:13	09:14	1:14	19.39
8	Customer 67	22.69	0:28	09:17	09:28	1:28	23.66
9	Customer 68	24.40	0:30	09:30	09:31	1:31	24.04
10	Customer 76	26.59	0:33	09:34	09:35	1:35	24.39
11	Depot	29.92	0:38	09:40		1:40	0.00
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.93	0.00%	4.78
1.41	4.00%	0.76
0.93	24.00%	0.53
2.53	29.00%	1.47
2.17	46.00%	1.31
1.36	56.00%	0.84
3.24	74.00%	2.10
2.13	76.00%	1.38
1.71	92.00%	1.15
2.19	94.00%	1.48
3.33	95.00%	2.26
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
29.92	**95.00%**	**18.07**
		18.07

Vehicle:	V17 (T2)	Stops:	13	Net profit:	-37.25		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 48	5.73	0:08	08:08	08:09	0:09	0.61
2	Customer 46	10.22	0:14	08:15	08:24	0:24	4.01
3	Customer 45	11.23	0:15	08:25	08:32	0:32	6.88
4	Customer 47	13.49	0:18	08:35	08:44	0:44	10.36
5	Customer 41	16.44	0:22	08:48	09:05	1:05	16.84
6	Customer 44	19.09	0:27	09:10	09:11	1:11	17.26
7	Customer 43	20.80	0:30	09:14	09:18	1:18	18.64
8	Customer 42	21.97	0:31	09:19	09:20	1:20	19.04
9	Customer 36	24.44	0:35	09:24	09:32	1:32	22.49
10	Customer 37	24.88	0:36	09:33	09:35	1:35	22.89
11	Customer 35	26.32	0:38	09:37	09:41	1:41	24.75
12	Customer 34	27.65	0:40	09:43	09:46	1:46	25.67
13	Depot	37.25	0:52	09:58		1:58	0.00
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.73	0.00%	3.07
4.49	3.00%	2.43
1.01	16.00%	0.56
2.26	27.00%	1.30
2.95	41.00%	1.76
2.65	66.00%	1.69
1.71	68.00%	1.09
1.17	73.00%	0.76
2.47	74.00%	1.60
0.44	88.00%	0.29
1.44	89.00%	0.97
1.33	97.00%	0.91
9.59	100.00%	6.59
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
37.25	**100.00%**	**23.01**
		23.01

Vehicle:	V18 (T2)	Stops:	10	Net profit:	-21.84						
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)	
0	Depot	0.00	0:00		08:00	0:00	0.00				
1	Customer 82	3.09	0:04	08:04	08:06	0:06	0.80	3.09	0.00%	1.65	
2	Customer 96	8.95	0:11	08:13	08:17	0:17	2.58	5.87	4.00%	3.18	
3	Customer 93	11.32	0:13	08:19	08:36	0:36	9.31	2.37	11.00%	1.31	
4	Customer 91	12.04	0:14	08:37	08:39	0:39	9.76	0.72	37.00%	0.42	
5	Customer 92	12.14	0:14	08:39	08:43	0:43	11.29	0.11	38.00%	0.06	
6	Customer 90	13.79	0:16	08:45	08:58	0:58	16.59	1.64	44.00%	0.99	
7	Customer 94	14.21	0:16	08:58	08:59	0:59	17.02	0.42	65.00%	0.27	
8	Customer 89	14.93	0:16	08:59	09:02	1:02	18.10	0.72	67.00%	0.46	
9	Customer 88	15.56	0:16	09:02	09:19	1:19	24.82	0.64	71.00%	0.41	
10	Depot	21.84	0:23	09:26		1:26	0.00	6.28	97.00%	4.28	
11								0.00	0.00%	0.00	
12								0.00	0.00%	0.00	
13								0.00	0.00%	0.00	
14								0.00	0.00%	0.00	
15								0.00	0.00%	0.00	
16								0.00	0.00%	0.00	
17								0.00	0.00%	0.00	
18								0.00	0.00%	0.00	
19								0.00	0.00%	0.00	
20								0.00	0.00%	0.00	
21								0.00	0.00%	0.00	
22								0.00	0.00%	0.00	
23								0.00	0.00%	0.00	
24								0.00	0.00%	0.00	
25								0.00	0.00%	0.00	
26								0.00	0.00%	0.00	
27								0.00	0.00%	0.00	
28								0.00	0.00%	0.00	
								21.84	**97.00%**	**13.03**	
										13.03	

Vehicle:	V21 (T3)	Stops:	28	Net profit:	-73.61		
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Load
0	Depot	0.00	0:00		08:00	0:00	0.00
1	Customer 11	7.15	0:10	08:10	08:17	0:17	2.81
2	Customer 12	7.82	0:11	08:18	08:21	0:21	3.93
3	Customer 14	11.12	0:16	08:26	08:30	0:30	5.60
4	Customer 28	12.14	0:17	08:31	08:32	0:32	6.01
5	Customer 29	12.62	0:17	08:32	08:38	0:38	8.35
6	Customer 9	14.89	0:20	08:41	08:46	0:46	10.23
7	Customer 8	16.18	0:23	08:49	09:01	1:01	14.98
8	Customer 7	18.75	0:27	09:05	09:16	1:16	19.25
9	Customer 16	21.38	0:31	09:20	09:25	1:25	20.98
10	Customer 5	22.80	0:33	09:27	09:28	1:28	21.38
11	Customer 4	23.41	0:34	09:29	09:36	1:36	24.32
12	Customer 1	27.46	0:38	09:40	09:49	1:49	27.56
13	Customer 18	27.52	0:38	09:49	09:49	1:49	27.93
14	Customer 3	28.55	0:40	09:51	09:57	1:57	29.88
15	Customer 17	29.84	0:43	10:00	10:03	2:03	31.27
16	Customer 6	30.65	0:45	10:05	10:11	2:11	33.72
17	Customer 2	36.02	0:54	10:20	10:22	2:22	34.15
18	Customer 20	39.91	1:00	10:28	10:35	2:35	37.09
19	Customer 21	42.16	1:04	10:39	10:42	2:42	38.33
20	Customer 22	45.25	1:09	10:47	10:48	2:48	38.78
21	Customer 23	47.30	1:12	10:51	11:04	3:04	43.76
22	Customer 24	50.76	1:17	11:09	11:10	3:10	44.19
23	Customer 25	53.54	1:21	11:14	11:16	3:16	44.78
24	Customer 26	60.04	1:29	11:24	11:25	3:25	45.15
25	Customer 95	64.26	1:35	11:31	11:46	3:46	51.08
26	Customer 27	64.78	1:35	11:46	11:56	3:56	54.80
27	Customer 97	66.70	1:37	11:58	12:16	4:16	61.91
28	Depot	73.61	1:46	12:25		4:25	0.00

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.15	0.00%	4.46
0.67	5.00%	0.43
3.29	7.00%	2.11
1.03	10.00%	0.67
0.48	10.00%	0.31
2.27	14.00%	1.51
1.29	17.00%	0.87
2.57	25.00%	1.80
2.63	31.00%	1.89
1.42	34.00%	1.03
0.61	35.00%	0.44
4.06	40.00%	3.02
0.05	45.00%	0.04
1.03	45.00%	0.78
1.29	49.00%	1.00
0.82	51.00%	0.63
5.37	55.00%	4.24
3.89	55.00%	3.07
2.26	60.00%	1.82
3.09	62.00%	2.51
2.04	63.00%	1.67
3.47	71.00%	2.91
2.77	72.00%	2.34
6.50	73.00%	5.50
4.22	73.00%	3.57
0.52	83.00%	0.46
1.93	89.00%	1.72
6.90	100.00%	6.41
0.00	0.00%	0.00
0.00	0.00%	0.00
73.61	**100.00%**	**57.23**
		57.23

Scenario 5 routing

Total net profit:	-261.04	35	10

Vehicle:	V1	Stops:	11	Net profit:	-17.72			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot A	0.00	0:00		08:00	0:00	0	0.00
1	Customer 75	2.50	0:04	08:04	08:05	0:05	0	0.43
2	Customer 76	3.33	0:05	08:06	08:07	0:07	0	0.78
3	Customer 70	3.69	0:06	08:08	08:12	0:12	0	2.63
4	Customer 71	5.29	0:08	08:14	08:22	0:22	0	5.64
5	Customer 72	6.05	0:09	08:23	08:28	0:28	0	7.39
6	Customer 73	7.05	0:10	08:29	08:31	0:31	0	8.19
7	Customer 74	7.80	0:12	08:33	08:38	0:38	0	10.27
8	Customer 99	9.45	0:14	08:40	08:44	0:44	0	11.96
9	Customer 100	10.19	0:15	08:45	08:53	0:53	0	15.08
10	Customer 69	13.39	0:18	08:56	09:07	1:07	0	19.35
11	Depot A	17.72	0:25	09:14		1:14	0	0.00
12								
13								
14								
15								
16								
17								

	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
	2.50	0.00%	1.34
	0.82	2.00%	0.44
	0.37	4.00%	0.20
	1.60	11.00%	0.88
	0.76	22.00%	0.43
	1.00	29.00%	0.58
	0.75	32.00%	0.44
	1.65	40.00%	0.98
	0.75	47.00%	0.45
	3.19	59.00%	2.00
	4.33	76.00%	2.81
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
Total	**17.72**	**76.00%**	11.52
CO2 all Routes	***176.17***		**11.52**

Vehicle:	V2	Stops:	7	Net profit:	-17.14			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot A	0.00	0:00		08:00	0:00	0	0.00
1	Customer 81	0.24	0:00	08:00	08:04	0:04	0	1.58
2	Customer 82	1.54	0:01	08:05	08:07	0:07	0	2.38
3	Customer 19	3.23	0:04	08:10	08:26	0:26	0	8.71
4	Customer 87	6.34	0:07	08:29	08:35	0:35	0	11.07
5	Customer 86	8.38	0:10	08:38	08:49	0:49	0	15.51
6	Customer 88	10.86	0:14	08:53	09:11	1:11	0	22.23
7	Depot A	17.14	0:20	09:17		1:17	0	0.00
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								

	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
	0.24	0.00%	0.13
	1.30	7.00%	0.71
	1.69	10.00%	0.93
	3.11	34.00%	1.83
	2.04	44.00%	1.23
	2.49	61.00%	1.56
	6.28	87.00%	4.19
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	17.14	**87.00%**	11.43
			11.43

Vehicle:	V3	Stops:	10	Net profit:	-21.00				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0	Depot A	0.00	0:00		08:00	0:00	0	0.00	6.33	0.00%	3.39
1	Customer 98	6.33	0:08	08:08	08:09	0:09	0	0.40	3.04	2.00%	1.64
2	Customer 27	9.38	0:12	08:13	08:22	0:22	0	4.12	0.52	16.00%	0.29
3	Customer 95	9.90	0:12	08:22	08:37	0:37	0	10.05	0.58	40.00%	0.35
4	Customer 93	10.48	0:12	08:37	08:55	0:55	0	16.77	0.72	66.00%	0.46
5	Customer 91	11.20	0:13	08:56	08:57	0:57	0	17.23	0.11	67.00%	0.07
6	Customer 92	11.30	0:13	08:57	09:01	1:01	0	18.76	1.64	73.00%	1.06
7	Customer 90	12.94	0:15	09:03	09:17	1:17	0	24.06	0.42	94.00%	0.29
8	Customer 94	13.37	0:15	09:17	09:18	1:18	0	24.49	0.72	96.00%	0.49
9	Customer 89	14.09	0:15	09:18	09:20	1:20	0	25.57	6.92	100.00%	4.75
10	Depot A	21.00	0:22	09:27		1:27	0	0.00	0.00	0.00%	0.00
11									0.00	0.00%	0.00
12									0.00	0.00%	0.00
13									0.00	0.00%	0.00
14									0.00	0.00%	0.00
15									0.00	0.00%	0.00
16									0.00	0.00%	0.00
17									**21.00**	**100.00%**	14.42
											14.42

Vehicle:	V4	Stops:	4	Net profit:	-4.31				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0	Depot A	0.00	0:00		08:00	0:00	0	0	0.82	0.00%	0.44
1	Customer 80	0.82	0:02	08:02	08:09	0:09	0	3.01	0.76	12.00%	0.42
2	Customer 79	1.59	0:03	08:10	08:13	0:13	0	4.11	0.57	16.00%	0.32
3	Customer 78	2.16	0:04	08:14	08:20	0:20	0	6.36	2.16	25.00%	1.24
4	Depot A	4.31	0:07	08:23		0:23	0	0.00	0.00	0.00%	0.00
5									0.00	0.00%	0.00
6									0.00	0.00%	0.00
7									0.00	0.00%	0.00
8									0.00	0.00%	0.00
9									0.00	0.00%	0.00
10									0.00	0.00%	0.00
11									0.00	0.00%	0.00
12									0.00	0.00%	0.00
13									0.00	0.00%	0.00
14									0.00	0.00%	0.00
15									0.00	0.00%	0.00
16									0.00	0.00%	0.00
17									**4.31**	**25.00%**	2.47
											2.47

Vehicle:	V5	Stops:	8	Net profit:	-24.49			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot A	0.00	0:00		08:00	0:00	0	0
1	Customer 85	4.90	0:06	08:06	08:07	0:07	0	0.40
2	Customer 83	5.92	0:08	08:09	08:12	0:12	0	1.92
3	Customer 84	6.67	0:09	08:13	08:36	0:36	0	10.59
4	Customer 49	13.00	0:18	08:45	09:02	1:02	0	17.42
5	Customer 67	16.92	0:22	09:06	09:17	1:17	0	21.68
6	Customer 68	18.63	0:24	09:19	09:20	1:20	0	22.07
7	Customer 77	21.09	0:28	09:24	09:31	1:31	0	24.68
8	Depot A	24.49	0:32	09:35		1:35	0	0.00
9								
10								
11								
12								
13								
14								
15								
16								
17								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.90	0.00%	2.62
1.02	2.00%	0.55
0.74	8.00%	0.41
6.34	42.00%	3.80
3.91	68.00%	2.50
1.71	85.00%	1.14
2.47	86.00%	1.64
3.40	96.00%	2.31
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
24.49	**96.00%**	16.67
		16.67

Depot B **65** **9**

Vehicle:	V11	Stops:	10	Net profit:	-16.61			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0
1	Customer 11	3.72	0:08	08:08	08:15	0:15	0	2.81
2	Customer 12	4.39	0:09	08:16	08:19	0:19	0	3.93
3	Customer 13	5.99	0:12	08:22	08:26	0:26	0	5.53
4	Customer 97	7.34	0:14	08:28	08:46	0:46	0	12.64
5	Customer 96	8.00	0:15	08:47	08:52	0:52	0	14.42
6	Customer 28	9.43	0:17	08:54	08:55	0:55	0	14.83
7	Customer 14	10.46	0:18	08:56	09:00	1:00	0	16.50
8	Customer 15	11.34	0:19	09:01	09:17	1:17	0	22.68
9	Customer 31	14.68	0:23	09:21	09:28	1:28	0	25.28
10	Depot B	16.61	0:28	09:33		1:33	0	0.00
11								
12								
13								
14								
15								
16								
17								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
3.72	0.00%	1.99
0.67	11.00%	0.37
1.60	16.00%	0.90
1.36	22.00%	0.77
0.66	50.00%	0.40
1.42	57.00%	0.89
1.03	58.00%	0.64
0.88	65.00%	0.56
3.35	89.00%	2.24
1.93	99.00%	1.32
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
16.61	**99.00%**	11.38
		11.38

Vehicle:	V12	Stops:	12	Net profit:	-29.51				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot B	0.00	0:00		08:00	0:00	0	0	
1	Customer 51	4.83	0:07	08:07	08:10	0:10	0	1.39	
2	Customer 66	8.49	0:13	08:16	08:17	0:17	0	1.82	
3	Customer 65	10.91	0:16	08:20	08:31	0:31	0	6.09	
4	Customer 64	11.73	0:17	08:32	08:44	0:44	0	10.65	
5	Customer 63	13.08	0:18	08:45	08:52	0:52	0	13.35	
6	Customer 62	17.79	0:25	08:59	09:02	1:02	0	14.68	
7	Customer 61	18.71	0:27	09:04	09:18	1:18	0	19.90	
8	Customer 59	20.12	0:30	09:21	09:23	1:23	0	20.78	
9	Customer 57	22.62	0:33	09:26	09:27	1:27	0	21.21	
10	Customer 50	24.90	0:36	09:30	09:35	1:35	0	23.20	
11	Customer 48	26.81	0:39	09:38	09:40	1:40	0	23.81	
12	Depot B	29.51	0:43	09:44		1:44	0	0	
13									
14									
15									
16									
17									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.83	0.00%	2.59
3.66	6.00%	1.99
2.42	8.00%	1.33
0.82	24.00%	0.47
1.36	42.00%	0.81
4.71	52.00%	2.89
0.93	58.00%	0.58
1.41	78.00%	0.92
2.49	81.00%	1.64
2.28	83.00%	1.51
1.92	91.00%	1.29
2.70	93.00%	1.82
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
29.51	**93.00%**	19.95
		19.95

Vehicle:	V13	Stops:	9	Net profit:	-24.65				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot B	0.00	0:00		08:00	0:00	0	0	
1	Customer 5	9.50	0:16	08:16	08:17	0:17	0	0.39	
2	Customer 4	10.11	0:17	08:18	08:25	0:25	0	3.34	
3	Customer 16	10.92	0:19	08:27	08:32	0:32	0	5.07	
4	Customer 7	13.54	0:24	08:37	08:48	0:48	0	9.34	
5	Customer 8	16.11	0:28	08:52	09:04	1:04	0	14.09	
6	Customer 33	21.50	0:35	09:11	09:20	1:20	0	17.57	
7	Customer 30	21.80	0:35	09:20	09:28	1:28	0	20.58	
8	Customer 32	22.90	0:37	09:30	09:40	1:40	0	24.49	
9	Depot B	24.65	0:41	09:44		1:44	0	0.00	
10									
11									
12									
13									
14									
15									
16									
17									

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
9.50	0.00%	5.09
0.61	2.00%	0.33
0.81	13.00%	0.45
2.63	20.00%	1.49
2.57	37.00%	1.52
5.38	55.00%	3.33
0.31	69.00%	0.20
1.10	80.00%	0.72
1.75	96.00%	1.19
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
24.65	**96.00%**	16.77
		16.77

Vehicle:	V14	Stops:	11	Net profit:	-25.53			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0
1	Customer 47	3.64	0:07	08:07	08:15	0:15	0	3.48
2	Customer 46	4.89	0:09	08:17	08:26	0:26	0	6.88
3	Customer 45	5.90	0:11	08:28	08:36	0:36	0	9.75
4	Customer 52	10.54	0:18	08:43	08:51	0:51	0	13.05
5	Customer 53	11.19	0:19	08:52	08:53	0:53	0	13.45
6	Customer 54	12.17	0:21	08:55	08:56	0:56	0	13.84
7	Customer 55	13.48	0:23	08:58	08:59	0:59	0	14.29
8	Customer 56	14.78	0:25	09:01	09:03	1:03	0	14.95
9	Customer 60	17.16	0:28	09:06	09:25	1:25	0	22.37
10	Customer 58	18.92	0:31	09:28	09:34	1:34	0	24.54
11	Depot B	25.53	0:41	09:44		1:44	0	0.00
12								
13								
14								
15								
16								
17								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
3.64	0.00%	1.95
1.25	14.00%	0.69
1.01	27.00%	0.58
4.64	38.00%	2.75
0.65	51.00%	0.40
0.97	53.00%	0.60
1.31	54.00%	0.81
1.31	56.00%	0.81
2.38	59.00%	1.48
1.76	87.00%	1.18
6.61	96.00%	4.50
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
25.53	**96.00%**	17.37
		17.37

Vehicle:	V15	Stops:	12	Net profit:	-20.88			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0
1	Customer 39	1.09	0:03	08:03	08:04	0:04	0	0.45
2	Customer 40	1.56	0:04	08:05	08:06	0:06	0	0.86
3	Customer 38	2.20	0:06	08:08	08:16	0:16	0	3.95
4	Customer 41	5.83	0:12	08:22	08:38	0:38	0	10.43
5	Customer 44	8.48	0:17	08:43	08:44	0:44	0	10.85
6	Customer 43	10.19	0:20	08:47	08:51	0:51	0	12.23
7	Customer 42	11.36	0:21	08:52	08:53	0:53	0	12.63
8	Customer 36	13.83	0:25	08:57	09:06	1:06	0	16.08
9	Customer 37	14.27	0:26	09:07	09:08	1:08	0	16.48
10	Customer 35	15.71	0:28	09:10	09:15	1:15	0	18.34
11	Customer 34	17.04	0:30	09:17	09:19	1:19	0	19.26
12	Depot B	20.88	0:37	09:26		1:26	0	0
13								
14								
15								
16								
17								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
1.09	0.00%	0.59
0.47	2.00%	0.25
0.64	4.00%	0.35
3.63	16.00%	2.03
2.65	41.00%	1.59
1.71	43.00%	1.03
1.17	48.00%	0.71
2.47	50.00%	1.51
0.44	63.00%	0.28
1.44	65.00%	0.91
1.33	72.00%	0.86
3.84	75.00%	2.49
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
20.88	**75.00%**	13.55
		13.55

Vehicle:	V16	Stops:	17	Net profit:	-59.18			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0
1	Customer 10	3.87	0:07	08:07	08:08	0:08	0	0.46
2	Customer 9	8.40	0:14	08:15	08:20	0:20	0	2.33
3	Customer 1	14.96	0:21	08:27	08:35	0:35	0	5.57
4	Customer 18	15.01	0:21	08:35	08:36	0:36	0	5.94
5	Customer 3	16.04	0:23	08:38	08:43	0:43	0	7.89
6	Customer 6	17.81	0:27	08:47	08:53	0:53	0	10.34
7	Customer 17	18.62	0:29	08:55	08:59	0:59	0	11.73
8	Customer 2	23.52	0:38	09:08	09:09	1:09	0	12.16
9	Customer 20	27.40	0:44	09:15	09:22	1:22	0	15.10
10	Customer 21	29.66	0:48	09:26	09:30	1:30	0	16.34
11	Customer 22	32.75	0:54	09:36	09:37	1:37	0	16.79
12	Customer 23	34.79	0:58	09:41	09:54	1:54	0	21.77
13	Customer 24	38.26	1:04	10:00	10:01	2:01	0	22.20
14	Customer 25	41.03	1:08	10:05	10:06	2:06	0	22.79
15	Customer 26	47.53	1:16	10:14	10:15	2:15	0	23.16
16	Customer 29	52.48	1:23	10:22	10:28	2:28	0	25.50
17	Depot B	59.18	1:34	10:39		2:39	0	0

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
3.87	0.00%	2.07
4.53	2.00%	2.44
6.56	10.00%	3.60
0.05	22.00%	0.03
1.03	24.00%	0.59
1.76	31.00%	1.03
0.82	41.00%	0.49
4.89	46.00%	2.96
3.89	48.00%	2.36
2.26	59.00%	1.41
3.09	64.00%	1.95
2.04	66.00%	1.30
3.47	85.00%	2.30
2.77	87.00%	1.85
6.50	89.00%	4.36
4.94	90.00%	3.32
6.71	100.00%	4.61
59.18	**100.00%**	40.63
		40.63

Scenario 6 routing

Total net profit:	**-218.68**		**3**					
		Depot A	**11**					
Vehicle:	**V1 (T1)**	**Stops:**	**4**	**Net profit:**	**-4.31**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot A	0.00	0:00		08:00	0:00	0	0.00
1	Customer 80	0.82	0:02	08:02	08:09	0:09	0	3.01
2	Customer 79	1.59	0:03	08:10	08:13	0:13	0	4.11
3	Customer 78	2.16	0:04	08:14	08:20	0:20	0	6.36
4	Depot A	4.31	0:07	08:23		0:23	0	0.00
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								

Detected reasons of infeasibility		Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
		0.82	0.00%	0.44
		0.76	12.00%	0.42
		0.57	16.00%	0.32
		2.16	25.00%	1.24
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
		0.00	0.00%	0.00
	Total	**4.31**	**25.00%**	2.47
	CO2 all Routes	***140.76***		**2.47**

Vehicle:	V2 (T1)	Stops:	6	Net profit:	-16.24			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot A	0.00	0:00		08:00	0:00	0	0.00
1	Customer 81	0.24	0:00	08:00	08:04	0:04	0	1.58
2	Customer 82	1.54	0:01	08:05	08:07	0:07	0	2.38
3	Customer 19	3.23	0:04	08:10	08:26	0:26	0	8.71
4	Customer 87	6.34	0:07	08:29	08:35	0:35	0	11.07
5	Customer 86	8.38	0:10	08:38	08:49	0:49	0	15.51
6	Depot A	16.24	0:20	08:59		0:59	0	0.00
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.24	0.00%	0.13
1.30	7.00%	0.71
1.69	10.00%	0.93
3.11	34.00%	1.83
2.04	44.00%	1.23
7.87	61.00%	4.94
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
16.24	**61.00%**	10.20
		10.20

Vehicle:	V3 (T1)	Stops:	4	Net profit:	-11.88			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot A	0.00	0:00		08:00	0:00	0	0.00
1	Customer 85	4.90	0:06	08:06	08:07	0:07	0	0.40
2	Customer 84	5.98	0:08	08:09	08:31	0:31	0	9.07
3	Customer 83	6.72	0:10	08:33	08:37	0:37	0	10.59
4	Depot A	11.88	0:16	08:43		0:43	0	0.00
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.90	0.00%	2.62
1.08	2.00%	0.58
0.74	36.00%	0.44
5.16	42.00%	3.09
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
11.88	**42.00%**	7.11
		7.11

Vehicle:	V6 (T2)	Stops:	20	Net profit:	-35.44			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot A	0.00	0:00		08:00	0:00	0	0.00
1	Customer 75	2.50	0:04	08:04	08:05	0:05	0	0.43
2	Customer 77	3.40	0:05	08:06	08:12	0:12	0	3.04
3	Customer 76	3.68	0:06	08:13	08:14	0:14	0	3.39
4	Customer 70	4.04	0:07	08:15	08:20	0:20	0	5.25
5	Customer 69	4.68	0:08	08:21	08:32	0:32	0	9.52
6	Customer 71	5.64	0:09	08:33	08:41	0:41	0	12.53
7	Customer 72	6.40	0:10	08:42	08:46	0:46	0	14.28
8	Customer 73	7.40	0:11	08:47	08:49	0:49	0	15.08
9	Customer 74	8.15	0:13	08:51	08:57	0:57	0	17.16
10	Customer 100	9.05	0:15	08:59	09:07	1:07	0	20.28
11	Customer 99	9.80	0:16	09:08	09:12	1:12	0	21.97
12	Customer 68	14.63	0:21	09:17	09:18	1:18	0	22.35
13	Customer 67	16.34	0:23	09:20	09:31	1:31	0	26.62
14	Customer 66	18.47	0:26	09:34	09:35	1:35	0	27.05
15	Customer 65	20.89	0:29	09:38	09:49	1:49	0	31.32
16	Customer 63	23.06	0:31	09:51	09:58	1:58	0	34.02
17	Customer 64	24.42	0:32	09:59	10:11	2:11	0	38.58
18	Customer 60	26.50	0:34	10:13	10:32	2:32	0	46.00
19	Customer 49	30.48	0:37	10:35	10:53	2:53	0	52.82
20	Depot A	35.44	0:43	10:59		2:59	0	0.00
21								
22								
23								
24								
25								
26								
27								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
2.50	0.00%	1.56
0.90	1.00%	0.56
0.28	5.00%	0.18
0.37	6.00%	0.23
0.64	9.00%	0.41
0.97	16.00%	0.65
0.76	21.00%	0.52
1.00	23.00%	0.69
0.75	25.00%	0.52
0.90	28.00%	0.64
0.75	33.00%	0.54
4.83	36.00%	3.54
1.71	36.00%	1.25
2.13	43.00%	1.60
2.42	44.00%	1.83
2.17	51.00%	1.69
1.36	55.00%	1.07
2.08	63.00%	1.70
3.98	75.00%	3.39
4.96	85.00%	4.37
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
35.44	**85.00%**	23.53
		23.53

	Depot B								
Vehicle:	V11 (T1)	Stops:	14	Net profit:	-26.97				
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load	
0	Depot B	0.00	0:00		08:00	0:00	0	0.00	
1	Customer 52	5.09	0:08	08:08	08:16	0:16	0	3.31	
2	Customer 53	5.74	0:09	08:17	08:18	0:18	0	3.70	
3	Customer 54	6.71	0:11	08:20	08:21	0:21	0	4.10	
4	Customer 55	8.02	0:13	08:23	08:24	0:24	0	4.54	
5	Customer 56	9.33	0:15	08:26	08:28	0:28	0	5.20	
6	Customer 57	10.48	0:17	08:30	08:31	0:31	0	5.64	
7	Customer 59	12.97	0:20	08:34	08:36	0:36	0	6.52	
8	Customer 62	15.30	0:25	08:41	08:45	0:45	0	7.85	
9	Customer 61	16.23	0:27	08:47	09:00	1:00	0	13.07	
10	Customer 58	19.40	0:33	09:06	09:12	1:12	0	15.24	
11	Customer 51	21.18	0:36	09:15	09:18	1:18	0	16.63	
12	Customer 50	22.35	0:38	09:20	09:25	1:25	0	18.61	
13	Customer 48	24.27	0:41	09:28	09:30	1:30	0	19.23	
14	Depot B	26.97	0:45	09:34		1:34	0	0.00	
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26									
27									

		Distance Travelled (km)		Load %	Emissions (kg CO2e-q)
		5.09		0.00%	2.73
		0.65		13.00%	0.36
		0.97		15.00%	0.54
		1.31		16.00%	0.73
		1.31		18.00%	0.73
		1.15		21.00%	0.65
		2.49		22.00%	1.42
		2.34		26.00%	1.34
		0.93		31.00%	0.54
		3.17		51.00%	1.94
		1.78		60.00%	1.11
		1.18		65.00%	0.75
		1.92		73.00%	1.24
		2.70		75.00%	1.75
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
		0.00		0.00%	0.00
	Total	**26.97**		**75.00%**	17.50
					17.50

Vehicle:	V16 (T2)	Stops:	18	Net profit:	-23.89			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0.00
1	Customer 11	3.72	0:08	08:08	08:15	0:15	0	2.81
2	Customer 12	4.39	0:09	08:16	08:19	0:19	0	3.93
3	Customer 13	5.99	0:12	08:22	08:26	0:26	0	5.53
4	Customer 98	6.22	0:12	08:26	08:27	0:27	0	5.92
5	Customer 88	8.61	0:16	08:31	08:48	0:48	0	12.64
6	Customer 89	9.25	0:16	08:48	08:51	0:51	0	13.73
7	Customer 94	9.97	0:16	08:51	08:52	0:52	0	14.16
8	Customer 90	10.39	0:16	08:52	09:06	1:06	0	19.45
9	Customer 91	12.14	0:18	09:08	09:09	1:09	0	19.90
10	Customer 92	12.25	0:18	09:09	09:13	1:13	0	21.44
11	Customer 93	12.86	0:19	09:14	09:31	1:31	0	28.16
12	Customer 95	13.44	0:19	09:31	09:46	1:46	0	34.09
13	Customer 27	13.96	0:19	09:46	09:56	1:56	0	37.82
14	Customer 96	15.22	0:21	09:58	10:03	2:03	0	39.60
15	Customer 97	15.89	0:22	10:04	10:22	2:22	0	46.71
16	Customer 10	20.02	0:29	10:29	10:30	2:30	0	47.16
17	Customer 31	21.96	0:31	10:32	10:39	2:39	0	49.77
18	Depot B	23.89	0:36	10:44		2:44	0	0.00
19								
20								
21								
22								
23								
24								
25								
26								
27								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
3.72	0.00%	2.32
0.67	5.00%	0.43
1.60	7.00%	1.03
0.24	9.00%	0.15
2.39	10.00%	1.56
0.64	21.00%	0.44
0.72	23.00%	0.50
0.42	23.00%	0.29
1.75	32.00%	1.26
0.11	33.00%	0.08
0.61	35.00%	0.45
0.58	46.00%	0.44
0.52	55.00%	0.41
1.26	61.00%	1.02
0.66	64.00%	0.54
4.14	76.00%	3.54
1.94	76.00%	1.66
1.93	81.00%	1.68
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
23.89	**81.00%**	15.72
		15.72

Vehicle:	V17 (T2)	Stops:	4	Net profit:	-11.78			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0.00
1	Customer 47	3.64	0:07	08:07	08:15	0:15	0	3.48
2	Customer 46	4.89	0:09	08:17	08:26	0:26	0	6.88
3	Customer 45	5.90	0:11	08:28	08:36	0:36	0	9.75
4	Depot B	11.78	0:20	08:45		0:45	0	0.00
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
3.64	0.00%	2.27
1.25	6.00%	0.80
1.01	12.00%	0.67
5.88	16.00%	3.95
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
11.78	**16.00%**	6.59
		6.59

11

Vehicle:	V18 (T2)	Stops:	12	Net profit:	-20.88			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0.00
1	Customer 39	1.09	0:03	08:03	08:04	0:04	0	0.45
2	Customer 40	1.56	0:04	08:05	08:06	0:06	0	0.86
3	Customer 38	2.20	0:06	08:08	08:16	0:16	0	3.95
4	Customer 34	4.22	0:09	08:19	08:21	0:21	0	4.87
5	Customer 35	5.55	0:11	08:23	08:28	0:28	0	6.73
6	Customer 37	7.00	0:14	08:31	08:32	0:32	0	7.14
7	Customer 36	7.43	0:15	08:33	08:42	0:42	0	10.58
8	Customer 42	9.90	0:19	08:46	08:47	0:47	0	10.99
9	Customer 43	11.07	0:20	08:48	08:51	0:51	0	12.36
10	Customer 44	12.78	0:23	08:54	08:55	0:55	0	12.78
11	Customer 41	15.43	0:28	09:00	09:17	1:17	0	19.26
12	Depot B	20.88	0:37	09:26		1:26	0	0.00
13								
14								
15								
16								
17								
18								
19								
20								
21								
22								
23								
24								
25								
26								
27								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
1.09	0.00%	0.68
0.47	1.00%	0.29
0.64	2.00%	0.40
2.02	7.00%	1.30
1.33	8.00%	0.86
1.44	11.00%	0.95
0.44	12.00%	0.29
2.47	18.00%	1.67
1.17	18.00%	0.79
1.71	20.00%	1.17
2.65	21.00%	1.82
5.45	31.00%	3.91
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
20.88	**31.00%**	12.16
		12.16

Vehicle:	V19 (T2)	Stops:	27	Net profit:	-67.29			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot B	0.00	0:00		08:00	0:00	0	0.00
1	Customer 32	1.75	0:05	08:05	08:15	0:15	0	3.91
2	Customer 30	2.85	0:07	08:17	08:24	0:24	0	6.92
3	Customer 33	3.15	0:08	08:25	08:34	0:34	0	10.40
4	Customer 8	8.54	0:15	08:41	08:54	0:54	0	15.15
5	Customer 9	9.83	0:17	08:56	09:00	1:00	0	17.03
6	Customer 7	13.14	0:22	09:05	09:16	1:16	0	21.30
7	Customer 2	17.84	0:29	09:23	09:24	1:24	0	21.72
8	Customer 20	21.73	0:35	09:30	09:38	1:38	0	24.67
9	Customer 21	23.98	0:39	09:42	09:45	1:45	0	25.91
10	Customer 22	27.07	0:45	09:51	09:52	1:52	0	26.36
11	Customer 23	29.12	0:49	09:56	10:09	2:09	0	31.33
12	Customer 24	32.58	0:55	10:15	10:16	2:16	0	31.77
13	Customer 25	35.35	0:59	10:20	10:22	2:22	0	32.36
14	Customer 26	41.86	1:07	10:30	10:31	2:31	0	32.72
15	Customer 3	47.30	1:14	10:38	10:43	2:43	0	34.67
16	Customer 17	48.59	1:17	10:46	10:49	2:49	0	36.06
17	Customer 6	49.41	1:19	10:51	10:58	2:58	0	38.51
18	Customer 18	52.02	1:24	11:03	11:04	3:04	0	38.88
19	Customer 1	52.08	1:24	11:04	11:12	3:12	0	42.12
20	Customer 16	56.38	1:30	11:18	11:23	3:23	0	43.85
21	Customer 4	57.18	1:32	11:25	11:32	3:32	0	46.80
22	Customer 5	57.79	1:33	11:33	11:34	3:34	0	47.19
23	Customer 28	60.11	1:37	11:38	11:39	3:39	0	47.60
24	Customer 29	60.59	1:37	11:39	11:45	3:45	0	49.95
25	Customer 14	61.13	1:38	11:46	11:51	3:51	0	51.62
26	Customer 15	62.01	1:39	11:52	12:07	4:07	0	57.79
27	Depot B	67.29	1:48	12:16		4:16	0	0.00

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
1.75	0.00%	1.09
1.10	7.00%	0.71
0.31	12.00%	0.20
5.38	17.00%	3.63
1.29	25.00%	0.90
3.31	28.00%	2.35
4.70	35.00%	3.43
3.89	35.00%	2.84
2.26	40.00%	1.68
3.09	42.00%	2.32
2.04	43.00%	1.54
3.47	51.00%	2.70
2.77	52.00%	2.17
6.50	53.00%	5.10
5.45	53.00%	4.27
1.29	56.00%	1.03
0.81	59.00%	0.65
2.62	62.00%	2.12
0.05	63.00%	0.04
4.30	68.00%	3.57
0.81	71.00%	0.68
0.61	76.00%	0.52
2.31	76.00%	1.98
0.48	77.00%	0.41
0.55	81.00%	0.48
0.88	84.00%	0.77
5.28	93.00%	4.79
67.29	**93.00%**	45.49
		45.49

Scenario 7 routing

Total net profit: **-613.07**

Vehicle:	**V1**		**Stops:**	**5**	**Net profit:**	**-27.34**			
Stop count	**Location Name**	**Location ID**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0	0.00	0:00		08:00	0:00	0	0.00
1	Customer 39	39	6.85	0:07	08:07	08:56	0:56	0	0.45
2	Customer 45	45	12.62	0:15	09:04	14:38	6:38	0	3.32
3	Customer 46	46	13.63	0:16	14:39	21:16	13:16	0	6.72
4	Customer 58	58	18.79	0:23	21:23	01:35	17:35	0	8.89
5	Depot	0	27.34	0:33	01:45		17:45	0	0.00
6									
7									
8									
9									

	Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
	6.85	0.00%	4.27
	5.78	3.00%	3.65
	1.01	20.00%	0.69
	5.16	40.00%	3.84
	8.56	53.00%	6.72
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.00
	0.00	0.00%	0.000
Total	**27.34**	**53.00%**	**19.17**
CO2 all Routes	***430.59***		**19.17**

Vehicle:	**V2**	**Stops:**	**4**	**Net profit:**	**-21.51**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 11	7.15	0:10	08:10	13:37	5:37	0	2.81
2	Customer 13	9.42	0:13	13:40	16:45	8:45	0	4.41
3	Customer 86	13.64	0:20	16:52	01:31	17:31	0	8.85
4	Depot	21.51	0:30	01:41		17:41	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.15	0.00%	4.46
2.27	17.00%	1.53
4.22	27.00%	2.97
7.87	53.00%	6.17
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
21.51	**53.00%**	**15.14**
		15.14

Vehicle:	**V3**	**Stops:**	**4**	**Net profit:**	**-4.31**			
Stop count	**Location Name**	**Distance travelled**	**Driving time**	**Arrival time**	**Departure time**	**Working time**	**Profit collected**	**Load**
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 80	0.82	0:02	08:02	13:53	5:53	0	3.01
2	Customer 79	1.59	0:03	13:54	16:00	8:00	0	4.11
3	Customer 78	2.16	0:04	16:01	20:23	12:23	0	6.36
4	Depot	4.31	0:07	20:26		12:26	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.82	0.00%	0.51
0.76	18.00%	0.52
0.57	25.00%	0.40
2.16	38.00%	1.59
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
4.31	**38.00%**	**3.02**
		3.02

Vehicle:	V4	Stops:	4	Net profit:	-21.25			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 35	10.11	0:11	08:11	11:46	3:46	0	1.86
2	Customer 33	12.34	0:14	11:49	18:35	10:35	0	5.34
3	Customer 30	12.65	0:14	18:35	00:26	16:26	0	8.35
4	Depot	21.25	0:25	00:37		16:37	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
10.11	0.00%	6.30
2.23	12.00%	1.47
0.31	32.00%	0.22
8.60	50.00%	6.67
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
21.25	**50.00%**	**14.67**
		14.67

Vehicle:	V5	Stops:	3	Net profit:	-11.19			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 85	4.90	0:06	08:06	08:50	0:50	0	0.40
2	Customer 84	5.98	0:08	08:52	01:47	17:47	0	9.07
3	Depot	11.19	0:15	01:54		17:54	0	0.00
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.90	0.00%	3.05
1.08	3.00%	0.68
5.21	55.00%	4.12
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
11.19	**55.00%**	**7.86**
		7.86

Vehicle:	V6	Stops:	5	Net profit:	-7.73			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 75	2.50	0:04	08:04	08:51	0:51	0	0.43
2	Customer 76	3.33	0:05	08:52	09:30	1:30	0	0.78
3	Customer 70	3.69	0:05	09:30	13:06	5:06	0	2.63
4	Customer 77	4.33	0:06	13:07	18:11	10:11	0	5.25
5	Depot	7.73	0:11	18:16		10:16	0	0.00
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
2.50	0.00%	1.56
0.82	3.00%	0.52
0.37	5.00%	0.23
0.64	16.00%	0.43
3.40	32.00%	2.45
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
7.73	**32.00%**	**5.20**
		5.20

Vehicle:	V7	Stops:	2	Net profit:	-9.91			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 49	4.96	0:06	08:06	21:25	13:25	0	6.82
2	Depot	9.91	0:12	21:31		13:31	0	0.00
3								
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.96	0.00%	3.09
4.96	41.00%	3.71
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
9.91	**41.00%**	**6.80**
		6.80

Vehicle:	V8	Stops:	4	Net profit:	-27.25			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 7	12.50	0:16	08:16	16:34	8:34	0	4.27
2	Customer 16	15.13	0:20	16:38	19:59	11:59	0	6.00
3	Customer 4	15.94	0:22	20:01	01:44	17:44	0	8.95
4	Depot	27.25	0:36	01:58		17:58	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
12.50	0.00%	7.79
2.63	26.00%	1.85
0.81	36.00%	0.59
11.32	54.00%	8.92
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
27.25	**54.00%**	**19.15**
		19.15

Vehicle:	V9	Stops:	5	Net profit:	-17.72			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 73	7.05	0:10	08:10	09:41	1:41	0	0.80
2	Customer 74	7.80	0:12	09:43	13:44	5:44	0	2.88
3	Customer 100	8.70	0:14	13:46	19:50	11:50	0	6.00
4	Customer 99	9.45	0:15	19:51	23:07	15:07	0	7.69
5	Depot	17.72	0:25	23:17		15:17	0	0.00
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.05	0.00%	4.40
0.75	5.00%	0.48
0.90	18.00%	0.61
0.75	36.00%	0.55
8.27	46.00%	6.32
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
17.72	**46.00%**	**12.35**
		12.35

Vehicle:	V10	Stops:	4	Net profit:	-22.54			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 59	8.93	0:10	08:10	09:50	1:50	0	0.88
2	Customer 62	11.27	0:14	09:54	12:28	4:28	0	2.21
3	Customer 61	12.20	0:15	12:29	22:39	14:39	0	7.43
4	Depot	22.54	0:27	22:51		14:51	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.93	0.00%	5.57
2.34	6.00%	1.50
0.93	14.00%	0.62
10.34	45.00%	7.87
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
22.54	**45.00%**	**15.55**
		15.55

Vehicle:	V11	Stops:	4	Net profit:	-18.97			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 12	7.82	0:10	08:10	10:18	2:18	0	1.12
2	Customer 15	10.24	0:14	10:22	22:25	14:25	0	7.30
3	Customer 14	11.12	0:15	22:26	01:39	17:39	0	8.97
4	Depot	18.97	0:25	01:49		17:49	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.82	0.00%	4.88
2.41	7.00%	1.55
0.88	44.00%	0.67
7.85	54.00%	6.19
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
18.97	**54.00%**	**13.28**
		13.28

Vehicle:	V12	Stops:	4	Net profit:	-12.10			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 69	4.33	0:06	08:06	16:24	8:24	0	4.27
2	Customer 71	5.29	0:07	16:25	22:16	14:16	0	7.28
3	Customer 72	6.05	0:08	22:17	01:40	17:40	0	9.03
4	Depot	12.10	0:16	01:48		17:48	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
4.33	0.00%	2.70
0.97	26.00%	0.68
0.76	44.00%	0.57
6.05	54.00%	4.77
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
12.10	**54.00%**	**8.72**
		8.72

Vehicle:	V13	Stops:	2	Net profit:	-17.88			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 60	8.94	0:10	08:10	22:38	14:38	0	7.41
2	Depot	17.88	0:20	22:48		14:48	0	0.00
3								
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.94	0.00%	5.57
8.94	45.00%	6.80
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
17.88	**45.00%**	**12.37**
		12.37

Vehicle:	V14	Stops:	5	Net profit:	-26.32			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 68	5.51	0:08	08:08	08:50	0:50	0	0.38
2	Customer 66	9.35	0:13	08:55	09:43	1:43	0	0.82
3	Customer 64	12.59	0:17	09:47	18:40	10:40	0	5.38
4	Customer 63	13.95	0:18	18:41	23:55	15:55	0	8.08
5	Depot	26.32	0:31	00:08		16:08	0	0.00
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.51	0.00%	3.44
3.84	3.00%	2.43
3.24	5.00%	2.07
1.36	33.00%	0.98
12.38	49.00%	9.56
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
26.32	**49.00%**	**18.48**
		18.48

Vehicle:	V15	Stops:	9	Net profit:	-47.59			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 98	6.33	0:08	08:08	08:51	0:51	0	0.40
2	Customer 26	12.40	0:16	08:59	09:40	1:40	0	0.76
3	Customer 21	21.26	0:26	09:50	12:13	4:13	0	2.00
4	Customer 22	24.35	0:31	12:18	13:08	5:08	0	2.45
5	Customer 23	26.39	0:34	13:11	22:52	14:52	0	7.42
6	Customer 24	29.86	0:39	22:57	23:46	15:46	0	7.86
7	Customer 25	32.63	0:43	23:50	00:56	16:56	0	8.45
8	Customer 94	39.95	0:51	01:04	01:52	17:52	0	8.88
9	Depot	47.59	0:59	02:00		18:00	0	0.00

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
6.33	0.00%	3.95
6.07	3.00%	3.84
8.85	5.00%	5.65
3.09	12.00%	2.04
2.04	15.00%	1.37
3.47	45.00%	2.64
2.77	47.00%	2.12
7.32	51.00%	5.70
7.64	53.00%	5.997
47.59	**53.00%**	**33.31**
		33.31

Vehicle:	V16	Stops:	3	Net profit:	-12.56			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 87	5.83	0:06	08:06	12:40	4:40	0	2.36
2	Customer 88	6.28	0:06	12:40	01:47	17:47	0	9.08
3	Depot	12.56	0:13	01:54		17:54	0	0.00
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.83	0.00%	3.63
0.45	15.00%	0.30
6.28	55.00%	4.97
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
12.56	**55.00%**	**8.90**
		8.90

Vehicle:	V17	Stops:	4	Net profit:	-11.14			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 82	1.54	0:02	08:02	09:33	1:33	0	0.80
2	Customer 83	5.16	0:06	09:37	12:33	4:33	0	2.32
3	Customer 19	7.91	0:10	12:37	00:58	16:58	0	8.66
4	Depot	11.14	0:14	01:02		17:02	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
1.54	0.00%	0.96
3.62	5.00%	2.31
2.75	14.00%	1.83
3.23	52.00%	2.53
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
11.14	**52.00%**	**7.63**
		7.63

Vehicle:	V18	Stops:	4	Net profit:	-19.87			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 96	7.56	0:09	08:09	11:36	3:36	0	1.78
2	Customer 95	9.35	0:11	11:38	23:12	15:12	0	7.72
3	Customer 89	12.96	0:14	23:15	01:19	17:19	0	8.80
4	Depot	19.87	0:21	01:26		17:26	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.56	0.00%	4.72
1.79	11.00%	1.17
3.61	46.00%	2.76
6.92	53.00%	5.43
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
19.87	**53.00%**	**14.07**
		14.07

Vehicle:	V19	Stops:	3	Net profit:	-22.10			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 27	11.05	0:11	08:11	15:25	7:25	0	3.72
2	Customer 90	14.03	0:14	15:28	01:47	17:47	0	9.02
3	Depot	22.10	0:22	01:55		17:55	0	0.00
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
11.05	0.00%	6.89
2.99	23.00%	2.07
8.06	54.00%	6.35
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
22.10	**54.00%**	**15.31**
		15.31

Vehicle:	V20	Stops:	6	Net profit:	-41.03			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 31	7.68	0:08	08:08	13:10	5:10	0	2.60
2	Customer 10	9.62	0:10	13:12	14:03	6:03	0	3.06
3	Customer 3	20.32	0:23	14:16	18:02	10:02	0	5.01
4	Customer 17	21.61	0:26	18:05	20:47	12:47	0	6.40
5	Customer 6	22.43	0:28	20:49	01:34	17:34	0	8.85
6	Depot	41.03	0:49	01:55		17:55	0	0.00
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.68	0.00%	4.79
1.94	16.00%	1.30
10.70	19.00%	7.29
1.29	30.00%	0.92
0.82	39.00%	0.60
18.61	53.00%	14.60
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
41.03	**53.00%**	**29.52**
		29.52

Vehicle:	V21	Stops:	4	Net profit:	-20.47			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 93	9.95	0:10	08:10	21:16	13:16	0	6.72
2	Customer 91	10.66	0:11	21:17	22:08	14:08	0	7.17
3	Customer 92	10.77	0:11	22:08	01:05	17:05	0	8.71
4	Depot	20.47	0:21	01:15		17:15	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
9.95	0.00%	6.20
0.72	41.00%	0.54
0.11	43.00%	0.08
9.71	52.00%	7.59
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
20.47	**52.00%**	**14.41**
		14.41

Vehicle:	V22	Stops:	4	Net profit:	-21.96			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 29	7.92	0:10	08:10	12:42	4:42	0	2.34
2	Customer 9	10.19	0:13	12:45	16:24	8:24	0	4.22
3	Customer 8	11.48	0:16	16:27	01:41	17:41	0	8.97
4	Depot	21.96	0:29	01:54		17:54	0	0.00
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.92	0.00%	4.93
2.27	14.00%	1.51
1.29	26.00%	0.91
10.48	54.00%	8.26
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
21.96	**54.00%**	**15.61**
		15.61

Vehicle:	V23	Stops:	5	Net profit:	-21.31			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 32	7.50	0:08	08:08	15:44	7:44	0	3.91
2	Customer 36	10.23	0:13	15:49	22:30	14:30	0	7.35
3	Customer 37	10.67	0:14	22:31	23:16	15:16	0	7.76
4	Customer 34	11.72	0:16	23:18	01:04	17:04	0	8.68
5	Depot	21.31	0:28	01:16		17:16	0	0.00
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
7.50	0.00%	4.68
2.73	24.00%	1.90
0.44	44.00%	0.33
1.05	47.00%	0.81
9.59	52.00%	7.50
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
21.31	**52.00%**	**15.22**
		15.22

Vehicle:	V24	Stops:	5	Net profit:	-19.43			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 48	5.73	0:08	08:08	09:17	1:17	0	0.61
2	Customer 47	8.99	0:13	09:22	16:08	8:08	0	4.09
3	Customer 38	11.79	0:16	16:11	22:12	14:12	0	7.18
4	Customer 40	12.12	0:16	22:12	22:57	14:57	0	7.60
5	Depot	19.43	0:24	23:05		15:05	0	0.00
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.73	0.00%	3.57
3.26	4.00%	2.07
2.79	25.00%	1.95
0.33	43.00%	0.25
7.31	46.00%	5.58
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
19.43	**46.00%**	**13.43**
		13.43

Vehicle:	V25	Stops:	5	Net profit:	-28.72			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 41	11.20	0:12	08:12	20:50	12:50	0	6.48
2	Customer 44	13.86	0:17	20:55	21:41	13:41	0	6.90
3	Customer 43	15.56	0:20	21:44	00:23	16:23	0	8.28
4	Customer 42	16.73	0:21	00:24	01:09	17:09	0	8.68
5	Depot	28.72	0:32	01:20		17:20	0	0.00
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
11.20	0.00%	6.98
2.65	39.00%	1.97
1.71	42.00%	1.28
1.17	50.00%	0.91
11.98	52.00%	9.37
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
28.72	**52.00%**	**20.52**
		20.52

Vehicle:	V26	Stops:	3	Net profit:	-13.80			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 81	0.24	0:00	08:00	11:02	3:02	0	1.58
2	Customer 97	6.90	0:08	11:10	01:02	17:02	0	8.69
3	Depot	13.80	0:17	01:11		17:11	0	0.00
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
0.24	0.00%	0.15
6.66	10.00%	4.33
6.90	52.00%	5.40
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.000
13.80	**52.00%**	**9.88**
		9.88

Vehicle:	V27	Stops:	9	Net profit:	-26.84			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 51	8.57	0:10	08:10	10:50	2:50	0	1.39
2	Customer 52	11.53	0:14	10:54	17:19	9:19	0	4.69
3	Customer 53	12.18	0:15	17:20	18:04	10:04	0	5.09
4	Customer 54	13.15	0:16	18:05	18:49	10:49	0	5.48
5	Customer 55	14.46	0:18	18:51	19:40	11:40	0	5.93
6	Customer 56	15.77	0:20	19:42	20:58	12:58	0	6.59
7	Customer 57	16.92	0:22	21:00	21:48	13:48	0	7.03
8	Customer 50	19.19	0:24	21:50	01:41	17:41	0	9.01
9	Depot	26.84	0:34	01:51		17:51	0	0.00

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.57	0.00%	5.34
2.96	9.00%	1.92
0.65	28.00%	0.46
0.97	31.00%	0.70
1.31	33.00%	0.95
1.31	36.00%	0.96
1.15	40.00%	0.85
2.28	42.00%	1.71
7.65	54.00%	6.026
26.84	**54.00%**	**18.93**
		18.93

Vehicle:	V28	Stops:	7	Net profit:	-39.64			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 28	8.40	0:10	08:10	08:55	0:55	0	0.41
2	Customer 2	16.14	0:21	09:06	09:53	1:53	0	0.84
3	Customer 20	20.02	0:27	09:59	15:42	7:42	0	3.78
4	Customer 1	24.16	0:32	15:47	22:04	14:04	0	7.02
5	Customer 18	24.21	0:32	22:04	22:45	14:45	0	7.39
6	Customer 5	28.93	0:38	22:51	23:34	15:34	0	7.78
7	Depot	39.64	0:52	23:48		15:48	0	0.00
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
8.40	0.00%	5.23
7.74	3.00%	4.90
3.89	5.00%	2.48
4.13	23.00%	2.87
0.05	42.00%	0.04
4.72	44.00%	3.58
10.71	47.00%	8.21
0.00	0.00%	0.00
0.00	0.00%	0.000
39.64	**47.00%**	**27.31**
		27.31

Vehicle:	V29	Stops:	3	Net profit:	-20.58			
Stop count	Location Name	Distance travelled	Driving time	Arrival time	Departure time	Working time	Profit collected	Load
0	Depot	0.00	0:00		08:00	0:00	0	0.00
1	Customer 67	5.83	0:08	08:08	16:26	8:26	0	4.27
2	Customer 65	10.38	0:14	16:32	00:51	16:51	0	8.54
3	Depot	20.58	0:25	01:02		17:02	0	0.00
4								
5								
6								
7								
8								
9								

Distance Travelled (km)	Load %	Emissions (kg CO2e-q)
5.83	0.00%	3.64
4.55	26.00%	3.20
10.20	51.00%	7.95
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
0.00	0.00%	0.00
20.58	**51.00%**	**14.78**
		14.78

Appendix D

Appendix D.1

The geographic co-ordinates of the AD plant sites and the biogas user can be seen in Table A-1.

AD plant	x	y
1	-8.649649844	52.37795158
2	-8.767642683	52.34195589
3	-8.608068501	52.36609016
4	-8.711236477	52.34871149
5	-8.615431165	52.37580981
6	-8.582987164	52.37928144
7	-8.681227919	52.29269797
8	-8.658148616	52.36038494
9	-8.616528623	52.34420621
10	-8.589338635	52.37472868
Biogas user	-8.675552399	52.37934109

Table D-1: AD plant site co-ordinates.

Appendix D.2

This QGIS methodology requires the GRASS plugin, MMQGIS plugin, and this script, adapted from publicly available user-created scripts (MrXsquared, 2020), to run. This script allows QGIS to connect all points in two individual point layers (or all points in one layer) to each other with lines.

```
from PyQt5.QtCore import QCoreApplication, QVariant
from qgis.core import (QgsField, QgsFeature, QgsProcessing, QgsExpression,
QgsGeometry, QgsPoint, QgsFields, QgsWkbTypes,
                       QgsFeatureSink, QgsFeatureRequest,
QgsProcessingAlgorithm,
                       QgsProcessingParameterFeatureSink,
QgsProcessingParameterField, QgsProcessingParameterFeatureSource,
QgsProcessingParameterEnum)

class ConnectAllPointsByLines(QgsProcessingAlgorithm):
    POSSIBILITY_LYR = 'POSSIBILITY_LYR'
    POSSIBILITY_IDFIELD = 'POSSIBILITY_IDFIELD'
    STOP_LYR = 'STOP_LYR'
    STOP_IDFIELD = 'STOP_IDFIELD'
    OUTPUT = 'OUTPUT'

    def initAlgorithm(self, config=None):

        self.addParameter(
            QgsProcessingParameterFeatureSource(
                self.STOP_LYR, self.tr('Source Points'),
[QgsProcessing.TypeVectorPoint]))
        self.addParameter(
            QgsProcessingParameterField(
                self.STOP_IDFIELD, self.tr('Unique ID Field of Source Layer
(Any Datatype)'),'ANY','STOP_LYR'))
        self.addParameter(
            QgsProcessingParameterFeatureSource(
                self.POSSIBILITY_LYR, self.tr('Target Points'),
[QgsProcessing.TypeVectorPoint]))
        self.addParameter(
```

```
            QgsProcessingParameterField(
                self.POSSIBILITY_IDFIELD, self.tr('Unique Target ID Field
(Any Datatype, should have a different name than Source ID
field)'),'ANY','POSSIBILITY_LYR'))
        self.addParameter(
            QgsProcessingParameterFeatureSink(
                self.OUTPUT, self.tr('Line Connections'),
QgsProcessing.TypeVectorLine))

    def processAlgorithm(self, parameters, context, feedback):
        # Get Parameters
        possibility_layer = self.parameterAsSource(parameters,
self.POSSIBILITY_LYR, context)
        possibility_idfield = self.parameterAsFields(parameters,
self.POSSIBILITY_IDFIELD, context)
        stop_layer = self.parameterAsSource(parameters, self.STOP_LYR,
context)
        stop_idfield = self.parameterAsFields(parameters,
self.STOP_IDFIELD, context)

        fields = QgsFields()
        fields.append(QgsField(stop_idfield[0]))
        fields.append(QgsField(possibility_idfield[0]))
        fields.append(QgsField("line_length", QVariant.Double, len=20,
prec=5))

        (sink, dest_id) = self.parameterAsSink(parameters, self.OUTPUT,
context,
                                               fields,
QgsWkbTypes.LineString,

possibility_layer.sourceCrs())

        # iterate over stop features
        for stop_feat in stop_layer.getFeatures():
            point1 = QgsPoint(stop_feat.geometry().asPoint())
            for source_feat in possibility_layer.getFeatures():
                point2 = QgsPoint(source_feat.geometry().asPoint())
                new_feat = QgsFeature(fields)
                new_feat.setGeometry(QgsGeometry.fromPolyline([point1,
point2]))
                new_feat[stop_idfield[0]] = stop_feat[stop_idfield[0]]
                new_feat[possibility_idfield[0]] =
source_feat[possibility_idfield[0]]
                new_feat["line_length"] = new_feat.geometry().length()
                sink.addFeature(new_feat, QgsFeatureSink.FastInsert)

        return {self.OUTPUT: dest_id}


    def tr(self, string):
        return QCoreApplication.translate('Processing', string)

    def createInstance(self):
        return ConnectAllPointsByLines()

    def name(self):
        return 'ConnectAllPointsByLines'

    def displayName(self):
        return self.tr('Connect All Points By Lines')

    def group(self):
        return self.tr('FROM GISSE')

    def groupId(self):
        return 'from_gisse'

    def shortHelpString(self):
        return self.tr('This Algorithm connects all points of the Source
layer with all points of the Target layer with lines and adds the lines
length')
```

Steiner node creation

1. Begin with a set of nodes (AD plants and biogas user).

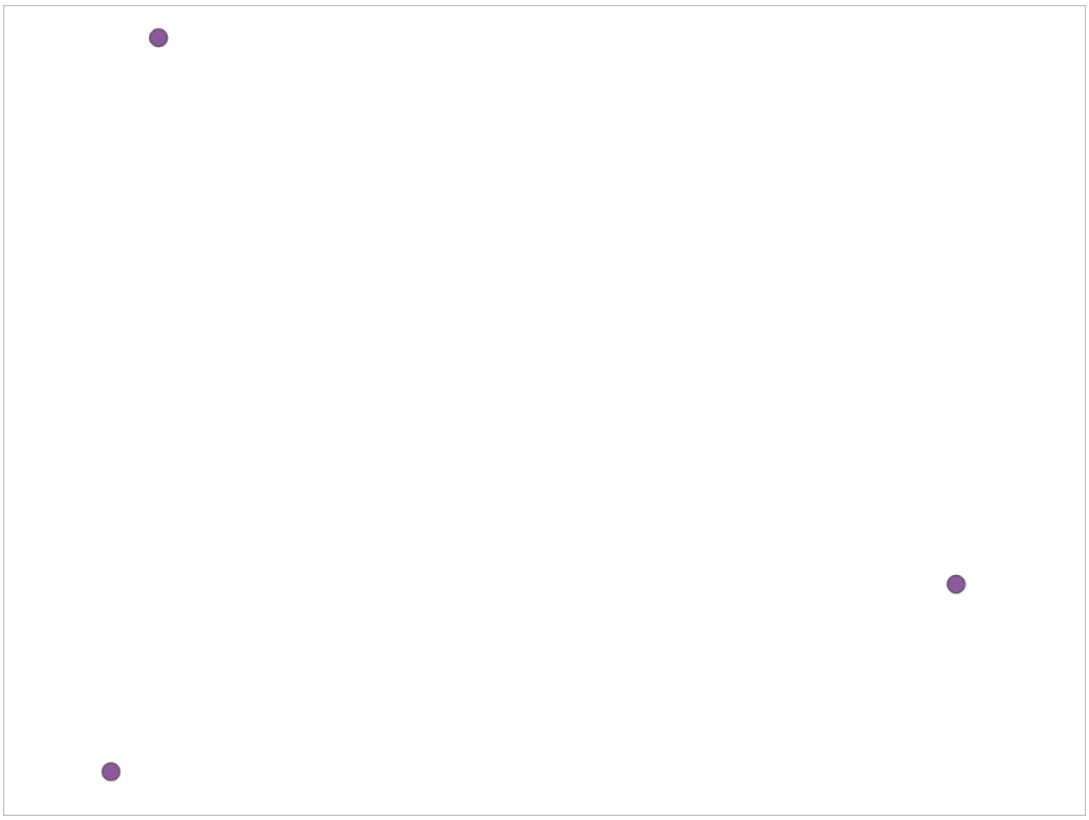


Figure D-1:Example AD plant site node layer.

2. For a given set of nodes on a point layer (AD plants and biogas user, example seen in Figure A-1), generate a grid of points overlaying the using the MMQGIS plugin. Higher density of points (X Spacing and Y Spacing) will increase the accuracy of the final MST w/ Steiner nodes created but will lead to increased load times and system memory use. The X and Y spacing of the layouts as described in section 2.2. were 100 m (see Figure A-2 and A-3).

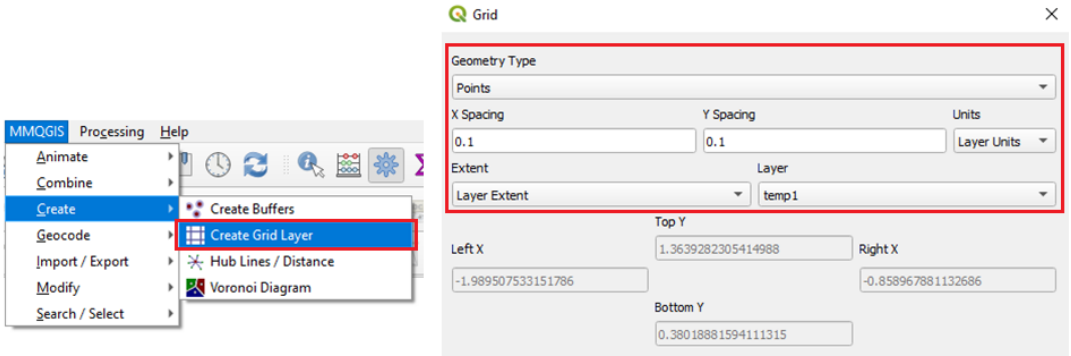


Figure D-2: MMQGIS grid of points creation.



Figure D-3: Grid of points over AD site layer.

3. Run the plugin above to generate lines between all AD plant site nodes (select this layer twice, see Figure D-4). This will create lines between all AD plant sites (and biogas user), which may be required as not all configurations of points require a Steiner node. See result in Figure D-5.

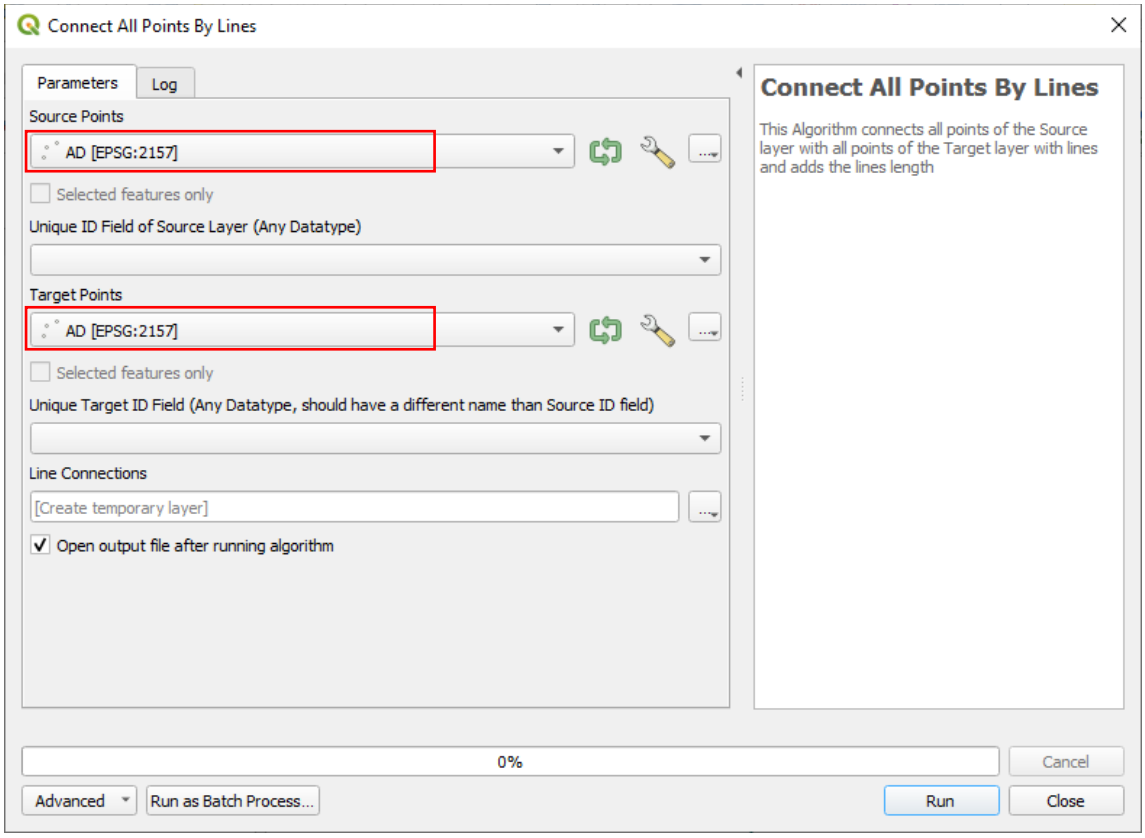


Figure D-4: Plugin interface window, connecting network nodes.

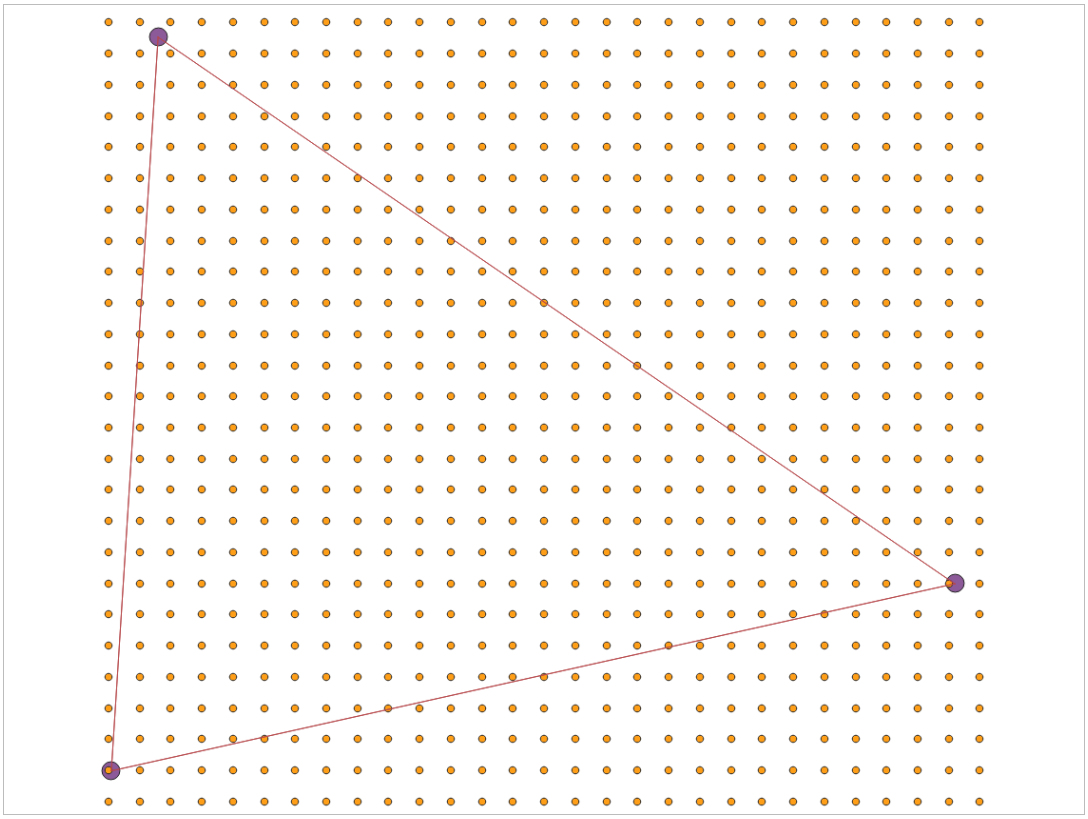


Figure D-5: Lines connecting network nodes.

4. Use the plugin above to generate lines between all AD plant nodes and all points on the grid of points layer created in step 1 (Figures A-6 and A-7).

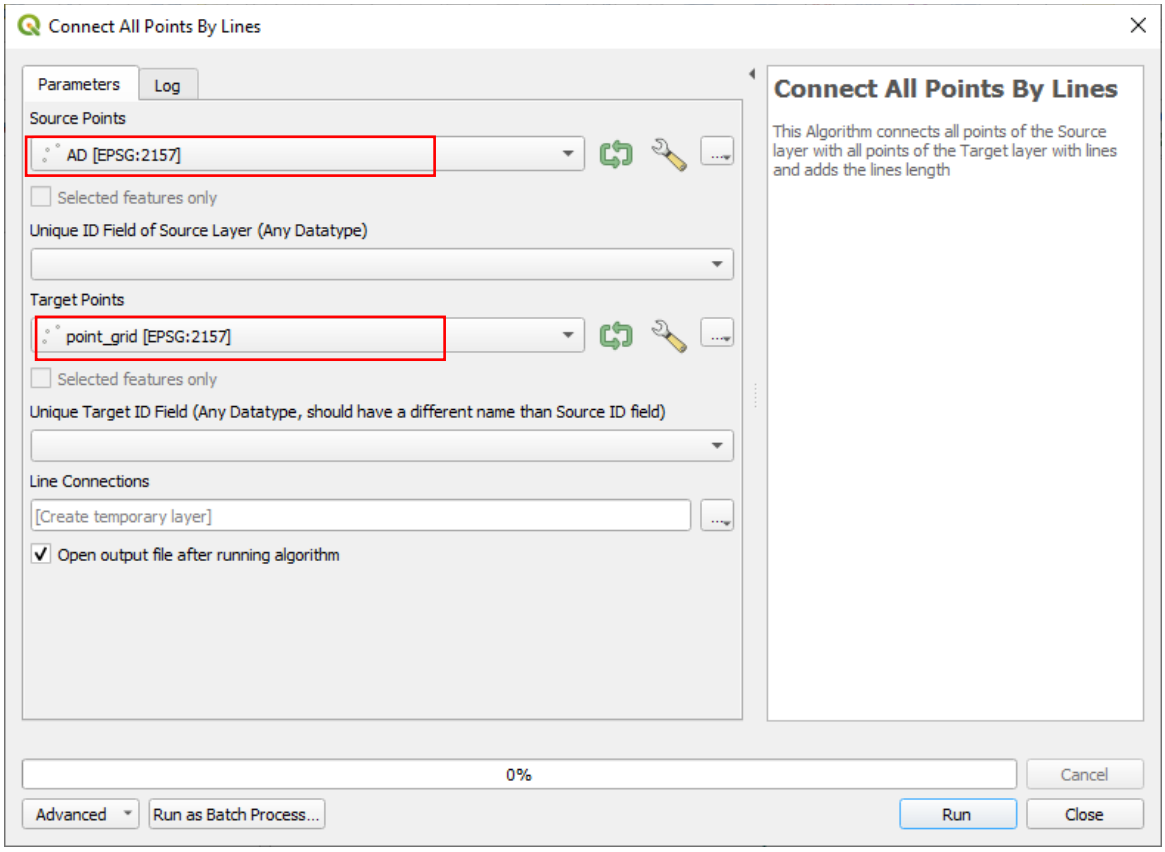


Figure D-6: Plugin interface window, connecting network nodes to point grid.

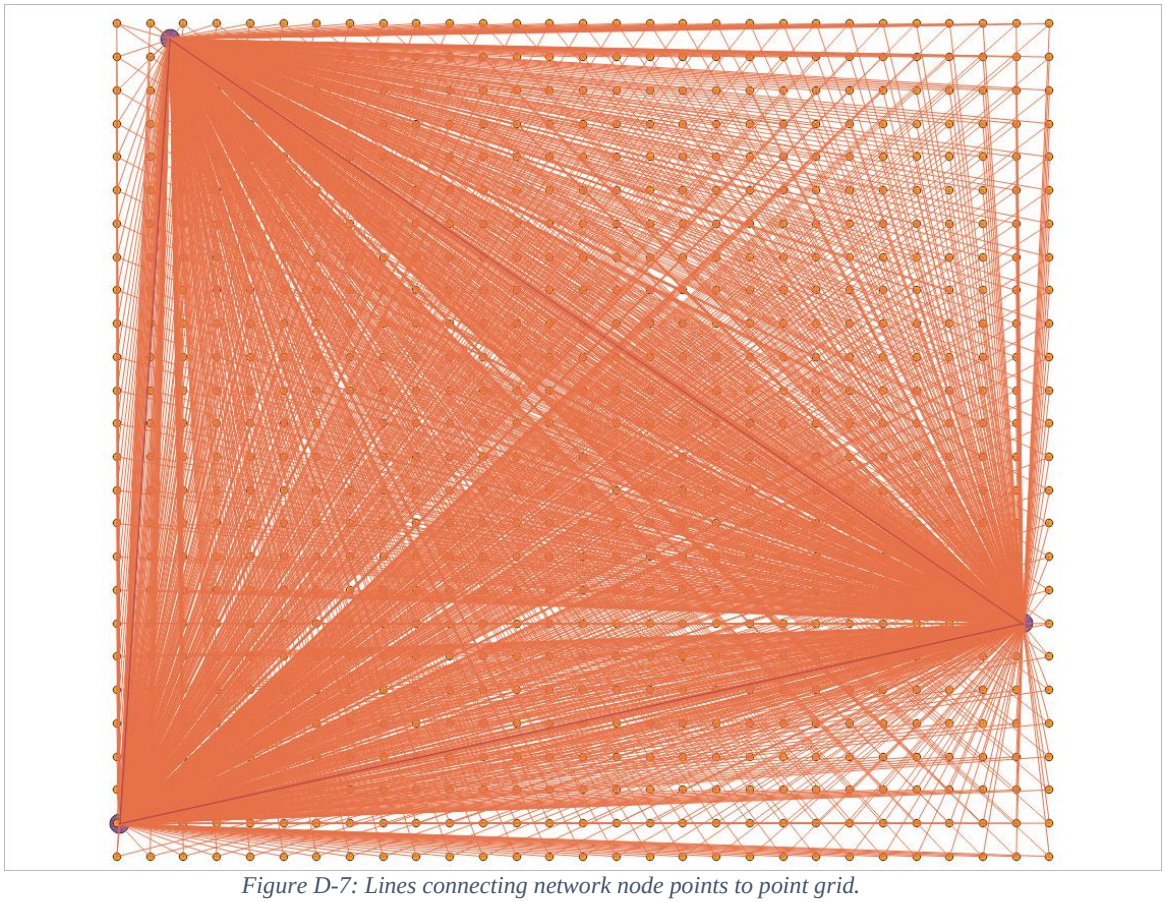


Figure D-7: Lines connecting network node points to point grid.

5. Merge the two line layers created in steps 3 and 4 using the MMQGIS plugin (see MMQGIS dialog box in Figure D-8). This merge will ensure that your MST w/ Steiner nodes will take either a direct point-to-point path between nodes OR connect the network via Steiner nodes, whichever makes for a shorter network. See result in Figure D-9.

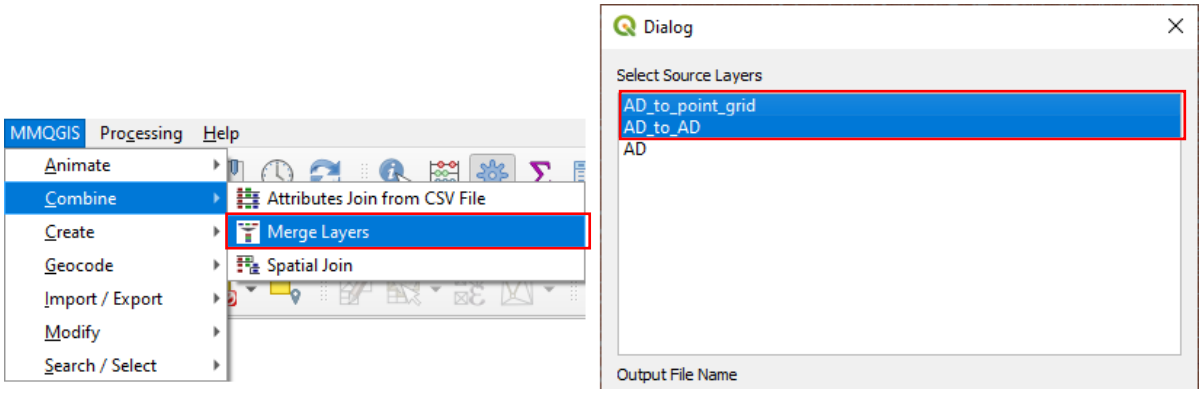


Figure D-8: MMQGIS Merge Layers dialog window.

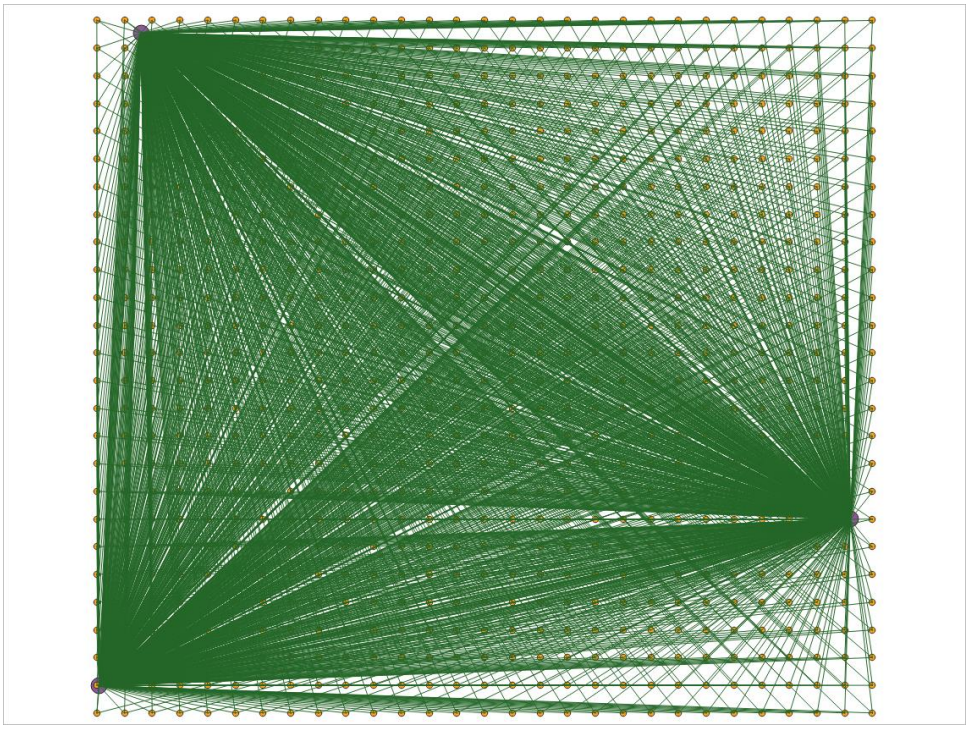


Figure D-9: Merged line layers.

6. Using the *v.net.steiner* tool, select your merged line layer from step 5 as your "Input vector line layer (arcs)", and your network node layer as the "Centers point layer (nodes)" (Figure D-10). The result of this will output as the MST w/ Steiner nodes for the network node system (Figure D-11). The run-time of this may be significant depending on the size of your network, the density of your point layer, and the specifications of your computer system.

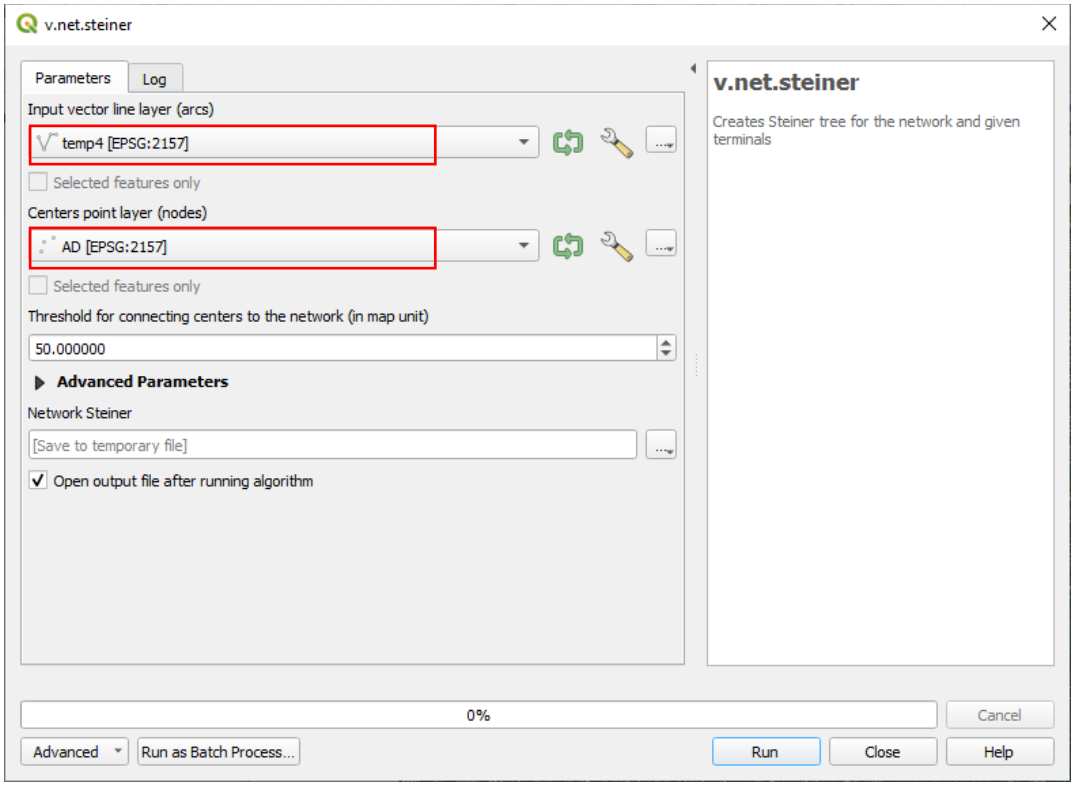


Figure D-10: v.net.steiner dialog window.

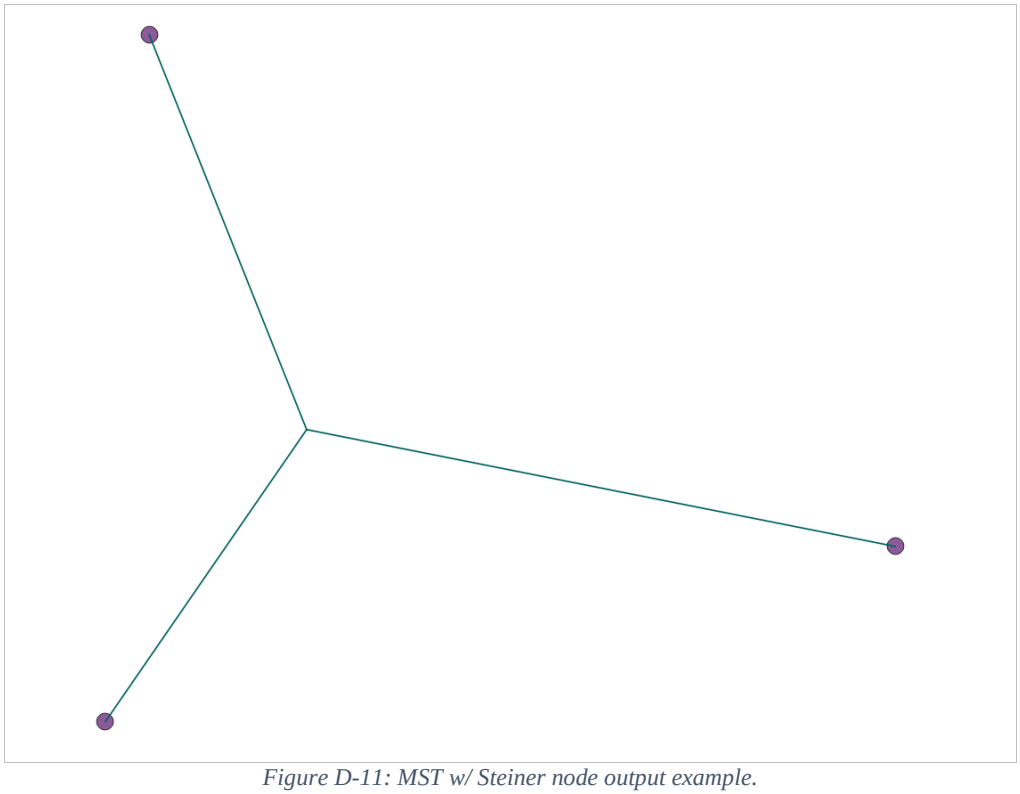


Figure D-11: MST w/ Steiner node output example.

AD site connection to road network

1. For connecting AD plant sites to the road network, a tangent may be drawn from the AD plant site to the road network. Begin with a set of nodes for connecting together via pipeline, and a road network layer (Figure D-12).



Figure D-12: Nodes and road network.

2. Use the “Points along geometry” tool to create points at small distance intervals along your road network (Figure D-13). Creating points along the road network will allow for the creation of tangents from the network nodes to the road. The smaller the distance interval, the more accurate the final tangent line. See result in Figure D-14.

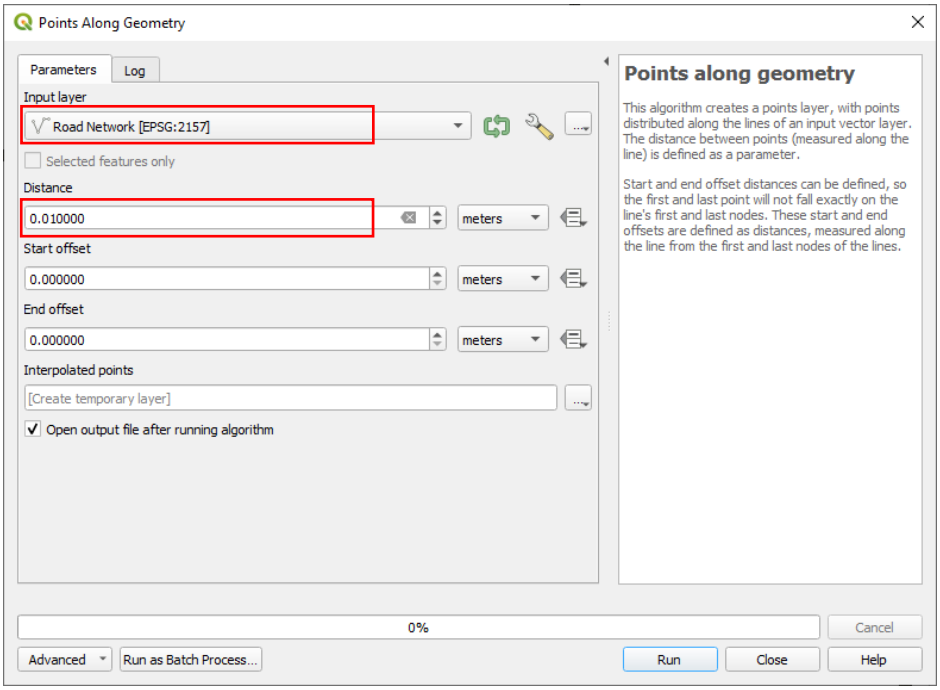


Figure D-13: Points along geometry dialog window.

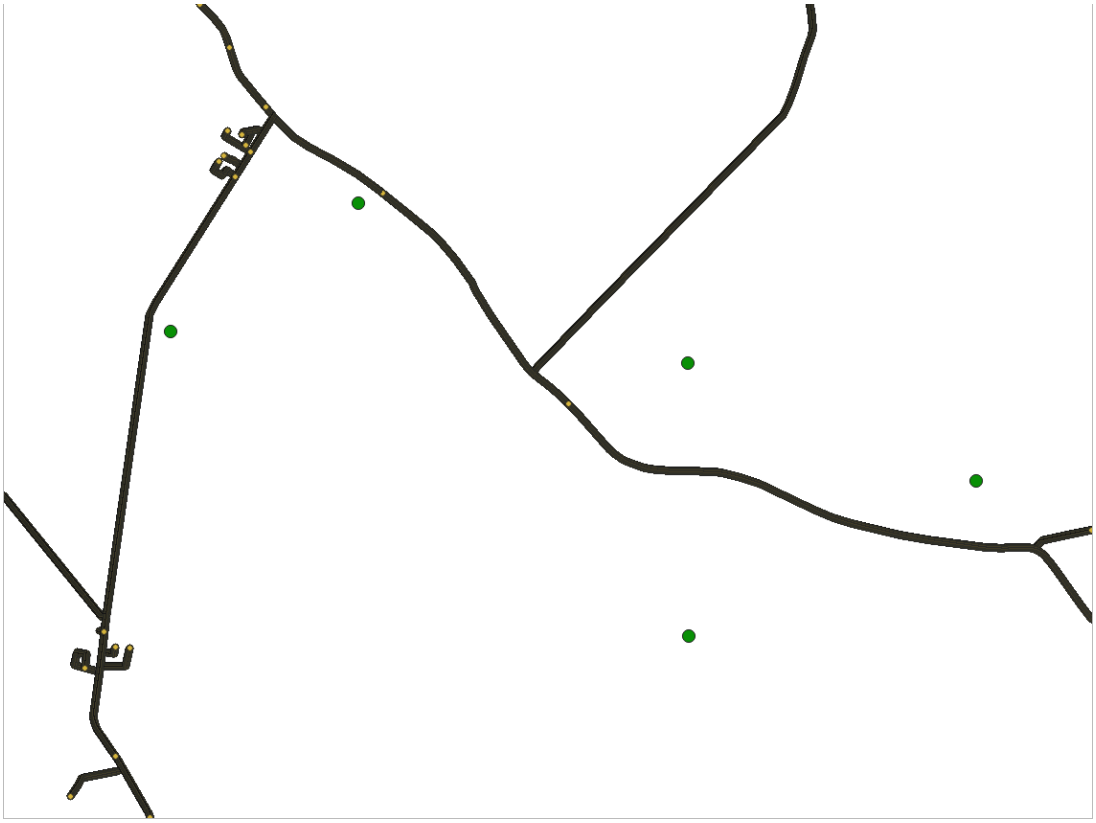


Figure D-14: Points along geometry output (points are densely located along road network).

3. Use the “Distance to nearest hub” tool (Figure D-15) to create a line from the network nodes to the closest point along the road network. See result in Figure D-16.

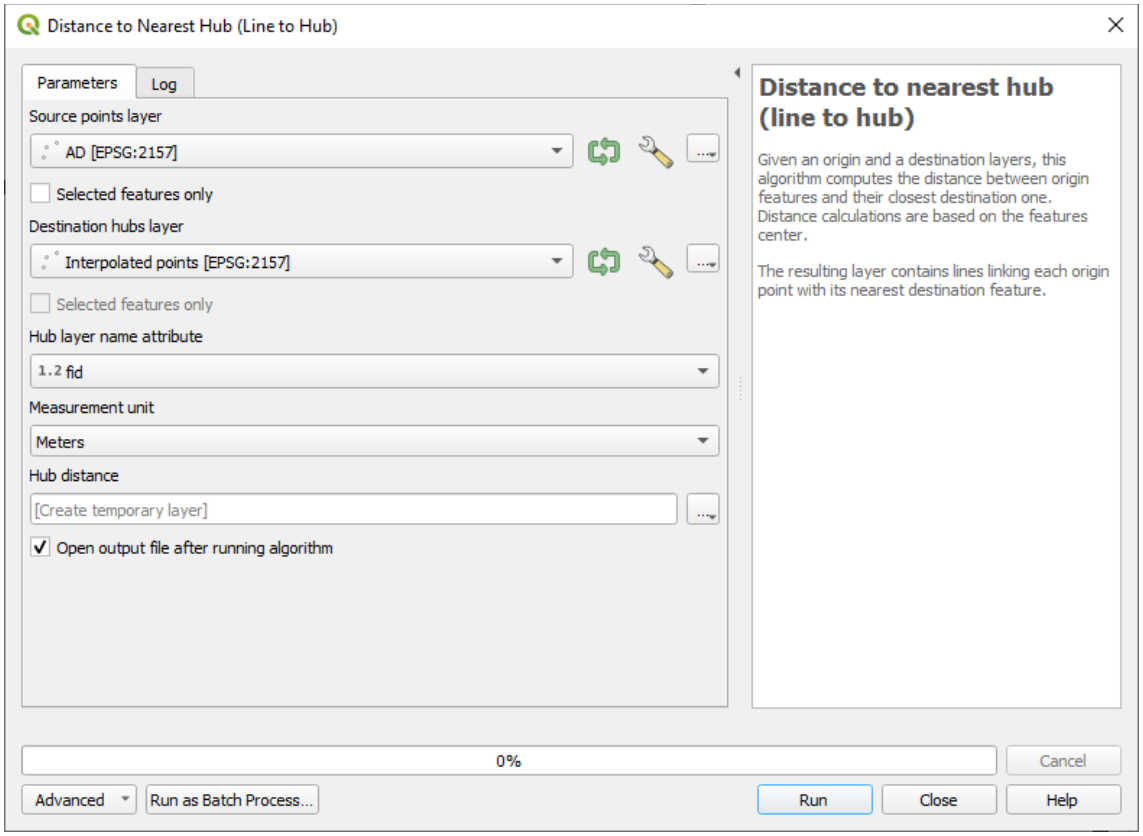


Figure D-15: Distance to Nearest Hub (Line to Hub) dialog window.



Figure D-16: Tangential lines from network nodes to road network layer.

4. Using the MMQGIS plugin (Figure D-17), merge the tangent line layer with the original road network layer. See result in Figure D-18.

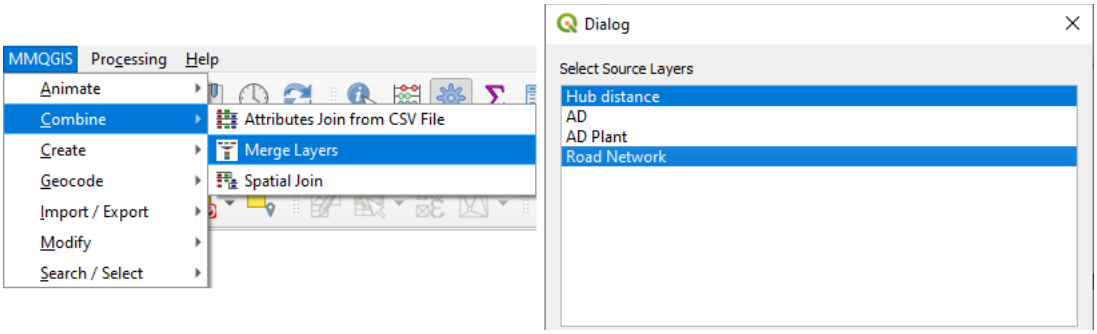


Figure D-17: MMQGIS merge layers dialog window.

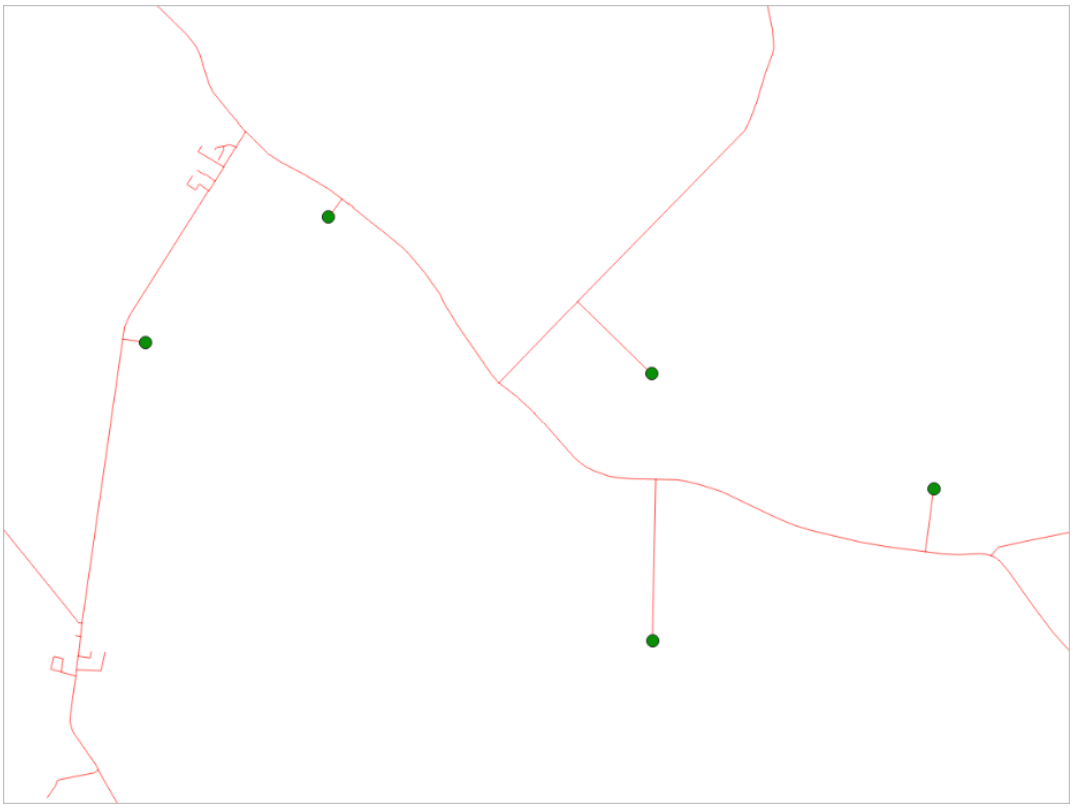


Figure D-18: Merged tangent line and road network layers.

5. Using the *v.net.steiner* tool, select your merged line layer from step 4 as your "Input vector line layer (arcs)", and your network node layer as the "Centers point layer (nodes)" (Figure D-19). The result of this will output as the MST along the road network for the network node system (Figure D-20).

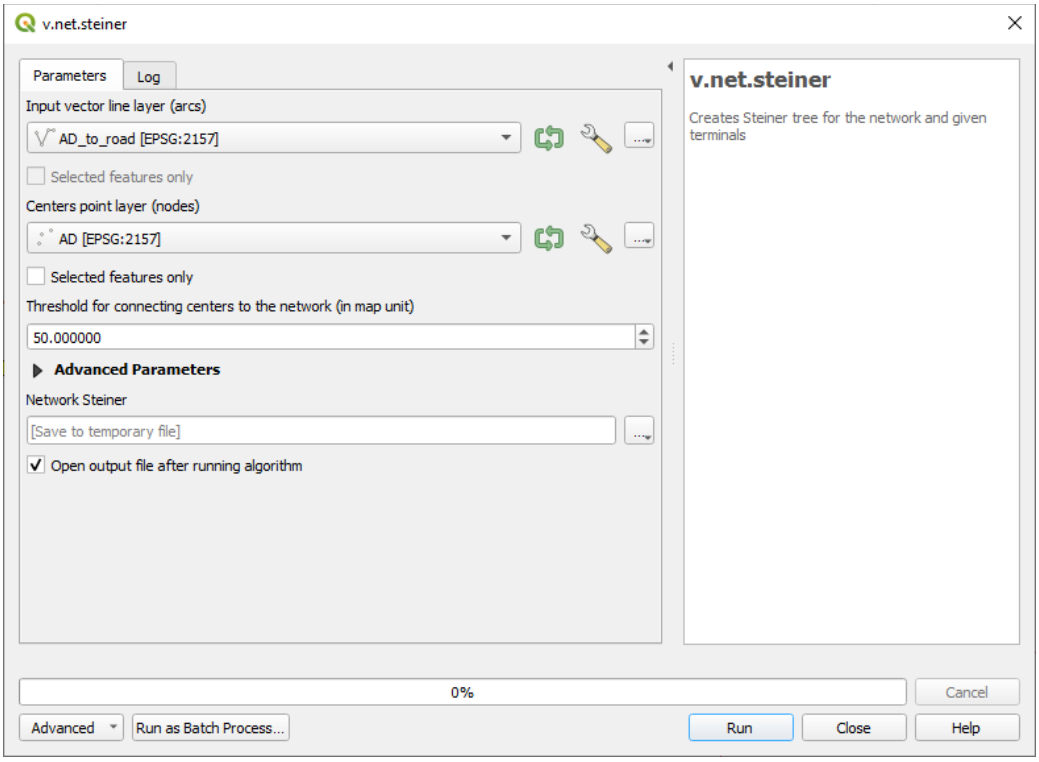


Figure D-19: v.net.steiner dialog window.

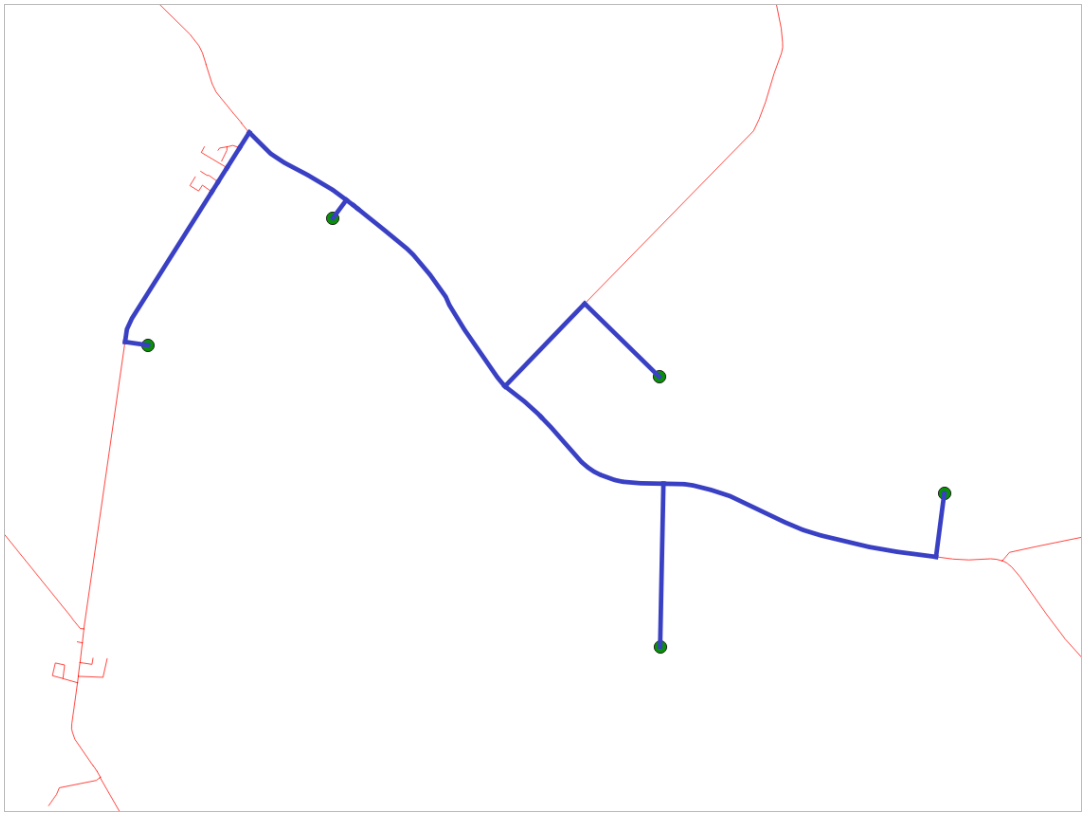


Figure D-20: MST along road network example.

Appendix D.3

Figure D-21 shows how to use SNAP for the purposes of biogas pipeline network design and analysis. The input and output files for the design and analysis of the scenarios in this work can be found in the supplementary data files provided.

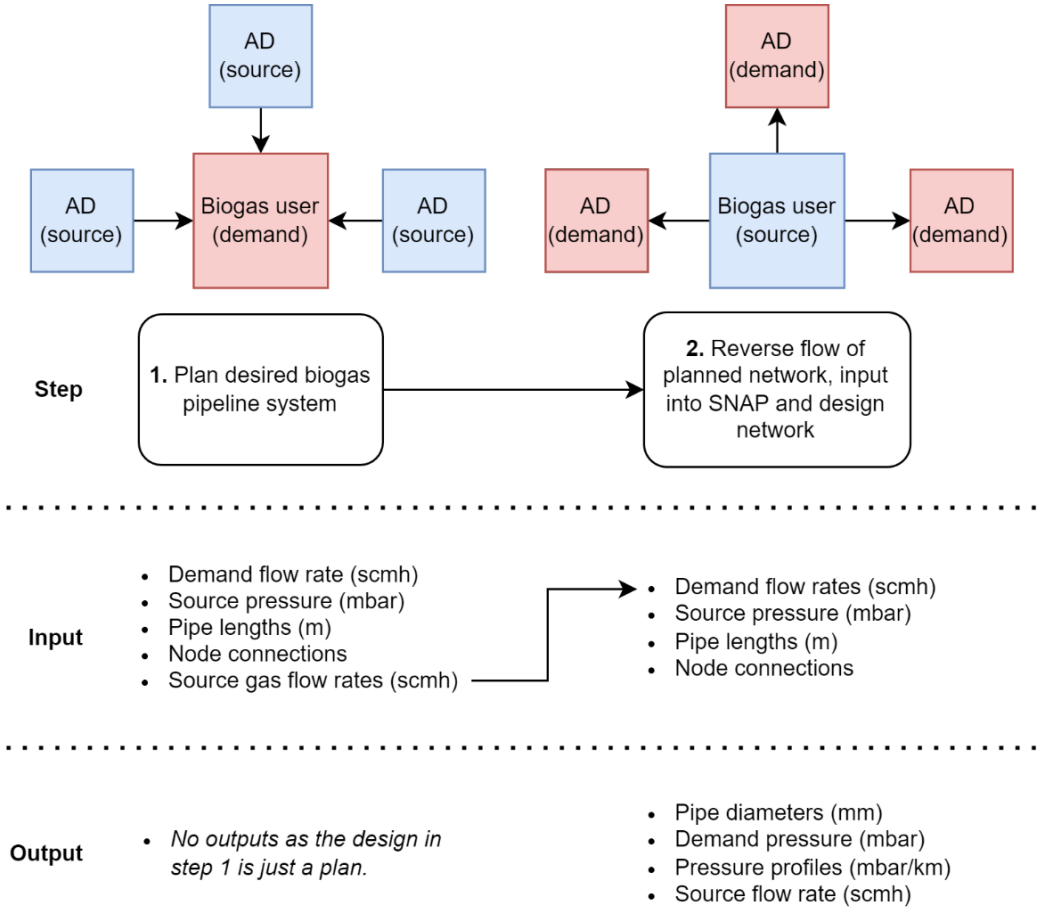


Figure D-21: SNAP methodology flowchart.

Appendix D.4

Output Heuristic

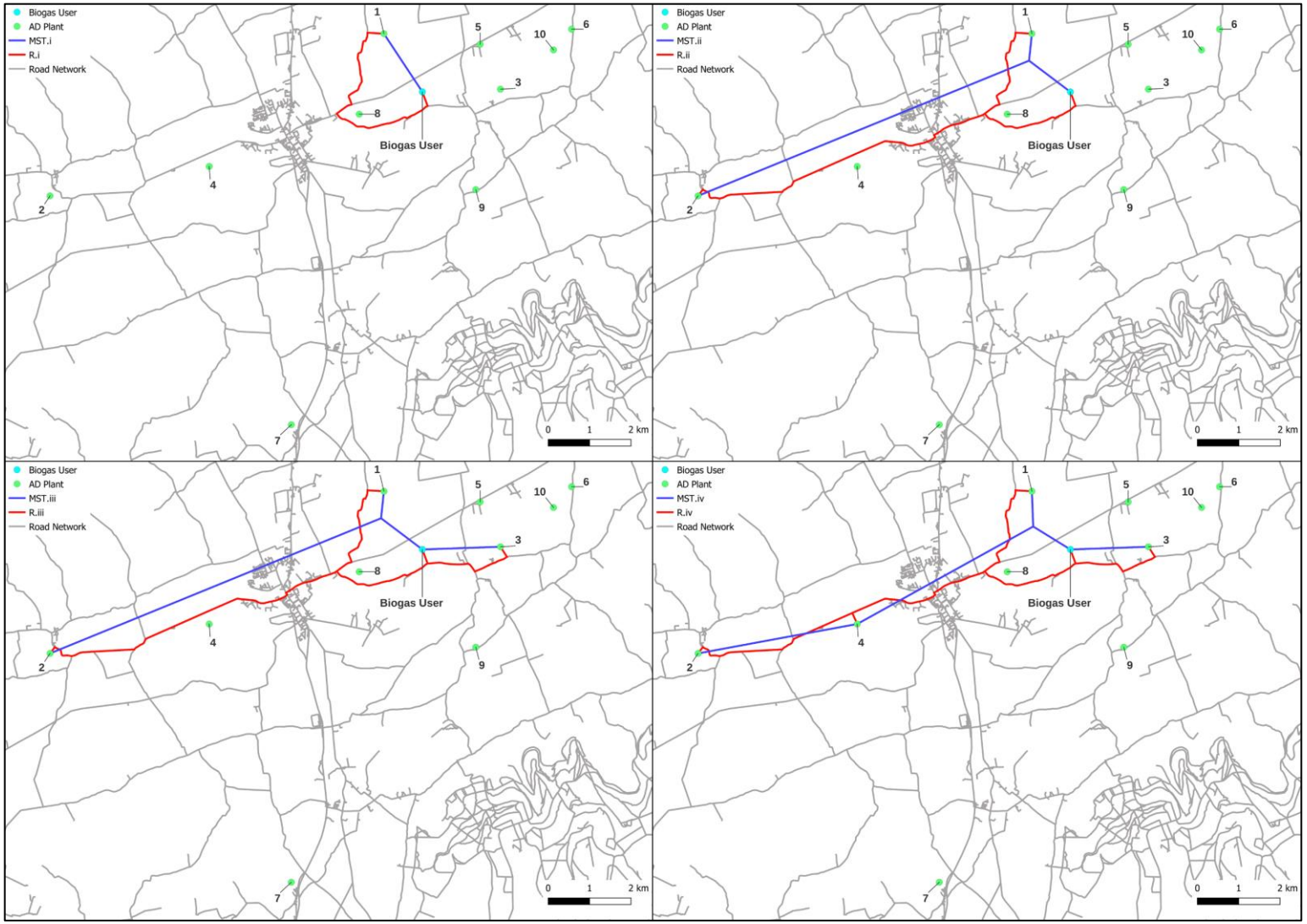


Figure D-22: Output heuristic scenarios i-iv.

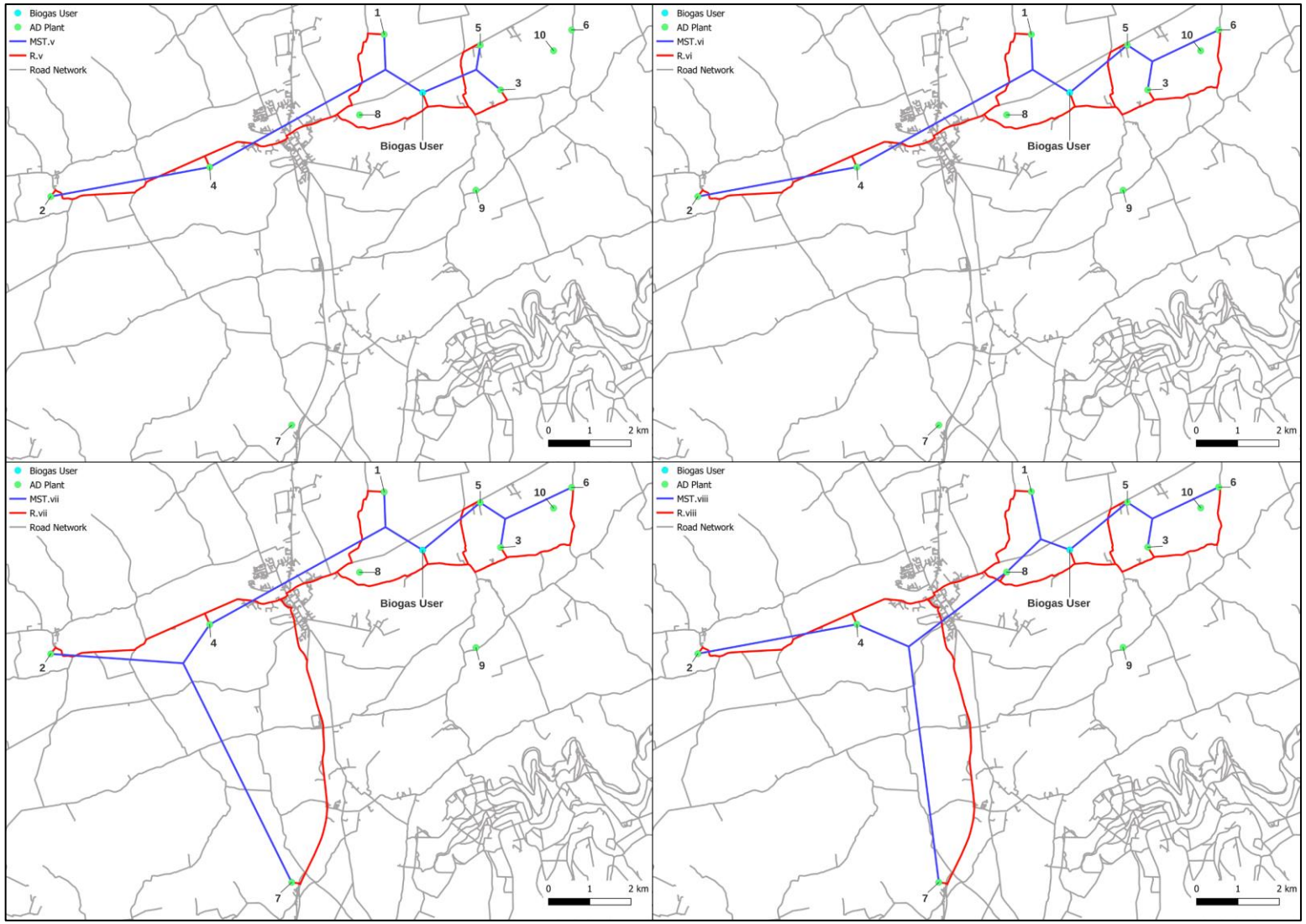


Figure D-23: Output heuristic scenarios v-viii.

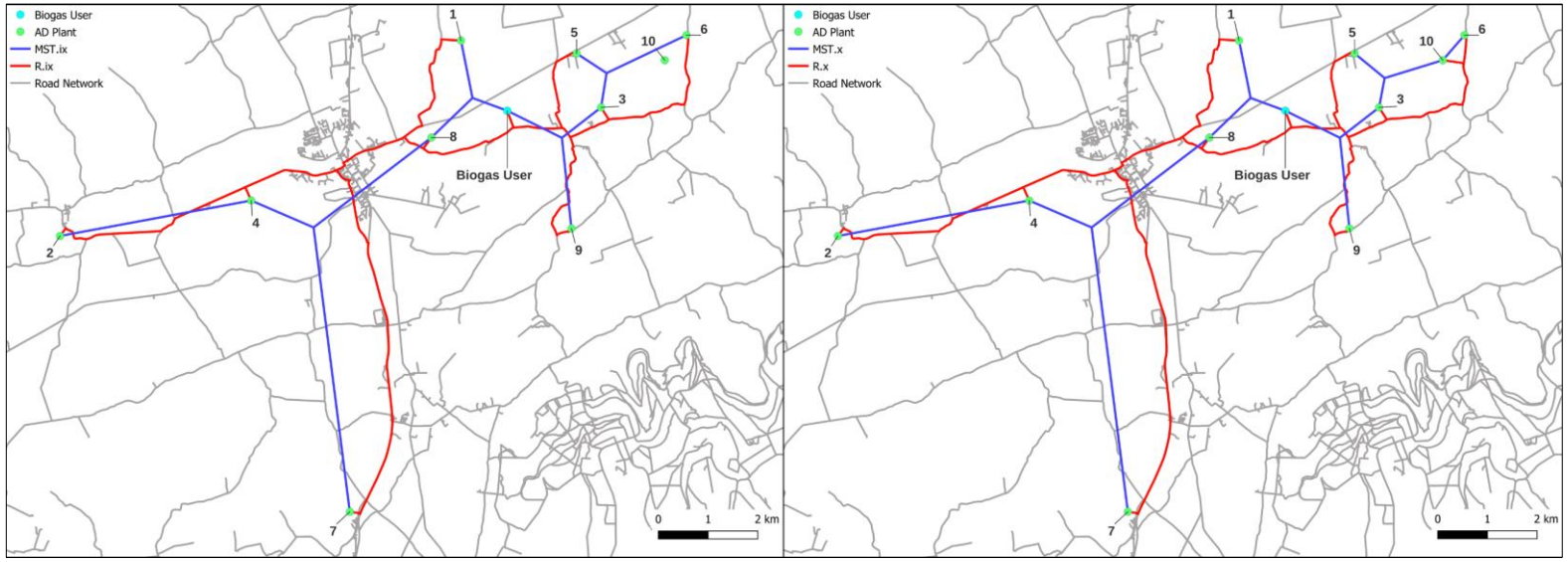


Figure D-24: Output heuristic scenarios ix-x.

Proximity Heuristic

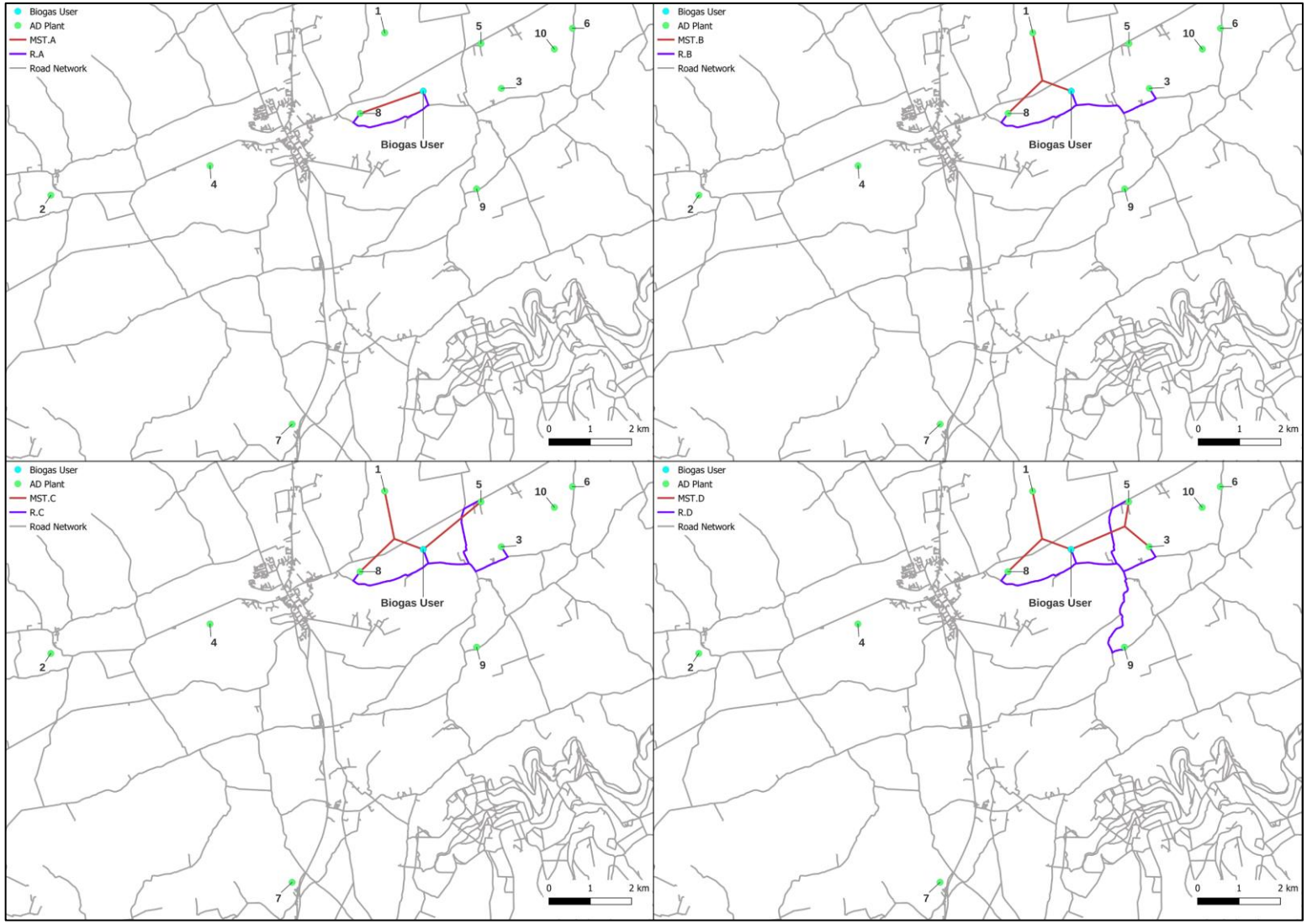


Figure D-25: Proximity heuristic scenarios A-D.

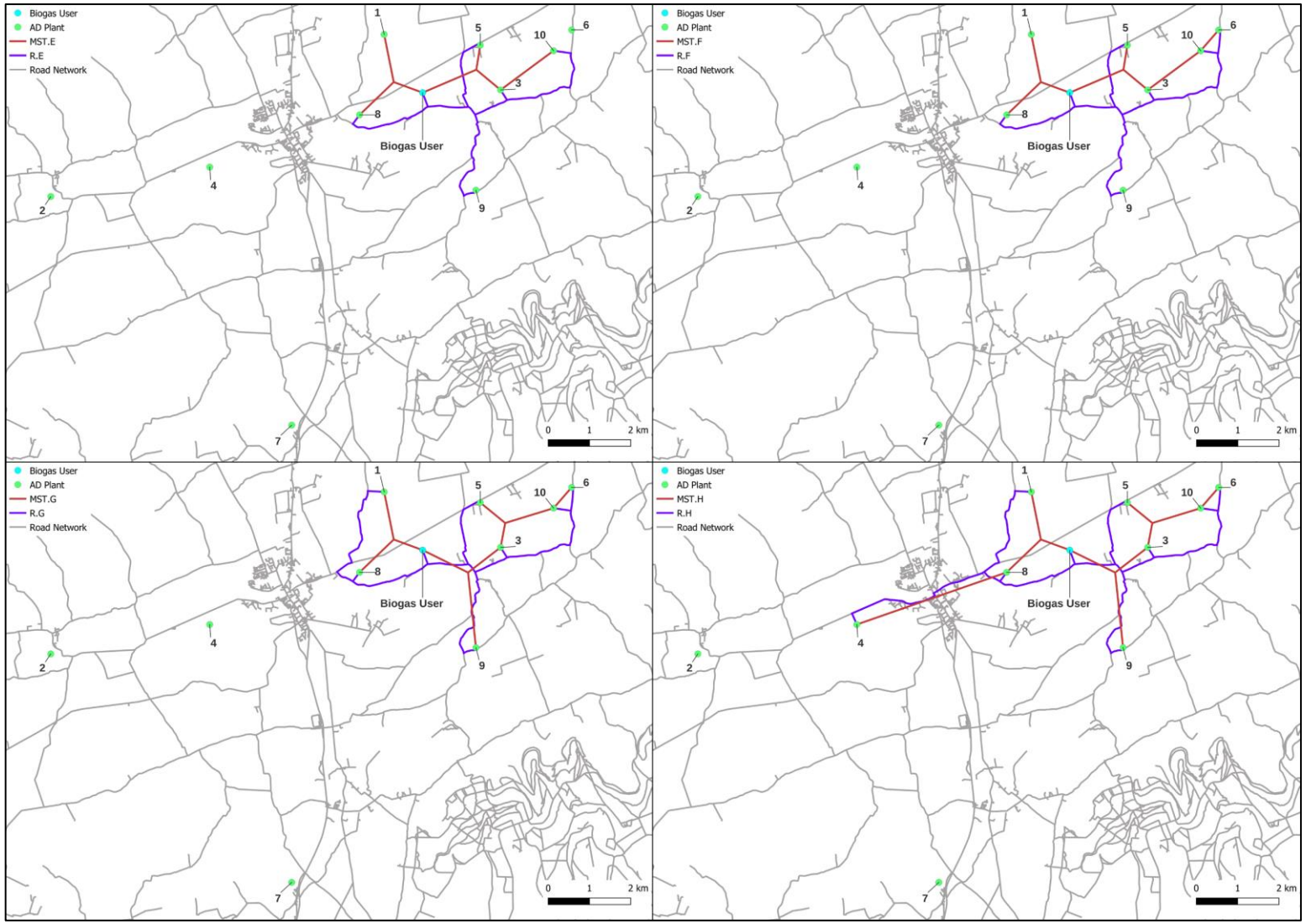


Figure D-26: Proximity heuristic scenarios E-H.

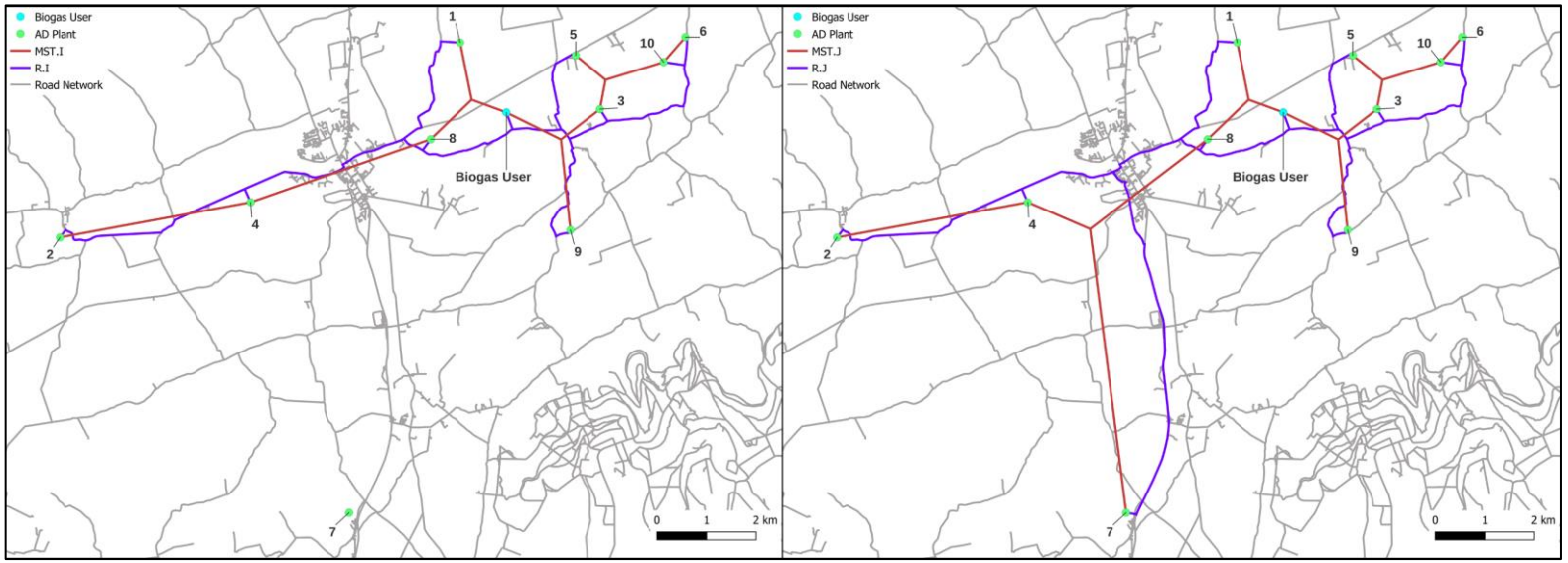


Figure D-27: Proximity heuristic scenarios I-J.

Appendix D.5

Below are each of the input parameters and output files generated by SNAP, for each scenario investigated.

MST.(i-x)

MST.i

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  11  1690.09 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                   M
    1    11   1690.1     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.i;
* WRITING NETWORK TO FILE MST.i
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   59.24 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   59.24 MBAR AT NODE     1
```

```
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR      KM
    1    11   1690.1    63   D    -31.399    4.05   90.76   53.70
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
         MBAR       SCMH
   11    150.00     31.399   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
         MBAR
    1     59.24
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    1690.1     8602.56
                       --------  ----------
                        1690.1     8602.56
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.i;
* READING NETWORK FROM FILE MST.i
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   59.24 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   59.24 MBAR AT NODE     1
        REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
MINIMUM PRESSURE IS   59.24 MBAR AT NODE     1
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR      KM
    1    11   1690.1    63   D    -31.399    4.05   90.76   53.70
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
         MBAR
    1     59.24
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
```

```
   63   D       5.09    1690.1     8602.56
                       --------  ----------
                         1690.1     8602.56
COMMAND >* Terminate the SNAP run.
```

MST.ii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  657.37 0 D
ENTER PIPE >   2  12  8650.43 0 D
ENTER PIPE >   12  11  1253.84 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                  M
    1    12    657.4     0   D
    2    12   8650.4     0   D
   11    12   1253.8     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.ii;
* WRITING NETWORK TO FILE MST.ii
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
```

```
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -382.54 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR     KM
    1    12    657.4    63   D    -31.399    3.94   35.22  53.57
    2    12   8650.4    90   D    -28.887    1.52   49.53   5.73
   11    12   1253.8    90   D     60.286    3.03   25.11  20.02
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    60.286   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     89.68
    2     75.36
   11    150.00
   12    124.89
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09     657.4     3346.01
   90   D       6.18    9904.3    61208.39
                       --------  ----------
                        10561.6    64554.40
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.ii;
* READING NETWORK FROM FILE MST.ii
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -382.54 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR     KM
    1    12    657.4    63   D    -31.399    3.94   35.22  53.57
    2    12   8650.4    90   D    -28.887    1.52   49.53   5.73
   11    12   1253.8    90   D     60.286    3.03   25.11  20.02
```

```
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE
-----   --------
           MBAR
    1      89.68
    2      75.36
   11     150.00
   12     124.89
* COST OF NETWORK
  ---------------
 DIAM  TAG     COST      LENGTH    TOTAL COST
 ----  ---   --------   --------   ----------
             /    M         M
   63    D       5.09      657.4      3346.01
   90    D       6.18     9904.3     61208.39
                         --------   ----------
                         10561.6     64554.40
COMMAND >* Terminate the SNAP run.
```

MST.iii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >    1  12  657.37 0 D
ENTER PIPE >    2  12  8650.43 0 D
ENTER PIPE >    12  11  1253.84 0 D
ENTER PIPE >    3  11  1889.17 0 D;
COMMAND >ES
ENTER SOURCE >    11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >    1  31.3988
ENTER DEMAND, DL OFF >    2  28.8869
ENTER DEMAND, DL OFF >    3  26.3750;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >    16 D 0.97 11.15 0.36
ENTER FACTOR >    20 D 0.97 15.15 0.40
ENTER FACTOR >    25 D 0.97 20.15 0.56
ENTER FACTOR >    32 D 0.97 25.75 1.35
ENTER FACTOR >    63 D 0.97 50.9 5.09
ENTER FACTOR >    90 D 0.97 79.2 6.18
ENTER FACTOR >    125 D 0.97 110.3 11.72
ENTER FACTOR >    180 D 0.97 158.75 24.23
ENTER FACTOR >    250 D 0.97 220.75 46.62
ENTER FACTOR >    315 D 0.97 278.25 73.92
ENTER FACTOR >    355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
-----  -----  -------  ----  ---
                M
    1     12    657.4     0   D
    2     12   8650.4     0   D
    3     11   1889.2     0   D
   11     12   1253.8     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15     0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15     0.40   *
   25   D   0.970     20.15     0.56   *
   32   D   0.970     25.75     1.35   *
   63   D   0.970     50.90     5.09   *
                                       *
   90   D   0.970     79.20     6.18   *
```

```
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.iii;
* WRITING NETWORK TO FILE MST.iii
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -382.54 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12    657.4    63   D    -31.399    3.94   35.22   53.57
    2    12   8650.4    90   D    -28.887    1.52   49.53    5.73
    3    11   1889.2    63   D    -26.375    3.35   74.24   39.30
   11    12   1253.8    90   D     60.286    3.03   25.11   20.02
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    86.661   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     89.68
    2     75.36
    3     75.76
   11    150.00
   12    124.89
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2546.5    12961.89
   90   D       6.18    9904.3    61208.39
                       --------  ----------
                       12450.8    74170.28
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.iii;
* READING NETWORK FROM FILE MST.iii
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
DESIGN CYCLE   2 :
```

```
MINIMUM PRESSURE IS -382.54 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
MINIMUM PRESSURE IS   75.36 MBAR AT NODE     2
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR     KM
    1    12    657.4    63   D    -31.399    3.94   35.22   53.57
    2    12   8650.4    90   D    -28.887    1.52   49.53    5.73
    3    11   1889.2    63   D    -26.375    3.35   74.24   39.30
   11    12   1253.8    90   D     60.286    3.03   25.11   20.02
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     89.68
    2     75.36
    3     75.76
   11    150.00
   12    124.89
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2546.5    12961.89
   90   D       6.18    9904.3    61208.39
                       --------  ----------
                       12450.8    74170.28
COMMAND >* Terminate the SNAP run.
```

MST.iv

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  13  854.40 0 D
ENTER PIPE >   4  13  4867.13 0 D
ENTER PIPE >   2  4  3916.22 0 D
ENTER PIPE >   13  11  1058.12 0 D
ENTER PIPE >   3  11  1889.17 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
```

```
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                   M
    1    13    854.4     0   D
    2     4   3916.2     0   D
    3    11   1889.2     0   D
    4    13   4867.1     0   D
   11    13   1058.1     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.iv;
* WRITING NETWORK TO FILE MST.iv
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -187.64 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.91   45.28   52.99
    2     4   3916.2    90   D    -28.887    1.57   23.46    5.99
    3    11   1889.2    63   D    -26.375    3.35   74.24   39.30
    4    13   4867.1    90   D    -52.750    2.80   79.52   16.34
   11    13   1058.1   125   D     84.149    2.15    7.82    7.39
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    110.524   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    1     96.91   *    13    142.18
    2     39.21   *
    3     75.76   *
    4     62.67   *
```

```
   11    150.00   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2743.6    13964.77
   90   D       6.18    8783.3    54281.10
  125   D      11.72    1058.1    12401.17
                       --------  ----------
                       12585.0    80647.03
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.iv;
* READING NETWORK FROM FILE MST.iv
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -187.64 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.91   45.28   52.99
    2     4   3916.2    90   D    -28.887    1.57   23.46    5.99
    3    11   1889.2    63   D    -26.375    3.35   74.24   39.30
    4    13   4867.1    90   D    -52.750    2.80   79.52   16.34
   11    13   1058.1   125   D     84.149    2.15    7.82    7.39
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    1     96.91   *    13    142.18
    2     39.21   *
    3     75.76   *
    4     62.67   *
   11    150.00   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2743.6    13964.77
   90   D       6.18    8783.3    54281.10
  125   D      11.72    1058.1    12401.17
                       --------  ----------
                       12585.0    80647.03
COMMAND >* Terminate the SNAP run.
```

MST.v

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >    1  13  854.40 0 D
ENTER PIPE >    4  13  4867.13 0 D
ENTER PIPE >    2  4  3916.22 0 D
ENTER PIPE >    13  11  1058.12 0 D
ENTER PIPE >    5  14  602.86 0 D
ENTER PIPE >    3  14  765.85 0 D
ENTER PIPE >    14  11  1413.77 0 D;
COMMAND >ES
ENTER SOURCE >    11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >    1  31.3988
ENTER DEMAND, DL OFF >    2  28.8869
ENTER DEMAND, DL OFF >    3  26.3750
ENTER DEMAND, DL OFF >    4  23.8631
ENTER DEMAND, DL OFF >    5  21.3512;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >    16 D 0.97 11.15 0.36
ENTER FACTOR >    20 D 0.97 15.15 0.40
ENTER FACTOR >    25 D 0.97 20.15 0.56
ENTER FACTOR >    32 D 0.97 25.75 1.35
ENTER FACTOR >    63 D 0.97 50.9 5.09
ENTER FACTOR >    90 D 0.97 79.2 6.18
ENTER FACTOR >    125 D 0.97 110.3 11.72
ENTER FACTOR >    180 D 0.97 158.75 24.23
ENTER FACTOR >    250 D 0.97 220.75 46.62
ENTER FACTOR >    315 D 0.97 278.25 73.92
ENTER FACTOR >    355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                 M                    *                  M
                                      *
    1    13    854.4     0   D        *    11    13   1058.1     0   D
    2     4   3916.2     0   D        *    11    14   1413.8     0   D
    3    14    765.8     0   D        *
    4    13   4867.1     0   D        *
    5    14    602.9     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST   *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----   *  ----  ---  -----  --------   -----
                       MM     /   M   *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.v;
* WRITING NETWORK TO FILE MST.v
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
```

```
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -48.31 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.91   45.28   52.99
    2     4   3916.2    90   D    -28.887    1.57   23.46    5.99
    3    14    765.8    63   D    -26.375    3.27   30.01   39.18
    4    13   4867.1    90   D    -52.750    2.80   79.52   16.34
    5    14    602.9    63   D    -21.351    2.62   16.24   26.95
   11    13   1058.1   125   D     84.149    2.15    7.82    7.39
   11    14   1413.8    90   D     47.726    2.38   18.74   13.26
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    131.875   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    1     96.91   *    11    150.00
    2     39.21   *    13    142.18
    3    101.25   *    14    131.26
    4     62.67   *
    5    115.02   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2223.1    11315.63
   90   D       6.18   10197.1    63018.20
  125   D      11.72    1058.1    12401.17
                       --------  ----------
                       13478.3    86734.99
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.v;
* READING NETWORK FROM FILE MST.v
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -48.31 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
```

```
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.91   45.28   52.99
    2     4   3916.2    90   D    -28.887    1.57   23.46    5.99
    3    14    765.8    63   D    -26.375    3.27   30.01   39.18
    4    13   4867.1    90   D    -52.750    2.80   79.52   16.34
    5    14    602.9    63   D    -21.351    2.62   16.24   26.95
   11    13   1058.1   125   D     84.149    2.15    7.82    7.39
   11    14   1413.8    90   D     47.726    2.38   18.74   13.26
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
-----  --------    * -----  --------
          MBAR     *           MBAR
                   *
    1     96.91    *    11    150.00
    2     39.21    *    13    142.18
    3    101.25    *    14    131.26
    4     62.67    *
    5    115.02    *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2223.1    11315.63
   90   D       6.18   10197.1    63018.20
  125   D      11.72    1058.1    12401.17
                       --------  ----------
                       13478.3    86734.99
COMMAND >* Terminate the SNAP run.
```

MST.vi

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  13  854.40 0 D
ENTER PIPE >   4  13  4867.13 0 D
ENTER PIPE >   2  4  3916.22 0 D
ENTER PIPE >   13  11  1058.12 0 D
ENTER PIPE >   5  11  1809.34 0 D
ENTER PIPE >   3  15  699.40 0 D
ENTER PIPE >   15  5  721.77 0 D
ENTER PIPE >   6  15  1780.04 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
```

```
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                  M
                                      *
    1    13    854.4     0   D        *     5    15    721.8     0   D
    2     4   3916.2     0   D        *     6    15   1780.0     0   D
    3    15    699.4     0   D        *    11    13   1058.1     0   D
    4    13   4867.1     0   D        *
    5    11   1809.3     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.vi;
* WRITING NETWORK TO FILE MST.vi
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -187.64 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----  ------  ----  ---  --------  ------  ------    MBAR
                 M                SCMH      MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.91   45.28   52.99
    2     4   3916.2    90   D    -28.887    1.57   23.46    5.99
    3    15    699.4    63   D    -26.375    3.37   28.22   40.35
    4    13   4867.1    90   D    -52.750    2.80   79.52   16.34
    5    11   1809.3    90   D    -66.565    3.40   43.47   24.03
    5    15    721.8    90   D     45.214    2.33    9.01   12.48
    6    15   1780.0    63   D    -18.839    2.43   40.21   22.59
   11    13   1058.1   125   D     84.149    2.15    7.82    7.39
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
         MBAR       SCMH
   11    150.00    150.714   100.0 %
```

```
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
-----  --------    * -----  --------
           MBAR    *           MBAR
                   *
    1     96.91    *     6     57.32
    2     39.21    *    11    150.00
    3     69.30    *    13    142.18
    4     62.67    *    15     97.52
    5    106.53    *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09    3333.8    16969.25
   90   D       6.18   11314.5    69923.35
  125   D      11.72    1058.1    12401.17
                       --------  ----------
                        15706.4    99293.76
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.vi;
* READING NETWORK FROM FILE MST.vi
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -187.64 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
MINIMUM PRESSURE IS   39.21 MBAR AT NODE     2
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH     MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.91   45.28   52.99
    2     4   3916.2    90   D    -28.887    1.57   23.46    5.99
    3    15    699.4    63   D    -26.375    3.37   28.22   40.35
    4    13   4867.1    90   D    -52.750    2.80   79.52   16.34
    5    11   1809.3    90   D    -66.565    3.40   43.47   24.03
    5    15    721.8    90   D     45.214    2.33    9.01   12.48
    6    15   1780.0    63   D    -18.839    2.43   40.21   22.59
   11    13   1058.1   125   D     84.149    2.15    7.82    7.39
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
-----  --------    * -----  --------
           MBAR    *           MBAR
                   *
    1     96.91    *     6     57.32
    2     39.21    *    11    150.00
    3     69.30    *    13    142.18
```

```
    4     62.67   *    15     97.52
    5    106.53   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M       M
   63   D       5.09    3333.8    16969.25
   90   D       6.18   11314.5    69923.35
  125   D      11.72    1058.1    12401.17
                       --------  ----------
                       15706.4    99293.76
COMMAND >* Terminate the SNAP run.
```

MST.vii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  13  854.40 0 D
ENTER PIPE >   4  13  4867.13 0 D
ENTER PIPE >   13  11  1058.12 0 D
ENTER PIPE >   5  11  1809.34 0 D
ENTER PIPE >   3  15  699.40 0 D
ENTER PIPE >   15  5  721.77 0 D
ENTER PIPE >   6  15  1780.04 0 D
ENTER PIPE >   2  16  3215.80 0 D
ENTER PIPE >   7  16  5926.09 0 D
ENTER PIPE >   16  4  1139.18 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
-----  -----  -------  ----  ---       * -----  -----  -------  ----  ---
                  M                   *                  M
                                      *
    1    13    854.4     0   D        *     5    11   1809.3     0   D
    2    16   3215.8     0   D        *     5    15    721.8     0   D
    3    15    699.4     0   D        *     6    15   1780.0     0   D
    4    13   4867.1     0   D        *     7    16   5926.1     0   D
    4    16   1139.2     0   D        *    11    13   1058.1     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
```

```
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.vii;
* WRITING NETWORK TO FILE MST.vii
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -8.32 MBAR AT NODE     7
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR      KM
    1    13    854.4    63   D    -31.399    3.92   45.40   53.13
    2    16   3215.8    90   D    -28.887    1.51   18.58    5.78
    3    15    699.4    63   D    -26.375    3.37   28.22   40.35
    4    13   4867.1   125   D    -69.077    1.81   25.87    5.32
    4    16   1139.2    90   D     45.214    2.32   14.16   12.43
    5    11   1809.3    90   D    -66.565    3.40   43.47   24.03
    5    15    721.8    90   D     45.214    2.33    9.01   12.48
    6    15   1780.0    63   D    -18.839    2.43   40.21   22.59
    7    16   5926.1    90   D    -16.327    0.85   12.76    2.15
   11    13   1058.1   125   D    100.476    2.57   10.69   10.10
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    167.042   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR
                  *                   *
    1     93.91   *     6     57.32   *    16     99.28
    2     80.70   *     7     86.52   *
    3     69.30   *    11    150.00   *
    4    113.44   *    13    139.31   *
    5    106.53   *    15     97.52   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    3333.8    16969.25
   90   D       6.18   12812.2    79179.27
  125   D      11.72    5925.2    69443.93
                       --------  ----------
                       22071.3   165592.44
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.vii;
* READING NETWORK FROM FILE MST.vii
*
```

```
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -8.32 MBAR AT NODE     7
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
1	13	854.4	63	D	-31.399	3.92	45.40	53.13
2	16	3215.8	90	D	-28.887	1.51	18.58	5.78
3	15	699.4	63	D	-26.375	3.37	28.22	40.35
4	13	4867.1	125	D	-69.077	1.81	25.87	5.32
4	16	1139.2	90	D	45.214	2.32	14.16	12.43
5	11	1809.3	90	D	-66.565	3.40	43.47	24.03
5	15	721.8	90	D	45.214	2.33	9.01	12.48
6	15	1780.0	63	D	-18.839	2.43	40.21	22.59
7	16	5926.1	90	D	-16.327	0.85	12.76	2.15
11	13	1058.1	125	D	100.476	2.57	10.69	10.10

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR
1	93.91	6	57.32	16	99.28
2	80.70	7	86.52		
3	69.30	11	150.00		
4	113.44	13	139.31		
5	106.53	15	97.52		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	3333.8	16969.25
90	D	6.18	12812.2	79179.27
125	D	11.72	5925.2	69443.93
			22071.3	165592.44

```
COMMAND >* Terminate the SNAP run.
```

MST.viii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  17  1176.86 0 D
```

```
ENTER PIPE >   8  17  1148.18 0 D
ENTER PIPE >   17  11  745.57 0 D
ENTER PIPE >   2  4  3916.22 0 D
ENTER PIPE >   4  18  1368.01 0 D
ENTER PIPE >   7  18  5757.36 0 D
ENTER PIPE >   18  8  2980.38 0 D
ENTER PIPE >   3  15  690.40 0 D
ENTER PIPE >   6  15  1780.04 0 D
ENTER PIPE >   15  5  721.77 0 D
ENTER PIPE >   5  11  1809.34 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274
ENTER DEMAND, DL OFF >   8  13.8155;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
```

NODE	NODE	LENGTH	DIAM	TAG	NODE	NODE	LENGTH	DIAM	TAG
		M					M		
1	17	1176.9	0	D	11	17	745.6	0	D
2	4	3916.2	0	D					
3	15	690.4	0	D					
4	18	1368.0	0	D					
5	11	1809.3	0	D					
5	15	721.8	0	D					
6	15	1780.0	0	D					
7	18	5757.4	0	D					
8	17	1148.2	0	D					
8	18	2980.4	0	D					

```
* FACTOR DATA
  -----------
```

DIAM	TAG	EFFIC	INT.DIAM	COST	DIAM	TAG	EFFIC	INT.DIAM	COST
			MM	/ M				MM	/ M
16	D	0.970	11.15	0.36	355	D	0.970	313.50	94.08
20	D	0.970	15.15	0.40					
25	D	0.970	20.15	0.56					
32	D	0.970	25.75	1.35					
63	D	0.970	50.90	5.09					
90	D	0.970	79.20	6.18					
125	D	0.970	110.30	11.72					
180	D	0.970	158.75	24.23					
250	D	0.970	220.75	46.62					
315	D	0.970	278.25	73.92					

```
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.viii;
*** INVALID FILE NAME
COMMAND >* Design the network
```

```
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   57.32 MBAR AT NODE     6
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR      KM
    1    17   1176.9    63   D    -31.399    3.98   62.95   53.49
    2     4   3916.2    90   D    -28.887    1.52   22.78    5.82
    3    15    690.4    63   D    -26.375    3.37   27.86   40.35
    4    18   1368.0    90   D    -52.750    2.72   22.29   16.30
    5    11   1809.3    90   D    -66.565    3.40   43.47   24.03
    5    15    721.8    90   D     45.214    2.33    9.01   12.48
    6    15   1780.0    63   D    -18.839    2.43   40.21   22.59
    7    18   5757.4    90   D    -16.327    0.83   12.21    2.12
    8    17   1148.2   125   D    -82.893    2.13    8.33    7.26
    8    18   2980.4   125   D     69.077    1.80   15.87    5.33
   11    17    745.6   125   D    114.292    2.92    9.45   12.68
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    180.857   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR   *           MBAR
                  *                  *
    1     77.60   *     6     57.32   *    17    140.55
    2     71.27   *     7    104.14   *    18    116.35
    3     69.67   *     8    132.22   *
    4     94.05   *    11    150.00   *
    5    106.53   *    15     97.52   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    3647.3    18564.76
   90   D       6.18   13572.7    83879.28
  125   D      11.72    4874.1    57124.80
                       --------  ----------
                       22094.1   159568.84
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.viii;
*** INVALID FILE NAME
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
*** NO PIPES TO BE DESIGNED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
*** NO RESULTS AVAILABLE
*** NO RESULTS AVAILABLE
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
```

```
 ----  ---  --------  --------  ----------
              /   M       M
   63   D       5.09    3647.3    18564.76
   90   D       6.18   13572.7    83879.28
  125   D      11.72    4874.1    57124.80
                       --------  ----------
                        22094.1   159568.84
COMMAND >* Terminate the SNAP run.
```

MST.ix

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >    1  17  1176.86 0 D
ENTER PIPE >    8  17  1148.18 0 D
ENTER PIPE >    17  11  745.57 0 D
ENTER PIPE >    2  4  3916.22 0 D
ENTER PIPE >    4  18  1368.01 0 D
ENTER PIPE >    7  18  5757.36 0 D
ENTER PIPE >    18  8  2980.38 0 D
ENTER PIPE >    3  15  690.40 0 D
ENTER PIPE >    6  15  1780.04 0 D
ENTER PIPE >    15  5  721.77 0 D
ENTER PIPE >    9  19  1830.21 0 D
ENTER PIPE >    3  19  996.44 0 D
ENTER PIPE >    19  11  1226.94 0 D;
COMMAND >ES
ENTER SOURCE >    11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >    1  31.3988
ENTER DEMAND, DL OFF >    2  28.8869
ENTER DEMAND, DL OFF >    3  26.3750
ENTER DEMAND, DL OFF >    4  23.8631
ENTER DEMAND, DL OFF >    5  21.3512
ENTER DEMAND, DL OFF >    6  18.8393
ENTER DEMAND, DL OFF >    7  16.3274
ENTER DEMAND, DL OFF >    8  13.8155
ENTER DEMAND, DL OFF >    9  11.3036;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >    16 D 0.97 11.15 0.36
ENTER FACTOR >    20 D 0.97 15.15 0.40
ENTER FACTOR >    25 D 0.97 20.15 0.56
ENTER FACTOR >    32 D 0.97 25.75 1.35
ENTER FACTOR >    63 D 0.97 50.9 5.09
ENTER FACTOR >    90 D 0.97 79.2 6.18
ENTER FACTOR >    125 D 0.97 110.3 11.72
ENTER FACTOR >    180 D 0.97 158.75 24.23
ENTER FACTOR >    250 D 0.97 220.75 46.62
ENTER FACTOR >    315 D 0.97 278.25 73.92
ENTER FACTOR >    355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                  M
                                      *
    1    17   1176.9     0   D        *     9    19   1830.2     0   D
    2     4   3916.2     0   D        *    11    17    745.6     0   D
    3    15    690.4     0   D        *    11    19   1226.9     0   D
    3    19    996.4     0   D        *
    4    18   1368.0     0   D        *
                                      *
    5    15    721.8     0   D        *
    6    15   1780.0     0   D        *
    7    18   5757.4     0   D        *
    8    17   1148.2     0   D        *
    8    18   2980.4     0   D        *
* FACTOR DATA
```

```
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.ix;
* WRITING NETWORK TO FILE MST.ix
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   38.62 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   38.62 MBAR AT NODE     6
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP    ------
-----  -----  ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH     MPS    MBAR      KM
    1     17  1176.9    63   D    -31.399    3.98   62.95   53.49
    2      4  3916.2    90   D    -28.887    1.52   22.78    5.82
    3     15   690.4    90   D     40.190    2.10    7.13   10.33
    3     19   996.4    90   D    -66.565    3.46   24.57   24.66
    4     18  1368.0    90   D    -52.750    2.72   22.29   16.30
    5     15   721.8    63   D    -21.351    2.75   20.42   28.29
    6     15  1780.0    63   D    -18.839    2.48   40.89   22.97
    7     18  5757.4    90   D    -16.327    0.83   12.21    2.12
    8     17  1148.2   125   D    -82.893    2.13    8.33    7.26
    8     18  2980.4   125   D     69.077    1.80   15.87    5.33
    9     19  1830.2    63   D    -11.304    1.41   16.72    9.14
   11     17   745.6   125   D    114.292    2.92    9.45   12.68
   11     19  1226.9    90   D     77.869    3.96   38.78   31.61
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    192.161   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR
                  *                   *
    1     77.60   *     6     38.62   *    15     79.51
    2     71.27   *     7    104.14   *    17    140.55
    3     86.64   *     8    132.22   *    18    116.35
    4     94.05   *     9     94.50   *    19    111.22
    5     59.09   *    11    150.00   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
```

```
   63   D       5.09    5508.9    28040.20
   90   D       6.18   13955.4    86244.19
  125   D      11.72    4874.1    57124.80
                       --------  ----------
                        24338.4   171409.19
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.ix;
* READING NETWORK FROM FILE MST.ix
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   38.62 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   38.62 MBAR AT NODE     6
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
MINIMUM PRESSURE IS   38.62 MBAR AT NODE     6
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	17	1176.9	63	D	-31.399	3.98	62.95	53.49
2	4	3916.2	90	D	-28.887	1.52	22.78	5.82
3	15	690.4	90	D	40.190	2.10	7.13	10.33
3	19	996.4	90	D	-66.565	3.46	24.57	24.66
4	18	1368.0	90	D	-52.750	2.72	22.29	16.30
5	15	721.8	63	D	-21.351	2.75	20.42	28.29
6	15	1780.0	63	D	-18.839	2.48	40.89	22.97
7	18	5757.4	90	D	-16.327	0.83	12.21	2.12
8	17	1148.2	125	D	-82.893	2.13	8.33	7.26
8	18	2980.4	125	D	69.077	1.80	15.87	5.33
9	19	1830.2	63	D	-11.304	1.41	16.72	9.14
11	17	745.6	125	D	114.292	2.92	9.45	12.68
11	19	1226.9	90	D	77.869	3.96	38.78	31.61

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR
		*			*		
1	77.60	*	6	38.62	*	15	79.51
2	71.27	*	7	104.14	*	17	140.55
3	86.64	*	8	132.22	*	18	116.35
4	94.05	*	9	94.50	*	19	111.22
5	59.09	*	11	150.00	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	5508.9	28040.20
90	D	6.18	13955.4	86244.19

```
  125   D      11.72    4874.1    57124.80
                       --------  ----------
                        24338.4   171409.19
COMMAND >* Terminate the SNAP run.
```

MST.x

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  17  1176.86 0 D
ENTER PIPE >   8  17  1148.18 0 D
ENTER PIPE >   17  11  745.57 0 D
ENTER PIPE >   2  4  3916.22 0 D
ENTER PIPE >   4  18  1368.01 0 D
ENTER PIPE >   7  18  5757.36 0 D
ENTER PIPE >   18  8  2980.38 0 D
ENTER PIPE >   9  19  1830.21 0 D
ENTER PIPE >   3  19  996.44 0 D
ENTER PIPE >   19  11  1226.94 0 D
ENTER PIPE >   5  20  781.02 0 D
ENTER PIPE >   10  20  1225.71 0 D
ENTER PIPE >   6  10  666.03 0 D
ENTER PIPE >   20  3  600.90 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    17   1176.9     0   D        *     9    19   1830.2     0   D
    2     4   3916.2     0   D        *    10    20   1225.7     0   D
    3    19    996.4     0   D        *    11    17    745.6     0   D
    3    20    600.9     0   D        *    11    19   1226.9     0   D
    4    18   1368.0     0   D        *
                                      *
    5    20    781.0     0   D        *
    6    10    666.0     0   D        *
    7    18   5757.4     0   D        *
    8    17   1148.2     0   D        *
    8    18   2980.4     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST   *  DIAM  TAG  EFFIC  INT.DIAM    COST
```

```
 ----  ---  -----  --------   -----   *  ----  ---  -----  --------   -----
                      MM     /   M    *                      MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.x;
* WRITING NETWORK TO FILE MST.x
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
1	17	1176.9	63	D	-31.399	3.98	62.95	53.49
2	4	3916.2	90	D	-28.887	1.52	22.78	5.82
3	19	996.4	90	D	-75.357	3.83	29.86	29.97
3	20	600.9	90	D	48.982	2.51	8.59	14.30
4	18	1368.0	90	D	-52.750	2.72	22.29	16.30
5	20	781.0	63	D	-21.351	2.70	21.65	27.73
6	10	666.0	63	D	-18.839	2.38	14.90	22.37
7	18	5757.4	90	D	-16.327	0.83	12.21	2.12
8	17	1148.2	125	D	-82.893	2.13	8.33	7.26
8	18	2980.4	125	D	69.077	1.80	15.87	5.33
9	19	1830.2	63	D	-11.304	1.37	16.29	8.90
10	20	1225.7	90	D	-27.631	1.42	6.51	5.31
11	17	745.6	125	D	114.292	2.92	9.45	12.68
11	19	1226.9	125	D	86.661	2.21	9.55	7.78

```
* SOURCE RESULTS
  --------------
```

NODE	PRESSURE	FLOW	% FLOW
	MBAR	SCMH	
11	150.00	200.952	100.0 %

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR
1	77.60	6	80.59	11	150.00
2	71.27	7	104.14	17	140.55
3	110.59	8	132.22	18	116.35
4	94.05	9	124.16	19	140.45
5	80.34	10	95.49	20	102.00

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST

```
              /   M        M
   63   D       5.09    4454.1    22671.47
   90   D       6.18   13864.6    85683.47
  125   D      11.72    6101.1    71504.54
                       --------  ----------
                        24419.8   179859.47
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.x;
* READING NETWORK FROM FILE MST.x
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    19 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	17	1176.9	63	D	-31.399	3.98	62.95	53.49
2	4	3916.2	90	D	-28.887	1.52	22.78	5.82
3	19	996.4	90	D	-75.357	3.97	30.89	31.00
3	20	600.9	90	D	48.982	2.60	8.90	14.81
4	18	1368.0	90	D	-52.750	2.72	22.29	16.30
5	20	781.0	63	D	-21.351	2.80	22.45	28.75
6	10	666.0	63	D	-18.839	2.47	15.45	23.20
7	18	5757.4	90	D	-16.327	0.83	12.21	2.12
8	17	1148.2	125	D	-82.893	2.13	8.33	7.26
8	18	2980.4	125	D	69.077	1.80	15.87	5.33
9	19	1830.2	63	D	-11.304	1.42	16.84	9.20
10	20	1225.7	90	D	-27.631	1.48	6.74	5.50
11	17	745.6	125	D	114.292	2.92	9.45	12.68
11	19	1226.9	90	D	86.661	4.44	47.01	38.32

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR
1	77.60	6	41.00	11	150.00
2	71.27	7	104.14	17	140.55
3	72.09	8	132.22	18	116.35
4	94.05	9	86.14	19	102.99
5	40.74	10	56.45	20	63.19

```
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH    TOTAL COST
 ----  ---  --------  --------  ----------
               /   M         M
   63   D       5.09    4454.1     22671.47
   90   D       6.18   15091.6     93265.96
  125   D      11.72    4874.1     57124.80
                       --------  ----------
                        24419.8   173062.25
COMMAND >* Terminate the SNAP run.
```

R.(i-x)

R.i

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  11  5629.43 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                  M
    1    11   5629.4     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.i;
* WRITING NETWORK TO FILE R.i
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
```

```
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  113.78 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -190.29 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS  113.78 MBAR AT NODE     1
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR     KM
    1    11   5629.4    90   D    -31.399    1.59   36.22    6.43
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00     31.399   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1    113.78
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   90   D       6.18    5629.4    34789.88
                       --------  ----------
                         5629.4    34789.88
COMMAND >* Read back the undesigned network.
COMMAND >RN R.i;
* READING NETWORK FROM FILE R.i
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  113.78 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -190.29 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS  113.78 MBAR AT NODE     1
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
MINIMUM PRESSURE IS  113.78 MBAR AT NODE     1
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR     KM
    1    11   5629.4    90   D    -31.399    1.59   36.22    6.43
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
```

```
-----  --------
          MBAR
    1    113.78
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   90   D       6.18    5629.4    34789.88
                       --------  ----------
                         5629.4    34789.88
COMMAND >* Terminate the SNAP run.
```

R.ii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   12  11  2802.49 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   2  12  7720.52 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
              M
    1    12   2826.9     0   D
    2    12   7720.5     0   D
   11    12   2802.5     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                      MM     /   M    *                        MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.ii;
* WRITING NETWORK TO FILE R.ii
COMMAND >* Design the network
COMMAND >DN;
```

```
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -72.72 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   94.88 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   94.88 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	2826.9	90	D	-31.399	1.58	18.23	6.45
2	12	7720.5	90	D	-28.887	1.49	43.56	5.64
11	12	2802.5	125	D	60.286	1.54	11.56	4.12

```
* SOURCE RESULTS
  --------------
```

NODE	PRESSURE	FLOW	% FLOW
	MBAR	SCMH	
11	150.00	60.286	100.0 %

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE
	MBAR
1	120.21
2	94.88
11	150.00
12	138.44

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
90	D	6.18	10547.5	65183.30
125	D	11.72	2802.5	32845.18
			13350.0	98028.48

```
COMMAND >* Read back the undesigned network.
COMMAND >RN R.ii;
* READING NETWORK FROM FILE R.ii
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -72.72 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   94.88 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   94.88 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    12 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   47.68 MBAR AT NODE     2
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
MINIMUM PRESSURE IS   47.68 MBAR AT NODE     2
```

```
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG     FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12   2826.9    90   D    -31.399    1.65   18.99    6.72
    2    12   7720.5    90   D    -28.887    1.56   45.42    5.88
   11    12   2802.5    90   D     60.286    3.11   56.90   20.30
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     74.11
    2     47.68
   11    150.00
   12     93.10
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   90   D       6.18   13350.0    82502.69
                       --------  ----------
                       13350.0    82502.69
COMMAND >* Terminate the SNAP run.
```

R.iii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   12  13  2438.86 0 D
ENTER PIPE >   3  13   2380.78 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   2  12  7720.52 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE    LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                   M
    1    12   2826.9     0   D
    2    12   7720.5     0   D
    3    13   2380.8     0   D
   11    13    363.6     0   D
   12    13   2438.9     0   D
```

```
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.iii;
* WRITING NETWORK TO FILE R.iii
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -67.32 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   52.52 MBAR AT NODE     3
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   52.52 MBAR AT NODE     3
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12  2826.9    90   D    -31.399    1.58   18.25    6.46
    2    12  7720.5    90   D    -28.887    1.49   43.61    5.65
    3    13  2380.8    63   D    -26.375    3.42   94.66   39.76
   11    13   363.6   125   D     86.661    2.20    2.82    7.76
   12    13  2438.9   125   D    -60.286    1.54   10.08    4.13
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    86.661   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    1    118.85   *    13    147.18
    2     93.49   *
    3     52.52   *
   11    150.00   *
   12    137.10   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2380.8    12118.17
   90   D       6.18   10547.5    65183.30
  125   D      11.72    2802.5    32845.19
                       --------  ----------
                       15730.7   110146.66
COMMAND >* Read back the undesigned network.
COMMAND >RN R.iii;
```

```
* READING NETWORK FROM FILE R.iii
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -67.32 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   52.52 MBAR AT NODE     3
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   52.52 MBAR AT NODE     3
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
PIPE    12    13 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   52.47 MBAR AT NODE     2
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
PIPE    11    13 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   40.58 MBAR AT NODE     2
...   2 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	2826.9	90	D	-31.399	1.66	19.11	6.76
2	12	7720.5	90	D	-28.887	1.57	45.71	5.92
3	13	2380.8	63	D	-26.375	3.46	95.64	40.17
11	13	363.6	90	D	86.661	4.31	13.73	37.77
12	13	2438.9	90	D	-60.286	3.13	49.97	20.49

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR
		*		
1	67.19	*	13	136.27
2	40.58	*		
3	40.63	*		
11	150.00	*		
12	86.29	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	2380.8	12118.17
90	D	6.18	13350.0	82502.69
			15730.7	94620.86

```
COMMAND >* Terminate the SNAP run.
COMMAND >.
```

R.iv

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   12  13  2438.86 0 D
ENTER PIPE >   3  13   2380.78 0 D
ENTER PIPE >   1  12  2826.94 0 D
```

```
ENTER PIPE >   14  12 3535.91 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   2826.9     0   D        *    12    13   2438.9     0   D
    2    14   4184.6     0   D        *    12    14   3535.9     0   D
    3    13   2380.8     0   D        *
    4    14    292.8     0   D        *
   11    13    363.6     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    * ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.iv;
* WRITING NETWORK TO FILE R.iv
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -32.49 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   44.61 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   44.61 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
```

```
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12   2826.9    90   D    -31.399    1.60   18.41    6.51
    2    14   4184.6    90   D    -28.887    1.56   24.92    5.96
    3    13   2380.8    63   D    -26.375    3.43   94.79   39.81
    4    14    292.8    63   D    -23.863    3.08   10.10   34.48
   11    13    363.6   125   D    110.524    2.81    4.34   11.92
   12    13   2438.9   125   D    -84.149    2.17   18.17    7.45
   12    14   3535.9    90   D     52.750    2.78   57.97   16.39
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    110.524   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------  * -----  --------
          MBAR   *           MBAR
                 *
    1    109.09  *    12    127.50
    2     44.61  *    13    145.66
    3     50.87  *    14     69.53
    4     59.43  *
   11    150.00  *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2673.6    13608.52
   90   D       6.18   10547.5    65183.30
  125   D      11.72    2802.5    32845.19
                       --------  ----------
                       16023.5   111637.02
COMMAND >* Read back the undesigned network.
COMMAND >RN R.iv;
* READING NETWORK FROM FILE R.iv
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -32.49 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   44.61 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   44.61 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
MINIMUM PRESSURE IS   44.61 MBAR AT NODE     2
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
```

```
    1    12   2826.9    90   D    -31.399    1.60   18.41    6.51
    2    14   4184.6    90   D    -28.887    1.56   24.92    5.96
    3    13   2380.8    63   D    -26.375    3.43   94.79   39.81
    4    14    292.8    63   D    -23.863    3.08   10.10   34.48
   11    13    363.6   125   D    110.524    2.81    4.34   11.92
   12    13   2438.9   125   D    -84.149    2.17   18.17    7.45
   12    14   3535.9    90   D     52.750    2.78   57.97   16.39
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
-----  --------    * -----  --------
          MBAR     *           MBAR
                   *
    1    109.09    *    12    127.50
    2     44.61    *    13    145.66
    3     50.87    *    14     69.53
    4     59.43    *
   11    150.00    *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    2673.6    13608.52
   90   D       6.18   10547.5    65183.30
  125   D      11.72    2802.5    32845.19
                       --------  ----------
                        16023.5   111637.02
COMMAND >* Terminate the SNAP run.
```

R.v

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   12  13  2438.86 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   14  12 3535.91 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   3  15  1399.41 0 D
ENTER PIPE >   15  13  981.37 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
-----  -----  -------  ----  ---       * -----  -----  -------  ----  ---
                  M                   *                   M
```

```
                                          *
    1    12   2826.9     0   D           *    11    13    363.6     0   D
    2    14   4184.6     0   D           *    12    13   2438.9     0   D
    3    15   1399.4     0   D           *    12    14   3535.9     0   D
    4    14    292.8     0   D           *    13    15    981.4     0   D
    5    15   1912.7     0   D           *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST     *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----     *  ----  ---  -----  --------   -----
                       MM     /   M     *                       MM     /   M
                                        *
   16   D   0.970     11.15    0.36     *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40     *
   25   D   0.970     20.15    0.56     *
   32   D   0.970     25.75    1.35     *
   63   D   0.970     50.90    5.09     *
                                        *
   90   D   0.970     79.20    6.18     *
  125   D   0.970    110.30   11.72     *
  180   D   0.970    158.75   24.23     *
  250   D   0.970    220.75   46.62     *
  315   D   0.970    278.25   73.92     *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.v;
* WRITING NETWORK TO FILE R.v
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -34.37 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   48.21 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   48.21 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
-----  -----  ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    1    12   2826.9    90   D    -31.399    1.59   18.35    6.49
    2    14   4184.6    90   D    -28.887    1.55   24.84    5.94
    3    15   1399.4    63   D    -26.375    3.33   55.22   39.46
    4    14    292.8    63   D    -23.863    3.07   10.06   34.37
    5    15   1912.7    63   D    -21.351    2.69   52.14   27.26
   11    13    363.6   180   D    131.875    1.61    1.04    2.87
   12    13   2438.9   125   D    -84.149    2.17   18.11    7.43
   12    14   3535.9    90   D     52.750    2.77   57.79   16.34
   13    15    981.4    90   D     47.726    2.37   12.99   13.23
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
         MBAR       SCMH
   11    150.00    131.875   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
         MBAR     *           MBAR
                  *
    1    112.49   *    11    150.00
    2     48.21   *    12    130.84
    3     80.75   *    13    148.96
    4     62.99   *    14     73.05
    5     83.82   *    15    135.97
* COST OF NETWORK
  ---------------
```

```
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09    3604.9    18348.74
   90   D       6.18   11528.8    71248.16
  125   D      11.72    2438.9    28583.44
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       17936.2   126991.10
COMMAND >* Read back the undesigned network.
COMMAND >RN R.v;
* READING NETWORK FROM FILE R.v
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -34.37 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   48.21 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   48.21 MBAR AT NODE     2
         REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    13 CHANGED FROM 180 TO 125
MINIMUM PRESSURE IS   42.86 MBAR AT NODE     2
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
MINIMUM PRESSURE IS   42.86 MBAR AT NODE     2
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
                                                          P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
               M                   SCMH      MPS    MBAR     KM
    1    12   2826.9    90   D    -31.399    1.60   18.43    6.52
    2    14   4184.6    90   D    -28.887    1.56   24.96    5.97
    3    15   1399.4    63   D    -26.375    3.35   55.47   39.64
    4    14    292.8    63   D    -23.863    3.08   10.11   34.54
    5    15   1912.7    63   D    -21.351    2.70   52.38   27.39
   11    13    363.6   125   D    131.875    3.36    5.93   16.30
   12    13   2438.9   125   D    -84.149    2.18   18.19    7.46
   12    14   3535.9    90   D     52.750    2.79   58.06   16.42
   13    15    981.4    90   D     47.726    2.38   13.04   13.29
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
         MBAR     *           MBAR
                  *
    1    107.45   *    11    150.00
    2     42.86   *    12    125.88
    3     75.56   *    13    144.07
    4     57.71   *    14     67.83
    5     78.65   *    15    131.03
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
```

```
   63    D        5.09     3604.9     18348.74
   90    D        6.18    11528.8     71248.16
  125    D       11.72     2802.5     32845.19
                         --------   ----------
                         17936.2    122442.09
COMMAND >* Terminate the SNAP run.
```

R.vi

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >    13  11  363.63 0 D
ENTER PIPE >    12  13  2438.86 0 D
ENTER PIPE >    1  12  2826.94 0 D
ENTER PIPE >    14  12 3535.91 0 D
ENTER PIPE >    4  14  292.80 0 D
ENTER PIPE >    2  14  4184.61 0 D
ENTER PIPE >    5  15  1912.65 0 D
ENTER PIPE >    3  16  290.20 0 D
ENTER PIPE >    15  13  981.37 0 D
ENTER PIPE >    6  16  3056.47 0 D
ENTER PIPE >    16  15  1109.21 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >    1  31.3988
ENTER DEMAND, DL OFF >    2  28.8869
ENTER DEMAND, DL OFF >    3  26.3750
ENTER DEMAND, DL OFF >    4  23.8631
ENTER DEMAND, DL OFF >    5  21.3512
ENTER DEMAND, DL OFF >    6  18.8393;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >    16 D 0.97 11.15 0.36
ENTER FACTOR >    20 D 0.97 15.15 0.40
ENTER FACTOR >    25 D 0.97 20.15 0.56
ENTER FACTOR >    32 D 0.97 25.75 1.35
ENTER FACTOR >    63 D 0.97 50.9 5.09
ENTER FACTOR >    90 D 0.97 79.2 6.18
ENTER FACTOR >    125 D 0.97 110.3 11.72
ENTER FACTOR >    180 D 0.97 158.75 24.23
ENTER FACTOR >    250 D 0.97 220.75 46.62
ENTER FACTOR >    315 D 0.97 278.25 73.92
ENTER FACTOR >    355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                  M
                                      *
    1    12   2826.9     0   D        *    15    16   1109.2     0   D
    2    14   4184.6     0   D        *
    3    16    290.2     0   D        *
    4    14    292.8     0   D        *
    5    15   1912.7     0   D        *
                                      *
    6    16   3056.5     0   D        *
   11    13    363.6     0   D        *
   12    13   2438.9     0   D        *
   12    14   3535.9     0   D        *
   13    15    981.4     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
```

```
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.vi;
* WRITING NETWORK TO FILE R.vi
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -36.24 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   42.59 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   42.59 MBAR AT NODE     6
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12  2826.9    90   D    -31.399    1.59   18.36    6.49
    2    14  4184.6    90   D    -28.887    1.56   24.85    5.94
    3    16   290.2    63   D    -26.375    3.28   11.48   39.54
    4    14   292.8    63   D    -23.863    3.07   10.07   34.38
    5    15  1912.7    63   D    -21.351    2.72   52.66   27.53
    6    16  3056.5    63   D    -18.839    2.47   69.06   22.59
   11    13   363.6   180   D    150.714    1.84    1.32    3.63
   12    13  2438.9   125   D    -84.149    2.17   18.12    7.43
   12    14  3535.9    90   D     52.750    2.78   57.81   16.35
   13    15   981.4    90   D     66.565    3.34   23.40   23.85
   15    16  1109.2    90   D     45.214    2.30   13.64   12.30
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    150.714   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR
                  *                   *
    1    112.20   *     6     42.59   *    15    125.28
    2     47.91   *    11    150.00   *    16    111.64
    3    100.17   *    12    130.56   *
    4     62.69   *    13    148.68   *
    5     72.62   *    14     72.76   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M         M
   63   D       5.09    5552.1    28260.29
   90   D       6.18   12638.0    78103.09
  125   D      11.72    2438.9    28583.44
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       20992.7   143757.56
COMMAND >* Read back the undesigned network.
COMMAND >RN R.vi;
* READING NETWORK FROM FILE R.vi
```

```
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -36.24 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   42.59 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   42.59 MBAR AT NODE     6
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    13 CHANGED FROM 180 TO 125
MINIMUM PRESSURE IS   35.77 MBAR AT NODE     6
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
MINIMUM PRESSURE IS   35.77 MBAR AT NODE     6
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	2826.9	90	D	-31.399	1.60	18.46	6.53
2	14	4184.6	90	D	-28.887	1.57	25.00	5.98
3	16	290.2	63	D	-26.375	3.30	11.54	39.77
4	14	292.8	63	D	-23.863	3.09	10.13	34.59
5	15	1912.7	63	D	-21.351	2.74	52.97	27.69
6	16	3056.5	63	D	-18.839	2.48	69.48	22.73
11	13	363.6	125	D	150.714	3.84	7.51	20.66
12	13	2438.9	125	D	-84.149	2.18	18.22	7.47
12	14	3535.9	90	D	52.750	2.79	58.14	16.44
13	15	981.4	90	D	66.565	3.36	23.53	23.98
15	16	1109.2	90	D	45.214	2.31	13.72	12.36

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR
1	105.81	6	35.77	15	118.96
2	41.12	11	150.00	16	105.24
3	93.70	12	124.27		
4	56.00	13	142.49		
5	65.99	14	66.13		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST / M	LENGTH M	TOTAL COST
63	D	5.09	5552.1	28260.29
90	D	6.18	12638.0	78103.09
125	D	11.72	2802.5	32845.19
			20992.7	139208.56

```
COMMAND >* Terminate the SNAP run.
```

R.vii

```
COMMAND >* Set units to low pressure, metric.
```

```
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   12  13  2438.86 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   14  17 1947.73 0 D
ENTER PIPE >   17  12  1588.18 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   6  16  3056.47 0 D
ENTER PIPE >   16  15  1109.21 0 D
ENTER PIPE >   7  17  7557.49 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                 M                    *                   M
                                      *
    1    12   2826.9     0   D        *    13    15    981.4     0   D
    2    14   4184.6     0   D        *    14    17   1947.7     0   D
    3    16    290.2     0   D        *    15    16   1109.2     0   D
    4    14    292.8     0   D        *
    5    15   1912.7     0   D        *
                                      *
    6    16   3056.5     0   D        *
    7    17   7557.5     0   D        *
   11    13    363.6     0   D        *
   12    13   2438.9     0   D        *
   12    17   1588.2     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
```

```
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.vii;
* WRITING NETWORK TO FILE R.vii
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -37.04 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   42.30 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   42.30 MBAR AT NODE     6
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  P/GRAD
----- -----   ------  ----  ---  --------  ------  ------  ------
                   M                 SCMH     MPS    MBAR    MBAR
                                                             KM
    1    12   2826.9    90   D    -31.399    1.60   18.47    6.53
    2    14   4184.6    90   D    -28.887    1.54   24.61    5.88
    3    16    290.2    63   D    -26.375    3.28   11.48   39.55
    4    14    292.8    63   D    -23.863    3.04    9.97   34.05
    5    15   1912.7    63   D    -21.351    2.72   52.67   27.54
    6    16   3056.5    63   D    -18.839    2.47   69.07   22.60
    7    17   7557.5    90   D    -16.327    0.84   16.07    2.13
   11    13    363.6   180   D    167.042    2.04    1.58    4.35
   12    13   2438.9   125   D   -100.476    2.60   24.83   10.18
   12    17   1588.2   125   D     69.077    1.80    8.49    5.35
   13    15    981.4    90   D     66.565    3.34   23.41   23.85
   14    17   1947.7    90   D    -52.750    2.75   31.91   16.39
   15    16   1109.2    90   D     45.214    2.30   13.64   12.30
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    167.042   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR
                  *                   *
    1    105.11   *     6     42.30   *    14     83.18
    2     58.57   *     7     99.02   *    15    125.01
    3     99.89   *    11    150.00   *    16    111.37
    4     73.21   *    12    123.59   *    17    115.09
    5     72.34   *    13    148.42   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M         M
   63   D       5.09    5552.1    28260.29
   90   D       6.18   18607.3   114993.41
  125   D      11.72    4027.0    47196.91
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       28550.1   199261.36
COMMAND >* Read back the undesigned network.
COMMAND >RN R.vii;
* READING NETWORK FROM FILE R.vii
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
```

```
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -37.04 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   42.30 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   42.30 MBAR AT NODE     6
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    13 CHANGED FROM 180 TO 125
MINIMUM PRESSURE IS   34.10 MBAR AT NODE     6
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
MINIMUM PRESSURE IS   34.10 MBAR AT NODE     6
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
1	12	2826.9	90	D	-31.399	1.62	18.60	6.58
2	14	4184.6	90	D	-28.887	1.55	24.79	5.92
3	16	290.2	63	D	-26.375	3.30	11.56	39.83
4	14	292.8	63	D	-23.863	3.06	10.04	34.30
5	15	1912.7	63	D	-21.351	2.74	53.04	27.73
6	16	3056.5	63	D	-18.839	2.49	69.58	22.76
7	17	7557.5	90	D	-16.327	0.84	16.18	2.14
11	13	363.6	125	D	167.042	4.26	9.02	24.81
12	13	2438.9	125	D	-100.476	2.62	24.99	10.25
12	17	1588.2	125	D	69.077	1.82	8.55	5.38
13	15	981.4	90	D	66.565	3.36	23.56	24.01
14	17	1947.7	90	D	-52.750	2.77	32.14	16.50
15	16	1109.2	90	D	45.214	2.31	13.73	12.38

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR
1	97.39	6	34.10	14	75.29
2	50.51	7	91.25	15	117.42
3	92.13	11	150.00	16	103.68
4	65.25	12	115.98	17	107.43
5	64.38	13	140.98		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	5552.1	28260.29
90	D	6.18	18607.3	114993.41
125	D	11.72	4390.7	51458.65
			28550.1	194712.36

```
COMMAND >* Terminate the SNAP run.
```

R.viii

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
```

```
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   12  18  459.96 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   14  17 1947.73 0 D
ENTER PIPE >   17  12  1588.18 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   6  16  3056.47 0 D
ENTER PIPE >   16  15  1109.21 0 D
ENTER PIPE >   7  17  7557.49 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274
ENTER DEMAND, DL OFF >   8  13.8155;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                  M
                                      *
    1    12   2826.9     0   D        *    12    18    460.0     0   D
    2    14   4184.6     0   D        *    13    15    981.4     0   D
    3    16    290.2     0   D        *    13    18   1978.9     0   D
    4    14    292.8     0   D        *    14    17   1947.7     0   D
    5    15   1912.7     0   D        *    15    16   1109.2     0   D
                                      *
    6    16   3056.5     0   D        *
    7    17   7557.5     0   D        *
    8    18    273.1     0   D        *
   11    13    363.6     0   D        *
   12    17   1588.2     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST   *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----   *  ----  ---  -----  --------   -----
                       MM     /   M   *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
```

```
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.viii;
*** INVALID FILE NAME
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.39 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   42.03 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.93 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
1	12	2826.9	90	D	-31.399	1.61	18.56	6.57
2	14	4184.6	90	D	-28.887	1.55	24.74	5.91
3	16	290.2	63	D	-26.375	3.28	11.48	39.56
4	14	292.8	63	D	-23.863	3.05	10.02	34.23
5	15	1912.7	63	D	-21.351	2.72	52.68	27.54
6	16	3056.5	63	D	-18.839	2.47	69.09	22.60
7	17	7557.5	90	D	-16.327	0.84	16.15	2.14
8	18	273.1	32	D	-13.816	7.14	90.95	333.04
11	13	363.6	180	D	180.857	2.21	1.82	5.01
12	17	1588.2	125	D	69.077	1.81	8.54	5.37
12	18	460.0	125	D	-100.476	2.62	4.75	10.32
13	15	981.4	90	D	66.565	3.34	23.41	23.86
13	18	1978.9	125	D	114.292	2.96	25.30	12.78
14	17	1947.7	90	D	-52.750	2.76	32.08	16.47
15	16	1109.2	90	D	45.214	2.30	13.64	12.30

```
* SOURCE RESULTS
  --------------
```

NODE	PRESSURE	FLOW	% FLOW
	MBAR	SCMH	
11	150.00	180.857	100.0 %

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR		MBAR
1	99.57	6	42.03	13	148.18	18	122.88
2	52.79	7	93.45	14	77.52		
3	99.64	8	31.93	15	124.77		
4	67.50	11	150.00	16	111.12		
5	72.08	12	118.13	17	109.60		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
32	D	1.35	273.1	368.67
63	D	5.09	5552.1	28260.29
90	D	6.18	18607.3	114993.41
125	D	11.72	4027.0	47196.91
180	D	24.23	363.6	8810.76
			28823.2	199630.03

```
COMMAND >* Read back the undesigned network.
COMMAND >RN R.viii;
```

```
*** INVALID FILE NAME
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
*** NO PIPES TO BE DESIGNED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
*** NO RESULTS AVAILABLE
*** NO RESULTS AVAILABLE
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   32   D       1.35     273.1      368.67
   63   D       5.09    5552.1    28260.29
   90   D       6.18   18607.3   114993.41
  125   D      11.72    4027.0    47196.91
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       28823.2   199630.03
COMMAND >* Terminate the SNAP run.
```

R.ix

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   12  18  459.96 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   14  17 1947.73 0 D
ENTER PIPE >   17  12  1588.18 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   6  16  3056.47 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   7  17  7557.49 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   9  11.3036;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
```

```
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
```

NODE	NODE	LENGTH	DIAM	TAG	*	NODE	NODE	LENGTH	DIAM	TAG
		M			*			M		
					*					
1	12	2826.9	0	D	*	12	17	1588.2	0	D
2	14	4184.6	0	D	*	12	18	460.0	0	D
3	16	290.2	0	D	*	13	15	981.4	0	D
4	14	292.8	0	D	*	13	18	1978.9	0	D
5	15	1912.7	0	D	*	14	17	1947.7	0	D
					*					
6	16	3056.5	0	D	*	15	19	253.4	0	D
7	17	7557.5	0	D	*	16	19	855.8	0	D
8	18	273.1	0	D	*					
9	19	2639.9	0	D	*					
11	13	363.6	0	D	*					

```
* FACTOR DATA
  -----------
```

DIAM	TAG	EFFIC	INT.DIAM	COST	*	DIAM	TAG	EFFIC	INT.DIAM	COST
			MM	/ M	*				MM	/ M
					*					
16	D	0.970	11.15	0.36	*	355	D	0.970	313.50	94.08
20	D	0.970	15.15	0.40	*					
25	D	0.970	20.15	0.56	*					
32	D	0.970	25.75	1.35	*					
63	D	0.970	50.90	5.09	*					
					*					
90	D	0.970	79.20	6.18	*					
125	D	0.970	110.30	11.72	*					
180	D	0.970	158.75	24.23	*					
250	D	0.970	220.75	46.62	*					
315	D	0.970	278.25	73.92	*					

```
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.ix;
* WRITING NETWORK TO FILE R.ix
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.64 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   32.04 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.70 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
1	12	2826.9	90	D	-31.399	1.61	18.57	6.57
2	14	4184.6	90	D	-28.887	1.55	24.74	5.91
3	16	290.2	63	D	-26.375	3.31	11.58	39.90
4	14	292.8	63	D	-23.863	3.05	10.02	34.24
5	15	1912.7	63	D	-21.351	2.74	53.06	27.74
6	16	3056.5	63	D	-18.839	2.49	69.71	22.81
7	17	7557.5	90	D	-16.327	0.84	16.15	2.14
8	18	273.1	32	D	-13.816	7.15	90.97	333.11
9	19	2639.9	63	D	-11.304	1.42	24.17	9.16
11	13	363.6	180	D	192.161	2.35	2.03	5.58
12	17	1588.2	125	D	69.077	1.81	8.54	5.38
12	18	460.0	125	D	-100.476	2.62	4.75	10.32
13	15	981.4	90	D	77.869	3.94	30.97	31.56
13	18	1978.9	125	D	114.292	2.96	25.30	12.79

```
   14    17   1947.7    90   D    -52.750    2.76   32.08   16.47
   15    19    253.4    90   D     56.518    2.87    4.62   18.24
   16    19    855.8    90   D    -45.214    2.32   10.63   12.42
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    192.161   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------   * -----  --------
          MBAR    *          MBAR    *          MBAR    *          MBAR
                  *                  *                  *
    1     99.36   *     6     32.04   *    12    117.92   *    17    109.38
    2     52.56   *     7     93.23   *    13    147.97   *    18    122.67
    3     90.17   *     8     31.70   *    14     77.30   *    19    112.38
    4     67.28   *     9     88.21   *    15    117.00   *
    5     63.94   *    11    150.00   *    16    101.75   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   32   D       1.35     273.1      368.67
   63   D       5.09    8192.1    41697.59
   90   D       6.18   18607.3   114993.41
  125   D      11.72    4027.0    47196.91
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       31463.2   213067.33
COMMAND >* Read back the undesigned network.
COMMAND >RN R.ix;
* READING NETWORK FROM FILE R.ix
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.64 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   32.04 MBAR AT NODE     6
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.70 MBAR AT NODE     8
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
REFINEMENT CYCLE  12 :
REFINEMENT CYCLE  13 :
MINIMUM PRESSURE IS   31.70 MBAR AT NODE     8
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
-----  -----  ------  ----  ---  --------  ------  ------    MBAR
                 M               SCMH      MPS    MBAR       KM
```

```
    1    12   2826.9    90   D    -31.399    1.61   18.57    6.57
    2    14   4184.6    90   D    -28.887    1.55   24.74    5.91
    3    16    290.2    63   D    -26.375    3.31   11.58   39.90
    4    14    292.8    63   D    -23.863    3.05   10.02   34.24
    5    15   1912.7    63   D    -21.351    2.74   53.06   27.74
    6    16   3056.5    63   D    -18.839    2.49   69.71   22.81
    7    17   7557.5    90   D    -16.327    0.84   16.15    2.14
    8    18    273.1    32   D    -13.816    7.15   90.97  333.11
    9    19   2639.9    63   D    -11.304    1.42   24.17    9.16
   11    13    363.6   180   D    192.161    2.35    2.03    5.58
   12    17   1588.2   125   D     69.077    1.81    8.54    5.38
   12    18    460.0   125   D   -100.476    2.62    4.75   10.32
   13    15    981.4    90   D     77.869    3.94   30.97   31.56
   13    18   1978.9   125   D    114.292    2.96   25.30   12.79
   14    17   1947.7    90   D    -52.750    2.76   32.08   16.47
   15    19    253.4    90   D     56.518    2.87    4.62   18.24
   16    19    855.8    90   D    -45.214    2.32   10.63   12.42
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------    * -----   --------    * -----   --------
           MBAR     *           MBAR     *           MBAR     *           MBAR
                    *                    *                    *
    1      99.36    *     6      32.04    *    12    117.92    *    17    109.38
    2      52.56    *     7      93.23    *    13    147.97    *    18    122.67
    3      90.17    *     8      31.70    *    14     77.30    *    19    112.38
    4      67.28    *     9      88.21    *    15    117.00    *
    5      63.94    *    11     150.00    *    16    101.75    *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
               /   M         M
   32    D        1.35      273.1       368.67
   63    D        5.09     8192.1     41697.59
   90    D        6.18    18607.3    114993.41
  125    D       11.72     4027.0     47196.91
  180    D       24.23      363.6      8810.76
                         --------   ----------
                         31463.2    213067.33
COMMAND >* Terminate the SNAP run.
```

R.x

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   12  18  459.96 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   14  17 1947.73 0 D
ENTER PIPE >   17  12  1588.18 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   6  20  600.48 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   7  17  7557.49 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  20  426.49 0 D
ENTER PIPE >   20  16 2455.99 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   5  21.3512
```

```
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   7  16.3274
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   2826.9     0   D        *    11    13    363.6     0   D
    2    14   4184.6     0   D        *    12    17   1588.2     0   D
    3    16    290.2     0   D        *    12    18    460.0     0   D
    4    14    292.8     0   D        *    13    15    981.4     0   D
    5    15   1912.7     0   D        *    13    18   1978.9     0   D
                                      *
    6    20    600.5     0   D        *    14    17   1947.7     0   D
    7    17   7557.5     0   D        *    15    19    253.4     0   D
    8    18    273.1     0   D        *    16    19    855.8     0   D
    9    19   2639.9     0   D        *    16    20   2456.0     0   D
   10    20    426.5     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.x;
* WRITING NETWORK TO FILE R.x
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.84 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   54.17 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
```

```
* FLOW RESULTS
  ------------
 NODE  NODE    LENGTH  DIAM  TAG     FLOW      VEL.    P/DROP   P/GRAD
                                                                 ------
                                                                  MBAR
                    M                          SCMH       MPS     MBAR       KM
    1    12   2826.9    90   D     -31.399     1.61    18.57     6.57
    2    14   4184.6    90   D     -28.887     1.55    24.75     5.91
    3    16    290.2    63   D     -26.375     3.25    11.39    39.25
    4    14    292.8    63   D     -23.863     3.06    10.03    34.24
    5    15   1912.7    63   D     -21.351     2.68    51.95    27.16
    6    20    600.5    63   D     -18.839     2.35    13.28    22.12
    7    17   7557.5    90   D     -16.327     0.84    16.15     2.14
    8    18    273.1    32   D     -13.816     7.15    90.98   333.16
    9    19   2639.9    63   D     -11.304     1.39    23.70     8.98
   10    20    426.5    63   D      -8.792     1.09     2.53     5.92
   11    13    363.6   180   D     200.952     2.46     2.20     6.04
   12    17   1588.2   125   D      69.077     1.81     8.54     5.38
   12    18    460.0   125   D    -100.476     2.62     4.75    10.32
   13    15    981.4   125   D      86.661     2.21     7.65     7.79
   13    18   1978.9   125   D     114.292     2.96    25.31    12.79
   14    17   1947.7    90   D     -52.750     2.76    32.09    16.47
   15    19    253.4    90   D      65.310     3.25     5.84    23.05
   16    19    855.8    90   D     -54.006     2.72    14.25    16.66
   16    20   2456.0    90   D      27.631     1.41    12.86     5.24
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
       --------    --------  ------
          MBAR       SCMH
   11    150.00    200.952   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
       --------   *       --------   *       --------   *       --------
          MBAR    *          MBAR    *          MBAR    *          MBAR
                  *                  *                  *
    1     99.18   *     6     93.92   *    11    150.00   *    16    120.06
    2     52.38   *     7     93.06   *    12    117.75   *    17    109.21
    3    108.67   *     8     31.52   *    13    147.80   *    18    122.50
    4     67.10   *     9    110.61   *    14     77.13   *    19    134.31
    5     88.21   *    10    104.67   *    15    140.16   *    20    107.20
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
       ---  --------   --------  ----------
            /   M         M
   32   D       1.35     273.1      368.67
   63   D       5.09    6162.6    31367.43
   90   D       6.18   20082.0   124106.58
  125   D      11.72    5008.4    58698.56
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       31889.7   223352.00
COMMAND >* Read back the undesigned network.
COMMAND >RN R.x;
* READING NETWORK FROM FILE R.x
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.84 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   54.17 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
```

```
PIPE    13    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
REFINEMENT CYCLE  12 :
REFINEMENT CYCLE  13 :
REFINEMENT CYCLE  14 :
REFINEMENT CYCLE  15 :
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	2826.9	90	D	-31.399	1.61	18.57	6.57
2	14	4184.6	90	D	-28.887	1.55	24.75	5.91
3	16	290.2	63	D	-26.375	3.34	11.71	40.34
4	14	292.8	63	D	-23.863	3.06	10.03	34.24
5	15	1912.7	63	D	-21.351	2.76	53.40	27.92
6	20	600.5	63	D	-18.839	2.42	13.66	22.75
7	17	7557.5	90	D	-16.327	0.84	16.15	2.14
8	18	273.1	32	D	-13.816	7.15	90.98	333.16
9	19	2639.9	63	D	-11.304	1.43	24.35	9.22
10	20	426.5	63	D	-8.792	1.12	2.60	6.09
11	13	363.6	180	D	200.952	2.46	2.20	6.04
12	17	1588.2	125	D	69.077	1.81	8.54	5.38
12	18	460.0	125	D	-100.476	2.62	4.75	10.32
13	15	981.4	90	D	86.661	4.41	37.52	38.23
13	18	1978.9	125	D	114.292	2.96	25.31	12.79
14	17	1947.7	90	D	-52.750	2.76	32.09	16.47
15	19	253.4	90	D	65.310	3.34	6.00	23.67
16	19	855.8	90	D	-54.006	2.80	14.64	17.11
16	20	2456.0	90	D	27.631	1.45	13.22	5.38

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR	*		MBAR
		*			*			*		
1	99.18	*	6	62.76	*	11	150.00	*	16	89.64
2	52.38	*	7	93.06	*	12	117.75	*	17	109.21
3	77.94	*	8	31.52	*	13	147.80	*	18	122.50
4	67.10	*	9	79.93	*	14	77.13	*	19	104.28
5	56.89	*	10	73.82	*	15	110.28	*	20	76.42

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
32	D	1.35	273.1	368.67
63	D	5.09	6162.6	31367.43
90	D	6.18	21063.3	130171.42
125	D	11.72	4027.0	47196.91
180	D	24.23	363.6	8810.76
			31889.7	217915.19

```
COMMAND >* Terminate the SNAP run.
```

MST.(A-J)

MST.A

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
```

```
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  11  1620.67 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                  M
    8    11   1620.7     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.A;
* WRITING NETWORK TO FILE MST.A
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  129.76 MBAR AT NODE     8
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -593.97 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS  129.76 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
                                                              P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M               SCMH      MPS    MBAR      KM
    8    11   1620.7    63   D    -13.816    1.67   20.24   12.49
* SOURCE RESULTS
  --------------
```

```
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    13.816   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    8    129.76
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
            /   M        M
   63   D       5.09    1620.7     8249.21
                       --------  ----------
                         1620.7     8249.21
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.A;
* READING NETWORK FROM FILE MST.A
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  129.76 MBAR AT NODE     8
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -593.97 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS  129.76 MBAR AT NODE     8
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
MINIMUM PRESSURE IS  129.76 MBAR AT NODE     8
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR      KM
    8    11   1620.7    63   D    -13.816    1.67   20.24   12.49
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    8    129.76
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
            /   M        M
   63   D       5.09    1620.7     8249.21
                       --------  ----------
                         1620.7     8249.21
COMMAND >* Terminate the SNAP run.
```

MST.B

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
```

```
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                  M
    1    12   1176.9     0   D
    8    12   1148.2     0   D
   11    12    745.6     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.B;
* WRITING NETWORK TO FILE MST.B
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.54 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
```

```
                    M                    SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D     -31.399     3.98   62.92   53.46
    8    12   1148.2    63   D     -13.816     1.68   14.42   12.56
   11    12    745.6    90   D      45.214     2.24    8.95   12.01
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00     45.214   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     78.13
    8    126.63
   11    150.00
   12    141.05
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M         M
   63   D       5.09    2325.0    11834.45
   90   D       6.18     745.6     4607.62
                       --------  ----------
                         3070.6    16442.08
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.B;
* READING NETWORK FROM FILE MST.B
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.54 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
-----  -----  ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D     -31.399     3.98   62.92   53.46
    8    12   1148.2    63   D     -13.816     1.68   14.42   12.56
   11    12    745.6    90   D      45.214     2.24    8.95   12.01
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     78.13
    8    126.63
   11    150.00
   12    141.05
* COST OF NETWORK
```

```
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09    2325.0    11834.45
   90   D       6.18     745.6     4607.62
                       --------  ----------
                         3070.6    16442.08
COMMAND >* Terminate the SNAP run.
```

MST.C

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D
ENTER PIPE >   5  11  1809.34 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                  M
    1    12   1176.9     0   D
    5    11   1809.3     0   D
    8    12   1148.2     0   D
   11    12    745.6     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.C;
* WRITING NETWORK TO FILE MST.C
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
```

```
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.54 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D    -31.399    3.98   62.92   53.46
    5    11   1809.3    63   D    -21.351    2.65   48.64   26.89
    8    12   1148.2    63   D    -13.816    1.68   14.42   12.56
   11    12    745.6    90   D     45.214    2.24    8.95   12.01
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00     66.565   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     78.13
    5    101.36
    8    126.63
   11    150.00
   12    141.05
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    4134.4    21043.99
   90   D       6.18     745.6     4607.62
                       --------  ----------
                         4879.9    25651.62
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.C;
* READING NETWORK FROM FILE MST.C
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.54 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
         REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
```

```
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG     FLOW      VEL.   P/DROP  ------
----- -----   ------  ----  ---  ---------  ------  ------   MBAR
                   M                 SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D     -31.399     3.98   62.92   53.46
    5    11   1809.3    63   D     -21.351     2.65   48.64   26.89
    8    12   1148.2    63   D     -13.816     1.68   14.42   12.56
   11    12    745.6    90   D      45.214     2.24    8.95   12.01
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    1     78.13
    5    101.36
    8    126.63
   11    150.00
   12    141.05
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M         M
   63   D       5.09    4134.4    21043.99
   90   D       6.18     745.6     4607.62
                       --------  ----------
                         4879.9    25651.62
COMMAND >* Terminate the SNAP run.
```

MST.D

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D
ENTER PIPE >   5  13  602.86 0 D
ENTER PIPE >   3  13  765.85 0 D
ENTER PIPE >   13  11  1413.77 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   3  26.3750;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE    LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
```

```
                                          *
    1    12   1176.9     0   D           *    11    13   1413.8     0   D
    3    13    765.8     0   D           *
    5    13    602.9     0   D           *
    8    12   1148.2     0   D           *
   11    12    745.6     0   D           *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST     *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----     *  ----  ---  -----  --------   -----
                       MM     /   M     *                       MM     /   M
                                        *
   16   D   0.970     11.15    0.36     *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40     *
   25   D   0.970     20.15    0.56     *
   32   D   0.970     25.75    1.35     *
   63   D   0.970     50.90    5.09     *
                                        *
   90   D   0.970     79.20    6.18     *
  125   D   0.970    110.30   11.72     *
  180   D   0.970    158.75   24.23     *
  250   D   0.970    220.75   46.62     *
  315   D   0.970    278.25   73.92     *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.D;
* WRITING NETWORK TO FILE MST.D
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -48.31 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
-----  -----  ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D    -31.399    3.98   62.92   53.46
    3    13    765.8    63   D    -26.375    3.27   30.01   39.18
    5    13    602.9    63   D    -21.351    2.62   16.24   26.95
    8    12   1148.2    63   D    -13.816    1.68   14.42   12.56
   11    12    745.6    90   D     45.214    2.24    8.95   12.01
   11    13   1413.8    90   D     47.726    2.38   18.74   13.26
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    92.940   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    1     78.13   *    12    141.05
    3    101.25   *    13    131.26
    5    115.02   *
    8    126.63   *
   11    150.00   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
```

```
   63    D       5.09    3693.8    18801.19
   90    D       6.18    2159.3    13344.72
                        --------  ----------
                          5853.1    32145.91
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.D;
* READING NETWORK FROM FILE MST.D
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -48.31 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                 SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D    -31.399    3.98   62.92   53.46
    3    13    765.8    63   D    -26.375    3.27   30.01   39.18
    5    13    602.9    63   D    -21.351    2.62   16.24   26.95
    8    12   1148.2    63   D    -13.816    1.68   14.42   12.56
   11    12    745.6    90   D     45.214    2.24    8.95   12.01
   11    13   1413.8    90   D     47.726    2.38   18.74   13.26
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
-----  --------    * -----  --------
          MBAR     *           MBAR
                   *
    1     78.13    *    12    141.05
    3    101.25    *    13    131.26
    5    115.02    *
    8    126.63    *
   11    150.00    *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63    D       5.09    3693.8    18801.19
   90    D       6.18    2159.3    13344.72
                        --------  ----------
                          5853.1    32145.91
COMMAND >* Terminate the SNAP run.
```

MST.E

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
```

```
COMMAND >EP
ENTER PIPE >    1  12  1176.86 0 D
ENTER PIPE >    8  12  1148.18 0 D
ENTER PIPE >    12  11  745.57 0 D
ENTER PIPE >    5  13  602.86 0 D
ENTER PIPE >    3  13  765.85 0 D
ENTER PIPE >    13  11  1413.77 0 D
ENTER PIPE >    10  3  1597.04 0 D;
COMMAND >ES
ENTER SOURCE >    11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >    8  13.8155
ENTER DEMAND, DL OFF >    1  31.3988
ENTER DEMAND, DL OFF >    5  21.3512
ENTER DEMAND, DL OFF >    3  26.3750
ENTER DEMAND, DL OFF >    10  8.7917;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >    16 D 0.97 11.15 0.36
ENTER FACTOR >    20 D 0.97 15.15 0.40
ENTER FACTOR >    25 D 0.97 20.15 0.56
ENTER FACTOR >    32 D 0.97 25.75 1.35
ENTER FACTOR >    63 D 0.97 50.9 5.09
ENTER FACTOR >    90 D 0.97 79.2 6.18
ENTER FACTOR >    125 D 0.97 110.3 11.72
ENTER FACTOR >    180 D 0.97 158.75 24.23
ENTER FACTOR >    250 D 0.97 220.75 46.62
ENTER FACTOR >    315 D 0.97 278.25 73.92
ENTER FACTOR >    355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   1176.9     0   D        *    11    12    745.6     0   D
    3    10   1597.0     0   D        *    11    13   1413.8     0   D
    3    13    765.8     0   D        *
    5    13    602.9     0   D        *
    8    12   1148.2     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST   *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----   *  ----  ---  -----  --------   -----
                       MM     /   M   *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.E;
* WRITING NETWORK TO FILE MST.E
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.54 MBAR AT NODE     1
DESIGN CYCLE   2 :
```

```
MINIMUM PRESSURE IS   64.55 MBAR AT NODE    10
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   64.55 MBAR AT NODE    10
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	1176.9	63	D	-31.399	3.98	62.92	53.46
3	10	1597.0	63	D	8.792	1.13	9.78	6.12
3	13	765.8	63	D	-35.167	4.47	50.40	65.80
5	13	602.9	63	D	-21.351	2.63	16.34	27.10
8	12	1148.2	63	D	-13.816	1.68	14.42	12.56
11	12	745.6	90	D	45.214	2.24	8.95	12.01
11	13	1413.8	90	D	56.518	2.84	25.28	17.88

```
* SOURCE RESULTS
  --------------
```

NODE	PRESSURE	FLOW	% FLOW
	MBAR	SCMH	
11	150.00	101.732	100.0 %

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR
		*		
1	78.13	*	11	150.00
3	74.33	*	12	141.05
5	108.38	*	13	124.72
8	126.63	*		
10	64.55	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	5290.8	26930.12
90	D	6.18	2159.3	13344.72
			7450.1	40274.84

```
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.E;
* READING NETWORK FROM FILE MST.E
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.54 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   64.55 MBAR AT NODE    10
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   64.55 MBAR AT NODE    10
        REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
MINIMUM PRESSURE IS   64.55 MBAR AT NODE    10
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
```

```
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----    ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D    -31.399    3.98   62.92   53.46
    3    10   1597.0    63   D      8.792    1.13    9.78    6.12
    3    13    765.8    63   D    -35.167    4.47   50.40   65.80
    5    13    602.9    63   D    -21.351    2.63   16.34   27.10
    8    12   1148.2    63   D    -13.816    1.68   14.42   12.56
   11    12    745.6    90   D     45.214    2.24    8.95   12.01
   11    13   1413.8    90   D     56.518    2.84   25.28   17.88
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------
           MBAR     *            MBAR
                    *
    1      78.13    *    11     150.00
    3      74.33    *    12     141.05
    5     108.38    *    13     124.72
    8     126.63    *
   10      64.55    *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------   --------  ----------
              /   M         M
   63   D       5.09     5290.8     26930.12
   90   D       6.18     2159.3     13344.72
                       --------  ----------
                         7450.1     40274.84
COMMAND >* Terminate the SNAP run.
```

MST.F

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D
ENTER PIPE >   5  13  602.86 0 D
ENTER PIPE >   3  13  765.85 0 D
ENTER PIPE >   13  11  1413.77 0 D
ENTER PIPE >   10  3  1597.04 0 D
ENTER PIPE >   6  10  666.03 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
```

```
* PIPE DATA
  ---------
 NODE  NODE    LENGTH  DIAM  TAG       *  NODE  NODE    LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                   M                  *                    M
                                      *
    1    12   1176.9     0   D        *     8    12   1148.2     0   D
    3    10   1597.0     0   D        *    11    12    745.6     0   D
    3    13    765.8     0   D        *    11    13   1413.8     0   D
    5    13    602.9     0   D        *
    6    10    666.0     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    * ----  ---  -----  --------   -----
                       MM     /   M    *                      MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.F;
* WRITING NETWORK TO FILE MST.F
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.25 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   71.14 MBAR AT NODE     6
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG     FLOW      VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                   M                SCMH      MPS    MBAR     KM
    1    12   1176.9    63   D    -31.399    3.98   62.92   53.46
    3    10   1597.0    90   D     27.631    1.44    8.54    5.35
    3    13    765.8    90   D    -54.006    2.78   13.05   17.04
    5    13    602.9    63   D    -21.351    2.67   16.59   27.52
    6    10    666.0    63   D    -18.839    2.40   15.03   22.56
    8    12   1148.2    63   D    -13.816    1.68   14.42   12.56
   11    12    745.6    90   D     45.214    2.24    8.95   12.01
   11    13   1413.8    90   D     75.357    3.84   42.24   29.88
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    120.572   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    1     78.13   *    10     86.16
    3     94.70   *    11    150.00
    5     91.17   *    12    141.05
```

```
    6     71.14   *    13    107.76
    8    126.63   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    3593.9    18293.10
   90   D       6.18    4522.2    27947.38
                       --------  ----------
                        8116.2    46240.48
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.F;
* READING NETWORK FROM FILE MST.F
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS    7.25 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   71.14 MBAR AT NODE     6
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
MINIMUM PRESSURE IS   71.14 MBAR AT NODE     6
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                 SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D    -31.399    3.98   62.92   53.46
    3    10   1597.0    90   D     27.631    1.44    8.54    5.35
    3    13    765.8    90   D    -54.006    2.78   13.05   17.04
    5    13    602.9    63   D    -21.351    2.67   16.59   27.52
    6    10    666.0    63   D    -18.839    2.40   15.03   22.56
    8    12   1148.2    63   D    -13.816    1.68   14.42   12.56
   11    12    745.6    90   D     45.214    2.24    8.95   12.01
   11    13   1413.8    90   D     75.357    3.84   42.24   29.88
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
         MBAR     *           MBAR
                  *
    1     78.13   *    10     86.16
    3     94.70   *    11    150.00
    5     91.17   *    12    141.05
    6     71.14   *    13    107.76
    8    126.63   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    3593.9    18293.10
   90   D       6.18    4522.2    27947.38
                       --------  ----------
```

```
                          8116.2    46240.48
COMMAND >* Terminate the SNAP run.
```

MST.G

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D
ENTER PIPE >   5  14  781.02 0 D
ENTER PIPE >   10  14  1225.71 0 D
ENTER PIPE >   14  3  600.90 0 D
ENTER PIPE >   3  15  996.44 0 D
ENTER PIPE >   9  15  1830.21 0 D
ENTER PIPE >   15  11  1226.94 0 D
ENTER PIPE >   6  10  666.03 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   9  11.3036;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   1176.9     0   D        *     8    12   1148.2     0   D
    3    14    600.9     0   D        *     9    15   1830.2     0   D
    3    15    996.4     0   D        *    10    14   1225.7     0   D
    5    14    781.0     0   D        *    11    12    745.6     0   D
    6    10    666.0     0   D        *    11    15   1226.9     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                      MM      /   M    *                      MM      /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
```

```
COMMAND >WN MST.G;
* WRITING NETWORK TO FILE MST.G
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	1176.9	63	D	-31.399	3.98	62.92	53.46
3	14	600.9	90	D	48.982	2.51	8.59	14.30
3	15	996.4	90	D	-75.357	3.83	29.86	29.97
5	14	781.0	63	D	-21.351	2.70	21.65	27.73
6	10	666.0	63	D	-18.839	2.38	14.90	22.37
8	12	1148.2	63	D	-13.816	1.68	14.42	12.56
9	15	1830.2	63	D	-11.304	1.37	16.29	8.90
10	14	1225.7	90	D	-27.631	1.42	6.51	5.31
11	12	745.6	90	D	45.214	2.24	8.95	12.01
11	15	1226.9	125	D	86.661	2.21	9.55	7.78

```
* SOURCE RESULTS
  --------------
```

NODE	PRESSURE	FLOW	% FLOW
	MBAR	SCMH	
11	150.00	131.875	100.0 %

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR
		*			*		
1	78.13	*	9	124.16	*	15	140.45
3	110.59	*	10	95.49	*		
5	80.34	*	11	150.00	*		
6	80.59	*	12	141.05	*		
8	126.63	*	14	102.00	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	5602.3	28515.71
90	D	6.18	3568.6	22054.07
125	D	11.72	1226.9	14379.74
			10397.9	64949.52

```
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.G;
* READING NETWORK FROM FILE MST.G
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
```

```
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   78.13 MBAR AT NODE     1
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
PIPE    11    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	1176.9	63	D	-31.399	3.98	62.92	53.46
3	14	600.9	90	D	48.982	2.60	8.90	14.81
3	15	996.4	90	D	-75.357	3.97	30.89	31.00
5	14	781.0	63	D	-21.351	2.80	22.45	28.75
6	10	666.0	63	D	-18.839	2.47	15.45	23.20
8	12	1148.2	63	D	-13.816	1.68	14.42	12.56
9	15	1830.2	63	D	-11.304	1.42	16.84	9.20
10	14	1225.7	90	D	-27.631	1.48	6.74	5.50
11	12	745.6	90	D	45.214	2.24	8.95	12.01
11	15	1226.9	90	D	86.661	4.44	47.01	38.32

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR
		*			*		
1	78.13	*	9	86.14	*	15	102.99
3	72.09	*	10	56.45	*		
5	40.74	*	11	150.00	*		
6	41.00	*	12	141.05	*		
8	126.63	*	14	63.19	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	5602.3	28515.71
90	D	6.18	4795.6	29636.56
			10397.9	58152.27

```
COMMAND >* Terminate the SNAP run.
```

MST.H

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D
ENTER PIPE >   5  14  781.02 0 D
ENTER PIPE >   10  14  1225.71 0 D
ENTER PIPE >   14  3  600.90 0 D
ENTER PIPE >   3  15  996.44 0 D
ENTER PIPE >   9  15  1830.21 0 D
ENTER PIPE >   15  11  1226.94 0 D
ENTER PIPE >   6  10  666.03 0 D
```

```
ENTER PIPE >   4  8  3842.67 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   4  23.8631;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   1176.9     0   D        *    11    15   1226.9     0   D
    3    14    600.9     0   D        *
    3    15    996.4     0   D        *
    4     8   3842.7     0   D        *
    5    14    781.0     0   D        *
                                      *
    6    10    666.0     0   D        *
    8    12   1148.2     0   D        *
    9    15   1830.2     0   D        *
   10    14   1225.7     0   D        *
   11    12    745.6     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.H;
* WRITING NETWORK TO FILE MST.H
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
```

```
MINIMUM PRESSURE IS  -12.93 MBAR AT NODE     4
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   83.48 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   67.58 MBAR AT NODE     1
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR      KM
    1    12   1176.9    63   D    -31.399    4.02   63.50   53.96
    3    14    600.9    90   D     48.982    2.51    8.59   14.30
    3    15    996.4    90   D    -75.357    3.83   29.86   29.97
    4     8   3842.7    90   D    -23.863    1.22   15.62    4.07
    5    14    781.0    63   D    -21.351    2.70   21.65   27.73
    6    10    666.0    63   D    -18.839    2.38   14.90   22.37
    8    12   1148.2    90   D    -37.679    1.90   10.20    8.88
    9    15   1830.2    63   D    -11.304    1.37   16.29    8.90
   10    14   1225.7    90   D    -27.631    1.42    6.51    5.31
   11    12    745.6    90   D     69.077    3.45   18.92   25.37
   11    15   1226.9   125   D     86.661    2.21    9.55    7.78
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    155.738   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR
                  *                   *
    1     67.58   *     8    120.88   *    14    102.00
    3    110.59   *     9    124.16   *    15    140.45
    4    105.26   *    10     95.49   *
    5     80.34   *    11    150.00   *
    6     80.59   *    12    131.08   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09    4454.1    22671.47
   90   D       6.18    8559.5    52897.53
  125   D      11.72    1226.9    14379.74
                       --------  ----------
                        14240.5    89948.73
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.H;
* READING NETWORK FROM FILE MST.H
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -12.93 MBAR AT NODE     4
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   83.48 MBAR AT NODE     1
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   67.58 MBAR AT NODE     1
         REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
REFINEMENT CYCLE   2 :
```

```
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	1176.9	63	D	-31.399	4.02	63.50	53.96
3	14	600.9	90	D	48.982	2.60	8.90	14.81
3	15	996.4	90	D	-75.357	3.97	30.89	31.00
4	8	3842.7	90	D	-23.863	1.22	15.62	4.07
5	14	781.0	63	D	-21.351	2.80	22.45	28.75
6	10	666.0	63	D	-18.839	2.47	15.45	23.20
8	12	1148.2	90	D	-37.679	1.90	10.20	8.88
9	15	1830.2	63	D	-11.304	1.42	16.84	9.20
10	14	1225.7	90	D	-27.631	1.48	6.74	5.50
11	12	745.6	90	D	69.077	3.45	18.92	25.37
11	15	1226.9	90	D	86.661	4.44	47.01	38.32

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR
		*			*		
1	67.58	*	8	120.88	*	14	63.19
3	72.09	*	9	86.14	*	15	102.99
4	105.26	*	10	56.45	*		
5	40.74	*	11	150.00	*		
6	41.00	*	12	131.08	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	4454.1	22671.47
90	D	6.18	9786.4	60480.02
			14240.5	83151.49

```
COMMAND >* Terminate the SNAP run.
```

MST.I

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  12  1176.86 0 D
ENTER PIPE >   8  12  1148.18 0 D
ENTER PIPE >   12  11  745.57 0 D
ENTER PIPE >   5  14  781.02 0 D
ENTER PIPE >   10  14  1225.71 0 D
ENTER PIPE >   14  3  600.90 0 D
ENTER PIPE >   3  15  996.44 0 D
ENTER PIPE >   9  15  1830.21 0 D
ENTER PIPE >   15  11  1226.94 0 D
ENTER PIPE >   6  10  666.03 0 D
ENTER PIPE >   4  8  3842.67 0 D
ENTER PIPE >   2  4  3916.22 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   10  8.7917
```

```
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   2  28.8869;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   1176.9     0   D        *    11    12    745.6     0   D
    2     4   3916.2     0   D        *    11    15   1226.9     0   D
    3    14    600.9     0   D        *
    3    15    996.4     0   D        *
    4     8   3842.7     0   D        *
                                      *
    5    14    781.0     0   D        *
    6    10    666.0     0   D        *
    8    12   1148.2     0   D        *
    9    15   1830.2     0   D        *
   10    14   1225.7     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.I;
* WRITING NETWORK TO FILE MST.I
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   51.37 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   51.37 MBAR AT NODE     2
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
```

```
  ------------                                                      P/GRAD
 NODE   NODE    LENGTH   DIAM   TAG     FLOW      VEL.    P/DROP   ------
----- -----    ------   ----   ---   --------   ------   ------    MBAR
                    M                    SCMH      MPS     MBAR      KM
    1     12   1176.9     63    D     -31.399     3.97    62.82    53.38
    2      4   3916.2     90    D     -28.887     1.55    23.20     5.92
    3     14    600.9     90    D      48.982     2.51     8.59    14.30
    3     15    996.4     90    D     -75.357     3.83    29.86    29.97
    4      8   3842.7     90    D     -52.750     2.77    62.59    16.29
    5     14    781.0     63    D     -21.351     2.70    21.65    27.73
    6     10    666.0     63    D     -18.839     2.38    14.90    22.37
    8     12   1148.2    125    D     -66.565     1.70     5.65     4.92
    9     15   1830.2     63    D     -11.304     1.37    16.29     8.90
   10     14   1225.7     90    D     -27.631     1.42     6.51     5.31
   11     12    745.6    125    D      97.964     2.50     7.19     9.65
   11     15   1226.9    125    D      86.661     2.21     9.55     7.78
* SOURCE RESULTS
  --------------
 NODE   PRESSURE      FLOW     % FLOW
-----   --------    --------   ------
           MBAR        SCMH
   11     150.00     184.625   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------    * -----   --------
           MBAR     *            MBAR     *             MBAR
                    *                     *
    1      79.99    *      6      80.59    *     12    142.81
    2      51.37    *      8     137.15    *     14    102.00
    3     110.59    *      9     124.16    *     15    140.45
    4      74.57    *     10      95.49    *
    5      80.34    *     11     150.00    *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
               /   M         M
   63    D       5.09     4454.1     22671.47
   90    D       6.18    10581.9     65396.39
  125    D      11.72     3120.7     36574.49
                        --------   ----------
                        18156.8    124642.34
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.I;
* READING NETWORK FROM FILE MST.I
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   51.37 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   51.37 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
REFINEMENT CYCLE   2 :
PIPE     8    12 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   27.65 MBAR AT NODE     2
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
```

```
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
MINIMUM PRESSURE IS   27.65 MBAR AT NODE     2
...   2 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	1176.9	63	D	-31.399	3.97	62.82	53.38
2	4	3916.2	90	D	-28.887	1.59	23.71	6.06
3	14	600.9	90	D	48.982	2.60	8.90	14.81
3	15	996.4	90	D	-75.357	3.97	30.89	31.00
4	8	3842.7	90	D	-52.750	2.83	63.87	16.62
5	14	781.0	63	D	-21.351	2.80	22.45	28.75
6	10	666.0	63	D	-18.839	2.47	15.45	23.20
8	12	1148.2	90	D	-66.565	3.37	27.57	24.01
9	15	1830.2	63	D	-11.304	1.42	16.84	9.20
10	14	1225.7	90	D	-27.631	1.48	6.74	5.50
11	12	745.6	125	D	97.964	2.50	7.19	9.65
11	15	1226.9	90	D	86.661	4.44	47.01	38.32

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR
1	79.99	*	6	41.00	*	12	142.81
2	27.65	*	8	115.24	*	14	63.19
3	72.09	*	9	86.14	*	15	102.99
4	51.36	*	10	56.45	*		
5	40.74	*	11	150.00	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	4454.1	22671.47
90	D	6.18	12957.1	80074.63
125	D	11.72	745.6	8738.08
			18156.8	111484.19

```
COMMAND >* Terminate the SNAP run.
```

MST.J

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   1  17  1176.86 0 D
ENTER PIPE >   8  17  1148.18 0 D
ENTER PIPE >   17  11  745.57 0 D
ENTER PIPE >   2  4  3916.22 0 D
ENTER PIPE >   4  18  1368.01 0 D
ENTER PIPE >   7  18  5757.36 0 D
ENTER PIPE >   18  8  2980.38 0 D
ENTER PIPE >   9  19  1830.21 0 D
ENTER PIPE >   3  19  996.44 0 D
ENTER PIPE >   19  11  1226.94 0 D
ENTER PIPE >   5  20  781.02 0 D
ENTER PIPE >   10  20  1225.71 0 D
ENTER PIPE >   6  10  666.03 0 D
ENTER PIPE >   20  3  600.90 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   10  8.7917
```

```
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   7  16.3274;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    17   1176.9     0   D        *     9    19   1830.2     0   D
    2     4   3916.2     0   D        *    10    20   1225.7     0   D
    3    19    996.4     0   D        *    11    17    745.6     0   D
    3    20    600.9     0   D        *    11    19   1226.9     0   D
    4    18   1368.0     0   D        *
                                      *
    5    20    781.0     0   D        *
    6    10    666.0     0   D        *
    7    18   5757.4     0   D        *
    8    17   1148.2     0   D        *
    8    18   2980.4     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN MST.J;
* WRITING NETWORK TO FILE MST.J
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
... DESIGN COMPLETED
```

```
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
 NODE  NODE    LENGTH  DIAM  TAG    FLOW      VEL.   P/DROP  P/GRAD
                                                              ------
                                                              MBAR
                   M                SCMH      MPS    MBAR      KM
    1    17   1176.9    63   D    -31.399    3.98   62.95   53.49
    2     4   3916.2    90   D    -28.887    1.52   22.78    5.82
    3    19    996.4    90   D    -75.357    3.83   29.86   29.97
    3    20    600.9    90   D     48.982    2.51    8.59   14.30
    4    18   1368.0    90   D    -52.750    2.72   22.29   16.30
    5    20    781.0    63   D    -21.351    2.70   21.65   27.73
    6    10    666.0    63   D    -18.839    2.38   14.90   22.37
    7    18   5757.4    90   D    -16.327    0.83   12.21    2.12
    8    17   1148.2   125   D    -82.893    2.13    8.33    7.26
    8    18   2980.4   125   D     69.077    1.80   15.87    5.33
    9    19   1830.2    63   D    -11.304    1.37   16.29    8.90
   10    20   1225.7    90   D    -27.631    1.42    6.51    5.31
   11    17    745.6   125   D    114.292    2.92    9.45   12.68
   11    19   1226.9   125   D     86.661    2.21    9.55    7.78
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
 -----  --------   --------  ------
          MBAR       SCMH
   11    150.00    200.952   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
 -----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR
                  *                   *
    1     77.60   *     6     80.59   *    11    150.00
    2     71.27   *     7    104.14   *    17    140.55
    3    110.59   *     8    132.22   *    18    116.35
    4     94.05   *     9    124.16   *    19    140.45
    5     80.34   *    10     95.49   *    20    102.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    4454.1    22671.47
   90   D       6.18   13864.6    85683.47
  125   D      11.72    6101.1    71504.54
                       --------  ----------
                       24419.8   179859.47
COMMAND >* Read back the undesigned network.
COMMAND >RN MST.J;
* READING NETWORK FROM FILE MST.J
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   -9.14 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   13.71 MBAR AT NODE     7
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   71.27 MBAR AT NODE     2
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    19 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
```

```
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
MINIMUM PRESSURE IS   40.74 MBAR AT NODE     5
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	17	1176.9	63	D	-31.399	3.98	62.95	53.49
2	4	3916.2	90	D	-28.887	1.52	22.78	5.82
3	19	996.4	90	D	-75.357	3.97	30.89	31.00
3	20	600.9	90	D	48.982	2.60	8.90	14.81
4	18	1368.0	90	D	-52.750	2.72	22.29	16.30
5	20	781.0	63	D	-21.351	2.80	22.45	28.75
6	10	666.0	63	D	-18.839	2.47	15.45	23.20
7	18	5757.4	90	D	-16.327	0.83	12.21	2.12
8	17	1148.2	125	D	-82.893	2.13	8.33	7.26
8	18	2980.4	125	D	69.077	1.80	15.87	5.33
9	19	1830.2	63	D	-11.304	1.42	16.84	9.20
10	20	1225.7	90	D	-27.631	1.48	6.74	5.50
11	17	745.6	125	D	114.292	2.92	9.45	12.68
11	19	1226.9	90	D	86.661	4.44	47.01	38.32

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR	*		MBAR
		*			*		
1	77.60	*	6	41.00	*	11	150.00
2	71.27	*	7	104.14	*	17	140.55
3	72.09	*	8	132.22	*	18	116.35
4	94.05	*	9	86.14	*	19	102.99
5	40.74	*	10	56.45	*	20	63.19

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	4454.1	22671.47
90	D	6.18	15091.6	93265.96
125	D	11.72	4874.1	57124.80
			24419.8	173062.25

```
COMMAND >* Terminate the SNAP run.
```

R.(A-J)

R.A

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  11  2615.62 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
```

```
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                   M
    8    11   2615.6     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.A;
* WRITING NETWORK TO FILE R.A
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  117.15 MBAR AT NODE     8
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS  117.15 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    8    11   2615.6    63   D    -13.816    1.69   32.85   12.56
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00     13.816   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    8    117.15
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
```

```
                /   M        M
   63   D       5.09    2615.6    13313.51
                       --------  ----------
                         2615.6    13313.51
COMMAND >* Read back the undesigned network.
COMMAND >RN R.A;
* READING NETWORK FROM FILE R.A
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  117.15 MBAR AT NODE     8
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS  117.15 MBAR AT NODE     8
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
MINIMUM PRESSURE IS  117.15 MBAR AT NODE     8
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
               M                   SCMH      MPS    MBAR     KM
    8    11   2615.6    63   D    -13.816    1.69   32.85   12.56
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
    8    117.15
   11    150.00
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
                /   M        M
   63   D       5.09    2615.6    13313.51
                       --------  ----------
                         2615.6    13313.51
COMMAND >* Terminate the SNAP run.
```

R.B

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  13  2251.99 0 D
ENTER PIPE >   3  13  2380.78 0 D
ENTER PIPE >   13  11  363.63 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
```

```
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                  M
    3    13   2380.8     0   D
    8    13   2252.0     0   D
   11    13    363.6     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                        MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.B;
* WRITING NETWORK TO FILE R.B
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   23.62 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   23.62 MBAR AT NODE     3
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP  ------
----- -----   ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR      KM
    3    13   2380.8    63   D    -26.375    3.52   97.07   40.77
    8    13   2252.0    63   D    -13.816    1.73   28.97   12.87
   11    13    363.6    63   D     40.190    4.90   29.31   80.60
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00     40.190   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE
-----  --------
          MBAR
```

```
    3     23.62
    8     91.72
   11    150.00
   13    120.69
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09    4996.4    25431.68
                       --------  ----------
                         4996.4    25431.68
COMMAND >* Read back the undesigned network.
COMMAND >RN R.B;
* READING NETWORK FROM FILE R.B
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   23.62 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   23.62 MBAR AT NODE     3
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
MINIMUM PRESSURE IS   23.62 MBAR AT NODE     3
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                  M                SCMH      MPS    MBAR      KM
    3    13   2380.8    63   D    -26.375    3.52   97.07   40.77
    8    13   2252.0    63   D    -13.816    1.73   28.97   12.87
   11    13    363.6    63   D     40.190    4.90   29.31   80.60
* PRESSURE RESULTS
  -----------------
 NODE  PRESSURE
-----  --------
          MBAR
    3     23.62
    8     91.72
   11    150.00
   13    120.69
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09    4996.4    25431.68
                       --------  ----------
                         4996.4    25431.68
COMMAND >* Terminate the SNAP run.
```

R.C

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  13  2251.99 0 D
```

```
ENTER PIPE >   3  15  1399.21 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   13  11  363.63 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---
                   M
    3    15   1399.2     0   D
    5    15   1912.7     0   D
    8    13   2252.0     0   D
   11    13    363.6     0   D
   13    15    981.4     0   D
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST   *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----   *  ----  ---  -----  --------   -----
                       MM     /   M   *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.C;
* WRITING NETWORK TO FILE R.C
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   73.91 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   73.91 MBAR AT NODE     3
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
```

```
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    3    15   1399.2    63   D    -26.375    3.36   55.54   39.69
    5    15   1912.7    63   D    -21.351    2.71   52.46   27.43
    8    13   2252.0    63   D    -13.816    1.70   28.41   12.62
   11    13    363.6    90   D     61.542    3.04    7.49   20.61
   13    15    981.4    90   D     47.726    2.39   13.06   13.31
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    61.542   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    3     73.91   *    15    129.45
    5     76.99   *
    8    114.09   *
   11    150.00   *
   13    142.51   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    5563.8    28320.00
   90   D       6.18    1345.0     8312.10
                       --------  ----------
                        6908.8    36632.09
COMMAND >* Read back the undesigned network.
COMMAND >RN R.C;
* READING NETWORK FROM FILE R.C
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   73.91 MBAR AT NODE     3
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   73.91 MBAR AT NODE     3
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
MINIMUM PRESSURE IS   73.91 MBAR AT NODE     3
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    3    15   1399.2    63   D    -26.375    3.36   55.54   39.69
    5    15   1912.7    63   D    -21.351    2.71   52.46   27.43
    8    13   2252.0    63   D    -13.816    1.70   28.41   12.62
   11    13    363.6    90   D     61.542    3.04    7.49   20.61
   13    15    981.4    90   D     47.726    2.39   13.06   13.31
```

```
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------
           MBAR     *            MBAR
                    *
    3      73.91    *    15     129.45
    5      76.99    *
    8     114.09    *
   11     150.00    *
   13     142.51    *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
               /   M         M
   63    D       5.09     5563.8     28320.00
   90    D       6.18     1345.0      8312.10
                        --------   ----------
                          6908.8     36632.09
COMMAND >* Terminate the SNAP run.
```

R.D

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >    8  13  2251.99 0 D
ENTER PIPE >    3  19  1145.99 0 D
ENTER PIPE >    15  13  981.37 0 D
ENTER PIPE >    5  15  1912.65 0 D
ENTER PIPE >    13  11  363.63 0 D
ENTER PIPE >    9  19  2639.94 0 D
ENTER PIPE >    19  15  253.42 0 D;
COMMAND >ES
ENTER SOURCE >    11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >    8  13.8155
ENTER DEMAND, DL OFF >    3  26.3750
ENTER DEMAND, DL OFF >    5  21.3512
ENTER DEMAND, DL OFF >    9  11.3036;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >    16 D 0.97 11.15 0.36
ENTER FACTOR >    20 D 0.97 15.15 0.40
ENTER FACTOR >    25 D 0.97 20.15 0.56
ENTER FACTOR >    32 D 0.97 25.75 1.35
ENTER FACTOR >    63 D 0.97 50.9 5.09
ENTER FACTOR >    90 D 0.97 79.2 6.18
ENTER FACTOR >    125 D 0.97 110.3 11.72
ENTER FACTOR >    180 D 0.97 158.75 24.23
ENTER FACTOR >    250 D 0.97 220.75 46.62
ENTER FACTOR >    315 D 0.97 278.25 73.92
ENTER FACTOR >    355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE   NODE    LENGTH   DIAM   TAG        *  NODE   NODE    LENGTH   DIAM   TAG
-----  -----   -------   ----   ---        * -----  -----   -------   ----   ---
                  M                        *                   M
                                           *
    3     19    1146.0      0    D         *    13     15     981.4      0    D
    5     15    1912.7      0    D         *    15     19     253.4      0    D
    8     13    2252.0      0    D         *
    9     19    2639.9      0    D         *
   11     13     363.6      0    D         *
* FACTOR DATA
  -----------
 DIAM   TAG   EFFIC   INT.DIAM     COST    *  DIAM   TAG   EFFIC   INT.DIAM     COST
 ----   ---   -----   --------    -----    *  ----   ---   -----   --------    -----
```

```
                        MM      /   M   *                          MM      /   M
                                        *
   16   D   0.970      11.15     0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970      15.15     0.40   *
   25   D   0.970      20.15     0.56   *
   32   D   0.970      25.75     1.35   *
   63   D   0.970      50.90     5.09   *
                                        *
   90   D   0.970      79.20     6.18   *
  125   D   0.970     110.30    11.72   *
  180   D   0.970     158.75    24.23   *
  250   D   0.970     220.75    46.62   *
  315   D   0.970     278.25    73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.D;
* WRITING NETWORK TO FILE R.D
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   67.98 MBAR AT NODE     5
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   55.80 MBAR AT NODE     3
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   55.80 MBAR AT NODE     3
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
 NODE  NODE    LENGTH  DIAM  TAG    FLOW      VEL.    P/DROP   P/GRAD
                                                                ------
                                                                MBAR
                   M                SCMH       MPS     MBAR      KM
    3    19   1146.0    63   D    -26.375     3.41    46.43   40.52
    5    15   1912.7    63   D    -21.351     2.73    52.87   27.64
    8    13   2252.0    63   D    -13.816     1.70    28.48   12.65
    9    19   2639.9    63   D    -11.304     1.43    24.40    9.24
   11    13    363.6    90   D     72.845     3.61    10.09   27.76
   13    15    981.4    90   D     59.030     2.97    19.05   19.42
   15    19    253.4    63   D     37.679     4.67    18.62   73.48
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
       MBAR         SCMH
   11    150.00     72.845   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
       MBAR        *        MBAR
                   *
    3     55.80    *    13    139.91
    5     67.98    *    15    120.85
    8    111.43    *    19    102.23
    9     77.83    *
   11    150.00    *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
              /   M         M
   63   D       5.09    8204.0     41758.31
   90   D       6.18    1345.0      8312.10
                       --------   ----------
                         9549.0     50070.41
COMMAND >* Read back the undesigned network.
COMMAND >RN R.D;
* READING NETWORK FROM FILE R.D
```

```
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   67.98 MBAR AT NODE     5
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   55.80 MBAR AT NODE     3
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS ******* MBAR AT NODE     8
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   55.80 MBAR AT NODE     3
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
MINIMUM PRESSURE IS   55.80 MBAR AT NODE     3
...   0 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
3	19	1146.0	63	D	-26.375	3.41	46.43	40.52
5	15	1912.7	63	D	-21.351	2.73	52.87	27.64
8	13	2252.0	63	D	-13.816	1.70	28.48	12.65
9	19	2639.9	63	D	-11.304	1.43	24.40	9.24
11	13	363.6	90	D	72.845	3.61	10.09	27.76
13	15	981.4	90	D	59.030	2.97	19.05	19.42
15	19	253.4	63	D	37.679	4.67	18.62	73.48

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	*	NODE	PRESSURE
	MBAR	*		MBAR
		*		
3	55.80	*	13	139.91
5	67.98	*	15	120.85
8	111.43	*	19	102.23
9	77.83	*		
11	150.00	*		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
63	D	5.09	8204.0	41758.31
90	D	6.18	1345.0	8312.10
			9549.0	50070.41

```
COMMAND >* Terminate the SNAP run.
```

R.E

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  13  2251.99 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   15  13  981.37 0 D
```

```
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  16  2882.48 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    3    16    290.2     0   D        *    11    13    363.6     0   D
    5    15   1912.7     0   D        *    13    15    981.4     0   D
    8    13   2252.0     0   D        *    15    19    253.4     0   D
    9    19   2639.9     0   D        *    16    19    855.8     0   D
   10    16   2882.5     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                       *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                       *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.E;
* WRITING NETWORK TO FILE R.E
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   59.97 MBAR AT NODE     5
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -320.54 MBAR AT NODE     3
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   59.97 MBAR AT NODE     5
```

```
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP    ------
----- -----   ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    3    16    290.2    63   D    -26.375    3.30   11.56   39.85
    5    15   1912.7    63   D    -21.351    2.75   53.25   27.84
    8    13   2252.0    63   D    -13.816    1.70   28.54   12.67
    9    19   2639.9    63   D    -11.304    1.42   24.23    9.18
   10    16   2882.5    63   D     -8.792    1.11   17.25    5.98
   11    13    363.6    90   D     81.637    4.05   12.35   33.97
   13    15    981.4    90   D     67.821    3.44   24.43   24.89
   15    19    253.4    90   D     46.470    2.36    3.29   12.98
   16    19    855.8    90   D    -35.167    1.80    6.86    8.01
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR      SCMH
   11    150.00    81.637   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------
          MBAR    *           MBAR
                  *
    3     91.51   *    11    150.00
    5     59.97   *    13    137.65
    8    109.11   *    15    113.22
    9     85.71   *    16    103.07
   10     85.82   *    19    109.93
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    9977.3    50784.25
   90   D       6.18    2454.2    15167.02
                       --------  ----------
                       12431.5    65951.27
COMMAND >* Read back the undesigned network.
COMMAND >RN R.E;
* READING NETWORK FROM FILE R.E
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS   59.97 MBAR AT NODE     5
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS -320.54 MBAR AT NODE     3
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   59.97 MBAR AT NODE     5
         REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    16    19 CHANGED FROM  90 TO  63
MINIMUM PRESSURE IS   34.60 MBAR AT NODE    10
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
MINIMUM PRESSURE IS   34.60 MBAR AT NODE    10
...   1 PIPES DOWNSIZED DURING REFINEMENT
```

```
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP     ------
----- -----   ------  ----  ---  --------  ------  ------     MBAR
                   M                SCMH      MPS    MBAR       KM
    3    16    290.2    63   D    -26.375    3.46   12.12    41.75
    5    15   1912.7    63   D    -21.351    2.75   53.25    27.84
    8    13   2252.0    63   D    -13.816    1.70   28.54    12.67
    9    19   2639.9    63   D    -11.304    1.42   24.23     9.18
   10    16   2882.5    63   D     -8.792    1.16   18.08     6.27
   11    13    363.6    90   D     81.637    4.05   12.35    33.97
   13    15    981.4    90   D     67.821    3.44   24.43    24.89
   15    19    253.4    90   D     46.470    2.36    3.29    12.98
   16    19    855.8    63   D    -35.167    4.56   57.25    66.90
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE    *  NODE  PRESSURE
-----  --------    * -----  --------
          MBAR     *           MBAR
                   *
    3     40.56    *    11    150.00
    5     59.97    *    13    137.65
    8    109.11    *    15    113.22
    9     85.71    *    16     52.68
   10     34.60    *    19    109.93
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M        M
   63   D       5.09   10833.0    55140.23
   90   D       6.18    1598.4     9878.24
                       --------  ----------
                       12431.5    65018.46
COMMAND >* Terminate the SNAP run.
```

R.F

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  13  2251.99 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  20  426.49 0 D
ENTER PIPE >   6  20  600.48 0 D
ENTER PIPE >   20  16  2455.99 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
```

```
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
```

NODE	NODE	LENGTH	DIAM	TAG	NODE	NODE	LENGTH	DIAM	TAG
		M					M		
3	16	290.2	0	D	16	20	2456.0	0	D
5	15	1912.7	0	D					
6	20	600.5	0	D					
8	13	2252.0	0	D					
9	19	2639.9	0	D					
10	20	426.5	0	D					
11	13	363.6	0	D					
13	15	981.4	0	D					
15	19	253.4	0	D					
16	19	855.8	0	D					

```
* FACTOR DATA
  -----------
```

DIAM	TAG	EFFIC	INT.DIAM	COST	DIAM	TAG	EFFIC	INT.DIAM	COST
			MM	/ M				MM	/ M
16	D	0.970	11.15	0.36	355	D	0.970	313.50	94.08
20	D	0.970	15.15	0.40					
25	D	0.970	20.15	0.56					
32	D	0.970	25.75	1.35					
63	D	0.970	50.90	5.09					
90	D	0.970	79.20	6.18					
125	D	0.970	110.30	11.72					
180	D	0.970	158.75	24.23					
250	D	0.970	220.75	46.62					
315	D	0.970	278.25	73.92					

```
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.F;
* WRITING NETWORK TO FILE R.F
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -39.80 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   86.66 MBAR AT NODE     5
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   86.66 MBAR AT NODE     5
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
3	16	290.2	63	D	-26.375	3.26	11.40	39.30
5	15	1912.7	63	D	-21.351	2.69	52.02	27.20
6	20	600.5	63	D	-18.839	2.36	13.30	22.15
8	13	2252.0	63	D	-13.816	1.69	28.32	12.57
9	19	2639.9	63	D	-11.304	1.39	23.73	8.99
10	20	426.5	63	D	-8.792	1.09	2.53	5.93
11	13	363.6	125	D	100.476	2.55	3.66	10.07
13	15	981.4	125	D	86.661	2.22	7.66	7.80
15	19	253.4	90	D	65.310	3.26	5.85	23.08
16	19	855.8	90	D	-54.006	2.73	14.27	16.68

```
   16    20   2456.0    90   D     27.631    1.41   12.88    5.24
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
         MBAR       SCMH
   11    150.00    100.476   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------
         MBAR     *           MBAR    *           MBAR
                  *                   *
    3    107.15   *    10    103.15   *    19    132.83
    5     86.66   *    11    150.00   *    20    105.68
    6     92.38   *    13    146.34   *
    8    118.02   *    15    138.68   *
    9    109.10   *    16    118.56   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
             /   M        M
   63   D       5.09    8121.8    41339.71
   90   D       6.18    3565.2    22032.94
  125   D      11.72    1345.0    15763.40
                       --------  ----------
                       13032.0    79136.05
COMMAND >* Read back the undesigned network.
COMMAND >RN R.F;
* READING NETWORK FROM FILE R.F
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -39.80 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   86.66 MBAR AT NODE     5
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   86.66 MBAR AT NODE     5
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    13    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   55.30 MBAR AT NODE     5
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
PIPE    11    13 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   39.86 MBAR AT NODE     5
...   2 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
-----  -----  ------  ----  ---  --------  ------  ------    MBAR
                 M                SCMH      MPS    MBAR       KM
    3    16    290.2    63   D    -26.375    3.40   11.89    40.96
    5    15   1912.7    63   D    -21.351    2.80   54.22    28.35
    6    20    600.5    63   D    -18.839    2.46   13.88    23.11
    8    13   2252.0    63   D    -13.816    1.71   28.68    12.73
    9    19   2639.9    63   D    -11.304    1.45   24.72     9.36
```

```
   10    20    426.5    63   D     -8.792    1.14    2.64    6.19
   11    13    363.6    90   D    100.476    5.01   17.87   49.15
   13    15    981.4    90   D     86.661    4.47   38.05   38.77
   15    19    253.4    90   D     65.310    3.39    6.09   24.02
   16    19    855.8    90   D    -54.006    2.84   14.86   17.37
   16    20   2456.0    90   D     27.631    1.47   13.43    5.47
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------    * -----   --------
           MBAR     *            MBAR     *            MBAR
                    *                     *
    3      61.24    *    10      57.06    *    19      87.99
    5      39.86    *    11     150.00    *    20      59.70
    6      45.83    *    13     132.13    *
    8     103.45    *    15      94.08    *
    9      63.27    *    16      73.13    *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
               /   M         M
   63    D        5.09     8121.8     41339.71
   90    D        6.18     4910.2     30345.04
                         --------   ----------
                         13032.0     71684.74
COMMAND >* Terminate the SNAP run.
```

R.G

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   5  15  1912.65  0 D
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  20  426.49 0 D
ENTER PIPE >   6  20  600.48 0 D
ENTER PIPE >   20  16  2455.99 0 D
ENTER PIPE >   1  18  3286.90 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   1  31.3988;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
```

```
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                   M                  *                   M
                                      *
    1    18   3286.9     0   D       *    15    19    253.4     0   D
    3    16    290.2     0   D       *    16    19    855.8     0   D
    5    15   1912.7     0   D       *    16    20   2456.0     0   D
    6    20    600.5     0   D       *
    8    18    273.1     0   D       *
                                      *
    9    19   2639.9     0   D       *
   10    20    426.5     0   D       *
   11    13    363.6     0   D       *
   13    15    981.4     0   D       *
   13    18   1978.9     0   D       *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST   *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----   *  ----  ---  -----  --------   -----
                       MM     /   M   *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36   *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40   *
   25   D   0.970     20.15    0.56   *
   32   D   0.970     25.75    1.35   *
   63   D   0.970     50.90    5.09   *
                                      *
   90   D   0.970     79.20    6.18   *
  125   D   0.970    110.30   11.72   *
  180   D   0.970    158.75   24.23   *
  250   D   0.970    220.75   46.62   *
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.G;
* WRITING NETWORK TO FILE R.G
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -42.50 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   28.83 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   28.83 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                 P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP   ------
----- -----  ------  ----  ---  --------  ------  ------   MBAR
                  M                SCMH      MPS    MBAR     KM
    1    18   3286.9    90   D   -31.399    1.61   21.58    6.56
    3    16    290.2    63   D   -26.375    3.26   11.43   39.38
    5    15   1912.7    63   D   -21.351    2.69   52.12   27.25
    6    20    600.5    63   D   -18.839    2.36   13.33   22.20
    8    18    273.1    32   D   -13.816    7.17   91.20  333.95
    9    19   2639.9    63   D   -11.304    1.40   23.78    9.01
   10    20    426.5    63   D    -8.792    1.09    2.53    5.94
   11    13    363.6   125   D   131.875    3.36    5.93   16.30
   13    15    981.4   125   D    86.661    2.22    7.67    7.82
   13    18   1978.9    90   D    45.214    2.28   24.04   12.15
   15    19    253.4    90   D    65.310    3.26    5.86   23.13
   16    19    855.8    90   D   -54.006    2.73   14.30   16.71
   16    20   2456.0    90   D    27.631    1.41   12.91    5.26
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
```

```
   11    150.00    131.875   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----  ---------    * -----  ---------    * -----  ---------
           MBAR     *            MBAR     *            MBAR
                    *                     *
    1     98.46     *     9    106.76     *    16    116.24
    3    104.81     *    10    100.80     *    18    120.03
    5     84.28     *    11    150.00     *    19    130.54
    6     90.00     *    13    144.07     *    20    103.33
    8     28.83     *    15    136.40     *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
               /   M         M
   32    D       1.35      273.1       368.67
   63    D       5.09     5869.8     29877.08
   90    D       6.18     8831.0     54575.58
  125    D      11.72     1345.0     15763.40
                        --------   ----------
                        16318.8    100584.73
COMMAND >* Read back the undesigned network.
COMMAND >RN R.G;
* READING NETWORK FROM FILE R.G
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -42.50 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   28.83 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   28.83 MBAR AT NODE     8
         REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    13    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   28.83 MBAR AT NODE     8
REFINEMENT CYCLE   2 :
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
MINIMUM PRESSURE IS   28.83 MBAR AT NODE     8
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE   NODE    LENGTH   DIAM   TAG     FLOW      VEL.    P/DROP  ------
-----  -----    ------   ----   ---   --------   ------   ------   MBAR
                   M                    SCMH       MPS     MBAR     KM
    1     18   3286.9     90    D     -31.399     1.61    21.58    6.56
    3     16    290.2     63    D     -26.375     3.36    11.75   40.49
    5     15   1912.7     63    D     -21.351     2.77    53.59   28.02
    6     20    600.5     63    D     -18.839     2.43    13.71   22.83
    8     18    273.1     32    D     -13.816     7.17    91.20  333.95
    9     19   2639.9     63    D     -11.304     1.44    24.44    9.26
   10     20    426.5     63    D      -8.792     1.12     2.61    6.11
   11     13    363.6    125    D     131.875     3.36     5.93   16.30
   13     15    981.4     90    D      86.661     4.42    37.65   38.36
```

```
   13    18   1978.9    90   D     45.214    2.28   24.04   12.15
   15    19    253.4    90   D     65.310    3.35    6.02   23.75
   16    19    855.8    90   D    -54.006    2.81   14.69   17.17
   16    20   2456.0    90   D     27.631    1.45   13.27    5.40
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------    * -----   --------
           MBAR     *            MBAR     *            MBAR
                    *                     *
    1      98.46    *     9      75.97    *    16      85.71
    3      73.97    *    10      69.84    *    18     120.03
    5      52.84    *    11     150.00    *    19     100.41
    6      58.73    *    13     144.07    *    20      72.44
    8      28.83    *    15     106.43    *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
              /   M         M
   32    D        1.35      273.1       368.67
   63    D        5.09     5869.8     29877.08
   90    D        6.18     9812.4     60640.45
  125    D       11.72      363.6      4261.74
                         --------   ----------
                         16318.8     95147.94
COMMAND >* Terminate the SNAP run.
```

R.H

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  20  426.49 0 D
ENTER PIPE >   6  20  600.48 0 D
ENTER PIPE >   20  16  2455.99 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   12  18  459.96 0 D
ENTER PIPE >   4  12  3828.71 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   4  23.8631;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
```

```
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                  M
                                      *
    1    12   2826.9     0   D        *    13    15    981.4     0   D
    3    16    290.2     0   D        *    13    18   1978.9     0   D
    4    12   3828.7     0   D        *    15    19    253.4     0   D
    5    15   1912.7     0   D        *    16    19    855.8     0   D
    6    20    600.5     0   D        *    16    20   2456.0     0   D
                                      *
    8    18    273.1     0   D        *
    9    19   2639.9     0   D        *
   10    20    426.5     0   D        *
   11    13    363.6     0   D        *
   12    18    460.0     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.H;
* WRITING NETWORK TO FILE R.H
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -85.23 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   -1.74 MBAR AT NODE     4
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   48.60 MBAR AT NODE     8
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   48.60 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE   LENGTH  DIAM  TAG    FLOW     VEL.   P/DROP    ------
----- -----   ------  ----  ---  --------  ------  ------     MBAR
                  M                SCMH      MPS    MBAR       KM
    1    12   2826.9    90   D    -31.399    1.59   18.36     6.50
    3    16    290.2    63   D    -26.375    3.25   11.38    39.22
    4    12   3828.7    90   D    -23.863    1.21   15.43     4.03
    5    15   1912.7    63   D    -21.351    2.68   51.91    27.14
    6    20    600.5    63   D    -18.839    2.35   13.27    22.10
    8    18    273.1    32   D    -13.816    7.03   89.63   328.22
    9    19   2639.9    63   D    -11.304    1.39   23.68     8.97
   10    20    426.5    63   D     -8.792    1.09    2.52     5.92
   11    13    363.6   180   D    155.738    1.91    1.40     3.85
   12    18    460.0    90   D    -55.262    2.76    7.93    17.23
   13    15    981.4   125   D     86.661    2.21    7.64     7.79
   13    18   1978.9   125   D     69.077    1.77   10.36     5.24
   15    19    253.4    90   D     65.310    3.25    5.84    23.04
```

```
   16    19    855.8    90   D    -54.006    2.72   14.24   16.64
   16    20   2456.0    90   D     27.631    1.41   12.85    5.23
* SOURCE RESULTS
  --------------
 NODE  PRESSURE      FLOW    % FLOW
-----  --------   --------  ------
          MBAR       SCMH
   11    150.00    155.738   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------   * -----  --------
          MBAR    *           MBAR    *           MBAR    *           MBAR
                  *                   *                   *
    1    111.95   *     8     48.60   *    13    148.60   *    20    108.02
    3    109.49   *     9    111.44   *    15    140.96   *
    4    114.88   *    10    105.50   *    16    120.88   *
    5     89.05   *    11    150.00   *    18    138.24   *
    6     94.75   *    12    130.31   *    19    135.12   *
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------   --------  ----------
             /   M         M
   32   D       1.35     273.1      368.67
   63   D       5.09    5869.8    29877.08
   90   D       6.18   10680.8    66007.41
  125   D      11.72    2960.3    34694.37
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       20147.6   139758.28
COMMAND >* Read back the undesigned network.
COMMAND >RN R.H;
* READING NETWORK FROM FILE R.H
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -85.23 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   -1.74 MBAR AT NODE     4
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   48.60 MBAR AT NODE     8
DESIGN CYCLE   4 :
MINIMUM PRESSURE IS   48.60 MBAR AT NODE     8
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    13 CHANGED FROM 180 TO 125
MINIMUM PRESSURE IS   41.42 MBAR AT NODE     8
REFINEMENT CYCLE   2 :
PIPE    13    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   41.42 MBAR AT NODE     8
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
REFINEMENT CYCLE  12 :
REFINEMENT CYCLE  13 :
MINIMUM PRESSURE IS   41.42 MBAR AT NODE     8
...   2 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
```

```
* FLOW RESULTS
  ------------                                                    P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG     FLOW      VEL.    P/DROP   ------
----- -----   ------  ----  ---  ---------  ------  ------   MBAR
                   M                SCMH       MPS    MBAR      KM
    1    12   2826.9    90   D    -31.399    1.60   18.47    6.53
    3    16    290.2    63   D    -26.375    3.36   11.77   40.57
    4    12   3828.7    90   D    -23.863    1.22   15.53    4.06
    5    15   1912.7    63   D    -21.351    2.78   53.69   28.07
    6    20    600.5    63   D    -18.839    2.44   13.74   22.88
    8    18    273.1    32   D    -13.816    7.08   90.20  330.28
    9    19   2639.9    63   D    -11.304    1.44   24.48    9.27
   10    20    426.5    63   D     -8.792    1.13    2.61    6.13
   11    13    363.6   125   D    155.738    3.97    7.96   21.90
   12    18    460.0    90   D    -55.262    2.78    7.97   17.33
   13    15    981.4    90   D     86.661    4.43   37.71   38.43
   13    18   1978.9   125   D     69.077    1.78   10.42    5.27
   15    19    253.4    90   D     65.310    3.36    6.03   23.80
   16    19    855.8    90   D    -54.006    2.81   14.72   17.20
   16    20   2456.0    90   D     27.631    1.46   13.30    5.41
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------    * -----   --------    * -----   --------
           MBAR     *            MBAR     *            MBAR     *            MBAR
                    *                     *                     *
    1    105.17     *     8      41.42     *    13    142.04     *    20      70.27
    3     71.80     *     9      73.81     *    15    104.32     *
    4    108.11     *    10      67.66     *    16     83.57     *
    5     50.63     *    11     150.00     *    18    131.61     *
    6     56.53     *    12     123.64     *    19     98.29     *
* COST OF NETWORK
  ---------------
 DIAM  TAG     COST      LENGTH   TOTAL COST
 ----  ---  --------   --------  ----------
               /   M         M
   32   D       1.35      273.1      368.67
   63   D       5.09     5869.8    29877.08
   90   D       6.18    11662.2    72072.27
  125   D      11.72     2342.5    27454.45
                       --------  ----------
                        20147.6   129772.48
COMMAND >* Terminate the SNAP run.
```

R.I

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  20  426.49 0 D
ENTER PIPE >   6  20  600.48 0 D
ENTER PIPE >   20  16  2455.99 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   12  18  459.96 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   14  12  3535.91 0 D
ENTER PIPE >   2  14  4184.61 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917
```

```
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   2  28.8869;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
 NODE  NODE   LENGTH  DIAM  TAG       *  NODE  NODE   LENGTH  DIAM  TAG
----- -----  -------  ----  ---       * ----- -----  -------  ----  ---
                  M                   *                   M
                                      *
    1    12   2826.9     0   D        *    12    14   3535.9     0   D
    2    14   4184.6     0   D        *    12    18    460.0     0   D
    3    16    290.2     0   D        *    13    15    981.4     0   D
    4    14    292.8     0   D        *    13    18   1978.9     0   D
    5    15   1912.7     0   D        *    15    19    253.4     0   D
                                      *
    6    20    600.5     0   D        *    16    19    855.8     0   D
    8    18    273.1     0   D        *    16    20   2456.0     0   D
    9    19   2639.9     0   D        *
   10    20    426.5     0   D        *
   11    13    363.6     0   D        *
* FACTOR DATA
  -----------
 DIAM  TAG  EFFIC  INT.DIAM    COST    *  DIAM  TAG  EFFIC  INT.DIAM    COST
 ----  ---  -----  --------   -----    *  ----  ---  -----  --------   -----
                       MM     /   M    *                       MM     /   M
                                      *
   16   D   0.970     11.15    0.36    *   355   D   0.970    313.50   94.08
   20   D   0.970     15.15    0.40    *
   25   D   0.970     20.15    0.56    *
   32   D   0.970     25.75    1.35    *
   63   D   0.970     50.90    5.09    *
                                      *
   90   D   0.970     79.20    6.18    *
  125   D   0.970    110.30   11.72    *
  180   D   0.970    158.75   24.23    *
  250   D   0.970    220.75   46.62    *
  315   D   0.970    278.25   73.92    *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.I;
* WRITING NETWORK TO FILE R.I
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
           SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -37.69 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   38.45 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   38.45 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
```

```
  ------------                                                    P/GRAD
 NODE   NODE    LENGTH   DIAM   TAG     FLOW      VEL.    P/DROP  ------
----- -----    ------   ----   ---   --------   ------   ------   MBAR
                    M                   SCMH      MPS     MBAR     KM
    1     12   2826.9     90    D     -31.399    1.60    18.44    6.52
    2     14   4184.6     90    D     -28.887    1.56    24.98    5.97
    3     16    290.2     63    D     -26.375    3.25    11.39   39.24
    4     14    292.8     63    D     -23.863    3.08    10.12   34.55
    5     15   1912.7     63    D     -21.351    2.68    51.93   27.15
    6     20    600.5     63    D     -18.839    2.35    13.28   22.11
    8     18    273.1     32    D     -13.816    7.10    90.43  331.14
    9     19   2639.9     63    D     -11.304    1.39    23.69    8.97
   10     20    426.5     63    D      -8.792    1.09     2.53    5.92
   11     13    363.6    180    D     184.625    2.26     1.89    5.20
   12     14   3535.9     90    D      52.750    2.79    58.08   16.43
   12     18    460.0    125    D     -84.149    2.18     3.45    7.51
   13     15    981.4    125    D      86.661    2.21     7.65    7.79
   13     18   1978.9    125    D      97.964    2.53    19.23    9.72
   15     19    253.4     90    D      65.310    3.25     5.84   23.05
   16     19    855.8     90    D     -54.006    2.72    14.25   16.65
   16     20   2456.0     90    D      27.631    1.41    12.86    5.24
* SOURCE RESULTS
  --------------
 NODE   PRESSURE      FLOW    % FLOW
-----   --------    --------  ------
          MBAR        SCMH
   11     150.00     184.625   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE    *  NODE   PRESSURE
-----   --------    * -----   --------    * -----   --------    * -----   --------
          MBAR      *            MBAR     *            MBAR     *            MBAR
                    *                     *                     *
    1     106.99    *     6      94.24    *    12     125.43    *    18     128.88
    2      42.37    *     8      38.45    *    13     148.11    *    19     134.62
    3     108.99    *     9     110.93    *    14      67.35    *    20     107.51
    4      57.23    *    10     104.99    *    15     140.46    *
    5      88.53    *    11     150.00    *    16     120.37    *
* COST OF NETWORK
  ---------------
 DIAM   TAG     COST      LENGTH    TOTAL COST
 ----   ---   --------   --------   ----------
               /   M         M
   32    D        1.35      273.1       368.67
   63    D        5.09     6162.6     31367.43
   90    D        6.18    14112.7     87216.23
  125    D       11.72     3420.2     40085.10
  180    D       24.23      363.6      8810.76
                         --------   ----------
                         24332.2    167848.19
COMMAND >* Read back the undesigned network.
COMMAND >RN R.I;
* READING NETWORK FROM FILE R.I
*
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
       DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -37.69 MBAR AT NODE     6
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   38.45 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   38.45 MBAR AT NODE     8
         REFINING DESIGN ...
REFINEMENT CYCLE   1 :
PIPE    11    13 CHANGED FROM 180 TO 125
MINIMUM PRESSURE IS   28.62 MBAR AT NODE     8
REFINEMENT CYCLE   2 :
PIPE    13    15 CHANGED FROM 125 TO  90
```

```
MINIMUM PRESSURE IS   28.62 MBAR AT NODE     8
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
REFINEMENT CYCLE  12 :
REFINEMENT CYCLE  13 :
REFINEMENT CYCLE  14 :
MINIMUM PRESSURE IS   28.62 MBAR AT NODE     8
...   2 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR KM
1	12	2826.9	90	D	-31.399	1.61	18.59	6.58
2	14	4184.6	90	D	-28.887	1.58	25.20	6.02
3	16	290.2	63	D	-26.375	3.37	11.80	40.68
4	14	292.8	63	D	-23.863	3.11	10.21	34.87
5	15	1912.7	63	D	-21.351	2.78	53.84	28.15
6	20	600.5	63	D	-18.839	2.44	13.78	22.95
8	18	273.1	32	D	-13.816	7.17	91.22	334.01
9	19	2639.9	63	D	-11.304	1.44	24.55	9.30
10	20	426.5	63	D	-8.792	1.13	2.62	6.14
11	13	363.6	125	D	184.625	4.72	10.78	29.66
12	14	3535.9	90	D	52.750	2.81	58.57	16.57
12	18	460.0	125	D	-84.149	2.19	3.48	7.57
13	15	981.4	90	D	86.661	4.44	37.81	38.53
13	18	1978.9	125	D	97.964	2.55	19.38	9.79
15	19	253.4	90	D	65.310	3.37	6.05	23.86
16	19	855.8	90	D	-54.006	2.82	14.76	17.25
16	20	2456.0	90	D	27.631	1.46	13.33	5.43

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR		MBAR
1	97.76	6	53.49	12	116.36	18	119.84
2	32.58	8	28.62	13	139.22	19	95.36
3	68.79	9	70.81	14	57.78	20	67.27
4	47.57	10	64.65	15	101.41		
5	47.56	11	150.00	16	80.60		

```
* COST OF NETWORK
  ---------------
```

DIAM	TAG	COST	LENGTH	TOTAL COST
		/ M	M	
32	D	1.35	273.1	368.67
63	D	5.09	6162.6	31367.43
90	D	6.18	15094.0	93281.10
125	D	11.72	2802.5	32845.18
			24332.2	157862.39

```
COMMAND >* Terminate the SNAP run.
```

R.J

```
COMMAND >* Set units to low pressure, metric.
COMMAND >EU LM
COMMAND >EO SG 0.949
COMMAND >EO GT 15
COMMAND >EO DV 0.000012687
COMMAND >EP
ENTER PIPE >   13  11  363.63 0 D
ENTER PIPE >   8  18  273.09 0 D
ENTER PIPE >   12  18  459.96 0 D
ENTER PIPE >   18  13  1978.90 0 D
ENTER PIPE >   1  12  2826.94 0 D
ENTER PIPE >   14  17 1947.73 0 D
```

```
ENTER PIPE >   17  12  1588.18 0 D
ENTER PIPE >   4  14  292.80 0 D
ENTER PIPE >   2  14  4184.61 0 D
ENTER PIPE >   5  15  1912.65 0 D
ENTER PIPE >   3  16  290.20 0 D
ENTER PIPE >   15  13  981.37 0 D
ENTER PIPE >   6  20  600.48 0 D
ENTER PIPE >   16  19  855.79 0 D
ENTER PIPE >   7  17  7557.49 0 D
ENTER PIPE >   9  19  2639.94 0 D
ENTER PIPE >   19  15  253.42 0 D
ENTER PIPE >   10  20  426.49 0 D
ENTER PIPE >   20  16 2455.99 0 D;
COMMAND >ES
ENTER SOURCE >   11  150;
COMMAND >* demand entered here in scmh, not Nm3
COMMAND >ED
ENTER DEMAND, DL OFF >   8  13.8155
ENTER DEMAND, DL OFF >   3  26.3750
ENTER DEMAND, DL OFF >   5  21.3512
ENTER DEMAND, DL OFF >   9  11.3036
ENTER DEMAND, DL OFF >   10  8.7917
ENTER DEMAND, DL OFF >   6  18.8393
ENTER DEMAND, DL OFF >   1  31.3988
ENTER DEMAND, DL OFF >   4  23.8631
ENTER DEMAND, DL OFF >   2  28.8869
ENTER DEMAND, DL OFF >   7  16.3274;
COMMAND >* Enter factor data for design.
COMMAND >EF
ENTER FACTOR >   16 D 0.97 11.15 0.36
ENTER FACTOR >   20 D 0.97 15.15 0.40
ENTER FACTOR >   25 D 0.97 20.15 0.56
ENTER FACTOR >   32 D 0.97 25.75 1.35
ENTER FACTOR >   63 D 0.97 50.9 5.09
ENTER FACTOR >   90 D 0.97 79.2 6.18
ENTER FACTOR >   125 D 0.97 110.3 11.72
ENTER FACTOR >   180 D 0.97 158.75 24.23
ENTER FACTOR >   250 D 0.97 220.75 46.62
ENTER FACTOR >   315 D 0.97 278.25 73.92
ENTER FACTOR >   355 D 0.97 313.5 94.08;
COMMAND >* Set the minimum design pressure to 22 mbar.
COMMAND >EO DP 22;
COMMAND >* List the pipes and factor data.
COMMAND >LP; LF;
* PIPE DATA
  ---------
```

NODE	NODE	LENGTH	DIAM	TAG	*	NODE	NODE	LENGTH	DIAM	TAG
		M			*			M		
					*					
1	12	2826.9	0	D	*	11	13	363.6	0	D
2	14	4184.6	0	D	*	12	17	1588.2	0	D
3	16	290.2	0	D	*	12	18	460.0	0	D
4	14	292.8	0	D	*	13	15	981.4	0	D
5	15	1912.7	0	D	*	13	18	1978.9	0	D
					*					
6	20	600.5	0	D	*	14	17	1947.7	0	D
7	17	7557.5	0	D	*	15	19	253.4	0	D
8	18	273.1	0	D	*	16	19	855.8	0	D
9	19	2639.9	0	D	*	16	20	2456.0	0	D
10	20	426.5	0	D	*					

```
* FACTOR DATA
  -----------
```

DIAM	TAG	EFFIC	INT.DIAM	COST	*	DIAM	TAG	EFFIC	INT.DIAM	COST
			MM	/ M	*				MM	/ M
					*					
16	D	0.970	11.15	0.36	*	355	D	0.970	313.50	94.08
20	D	0.970	15.15	0.40	*					
25	D	0.970	20.15	0.56	*					
32	D	0.970	25.75	1.35	*					
63	D	0.970	50.90	5.09	*					
					*					
90	D	0.970	79.20	6.18	*					
125	D	0.970	110.30	11.72	*					
180	D	0.970	158.75	24.23	*					
250	D	0.970	220.75	46.62	*					

```
  315   D   0.970    278.25   73.92   *
COMMAND >* Write the network to a disk file (for redesign).
COMMAND >WN R.J;
* WRITING NETWORK TO FILE R.J
COMMAND >* Design the network
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.84 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   54.17 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PR; PC;
* FLOW RESULTS
  ------------                                                  P/GRAD
 NODE  NODE    LENGTH  DIAM  TAG    FLOW      VEL.   P/DROP   ------
----- -----    ------  ----  ---  --------  ------  ------    MBAR
                   M                SCMH      MPS    MBAR      KM
    1    12   2826.9    90   D    -31.399    1.61   18.57    6.57
    2    14   4184.6    90   D    -28.887    1.55   24.75    5.91
    3    16    290.2    63   D    -26.375    3.25   11.39   39.25
    4    14    292.8    63   D    -23.863    3.06   10.03   34.24
    5    15   1912.7    63   D    -21.351    2.68   51.95   27.16
    6    20    600.5    63   D    -18.839    2.35   13.28   22.12
    7    17   7557.5    90   D    -16.327    0.84   16.15    2.14
    8    18    273.1    32   D    -13.816    7.15   90.98  333.16
    9    19   2639.9    63   D    -11.304    1.39   23.70    8.98
   10    20    426.5    63   D     -8.792    1.09    2.53    5.92
   11    13    363.6   180   D    200.952    2.46    2.20    6.04
   12    17   1588.2   125   D     69.077    1.81    8.54    5.38
   12    18    460.0   125   D   -100.476    2.62    4.75   10.32
   13    15    981.4   125   D     86.661    2.21    7.65    7.79
   13    18   1978.9   125   D    114.292    2.96   25.31   12.79
   14    17   1947.7    90   D    -52.750    2.76   32.09   16.47
   15    19    253.4    90   D     65.310    3.25    5.84   23.05
   16    19    855.8    90   D    -54.006    2.72   14.25   16.66
   16    20   2456.0    90   D     27.631    1.41   12.86    5.24
* SOURCE RESULTS
  --------------
 NODE  PRESSURE     FLOW    % FLOW
-----  --------   --------  ------
         MBAR       SCMH
   11    150.00    200.952   100.0 %
* PRESSURE RESULTS
  ----------------
 NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE   *  NODE  PRESSURE
-----  --------   * -----  --------   * -----  --------   * -----  --------
         MBAR     *           MBAR    *           MBAR    *           MBAR
                  *                   *                   *
    1     99.18   *     6     93.92   *    11    150.00   *    16    120.06
    2     52.38   *     7     93.06   *    12    117.75   *    17    109.21
    3    108.67   *     8     31.52   *    13    147.80   *    18    122.50
    4     67.10   *     9    110.61   *    14     77.13   *    19    134.31
    5     88.21   *    10    104.67   *    15    140.16   *    20    107.20
* COST OF NETWORK
  ---------------
 DIAM  TAG    COST      LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M         M
   32   D       1.35     273.1      368.67
   63   D       5.09    6162.6    31367.43
   90   D       6.18   20082.0   124106.58
  125   D      11.72    5008.4    58698.56
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       31889.7   223352.00
COMMAND >* Read back the undesigned network.
COMMAND >RN R.J;
```

```
* READING NETWORK FROM FILE R.J
COMMAND >* Turn design refinement option on.
COMMAND >EO DR ON;
COMMAND >* Redesign the network.
COMMAND >DN;
CHECKING NETWORK TOPOLOGY ...
    CHECKING PIPE FACTORS ...
   FORMING TREE STRUCTURE ...
... NETWORK CHECK SUCCESSFULLY COMPLETED
          SAVING NETWORK ...
        DESIGNING NETWORK ...
DESIGN CYCLE   0 :
DESIGN CYCLE   1 :
MINIMUM PRESSURE IS  -43.84 MBAR AT NODE     1
DESIGN CYCLE   2 :
MINIMUM PRESSURE IS   54.17 MBAR AT NODE     8
DESIGN CYCLE   3 :
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
          REFINING DESIGN ...
REFINEMENT CYCLE   1 :
REFINEMENT CYCLE   2 :
PIPE    13    15 CHANGED FROM 125 TO  90
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
REFINEMENT CYCLE   3 :
REFINEMENT CYCLE   4 :
REFINEMENT CYCLE   5 :
REFINEMENT CYCLE   6 :
REFINEMENT CYCLE   7 :
REFINEMENT CYCLE   8 :
REFINEMENT CYCLE   9 :
REFINEMENT CYCLE  10 :
REFINEMENT CYCLE  11 :
REFINEMENT CYCLE  12 :
REFINEMENT CYCLE  13 :
REFINEMENT CYCLE  14 :
REFINEMENT CYCLE  15 :
MINIMUM PRESSURE IS   31.52 MBAR AT NODE     8
...   1 PIPES DOWNSIZED DURING REFINEMENT
... DESIGN COMPLETED
COMMAND >* Print all the results and the cost of the designed network.
COMMAND >PF; PP; PC;
* FLOW RESULTS
  ------------
```

NODE	NODE	LENGTH	DIAM	TAG	FLOW	VEL.	P/DROP	P/GRAD
		M			SCMH	MPS	MBAR	MBAR/KM
1	12	2826.9	90	D	-31.399	1.61	18.57	6.57
2	14	4184.6	90	D	-28.887	1.55	24.75	5.91
3	16	290.2	63	D	-26.375	3.34	11.71	40.34
4	14	292.8	63	D	-23.863	3.06	10.03	34.24
5	15	1912.7	63	D	-21.351	2.76	53.40	27.92
6	20	600.5	63	D	-18.839	2.42	13.66	22.75
7	17	7557.5	90	D	-16.327	0.84	16.15	2.14
8	18	273.1	32	D	-13.816	7.15	90.98	333.16
9	19	2639.9	63	D	-11.304	1.43	24.35	9.22
10	20	426.5	63	D	-8.792	1.12	2.60	6.09
11	13	363.6	180	D	200.952	2.46	2.20	6.04
12	17	1588.2	125	D	69.077	1.81	8.54	5.38
12	18	460.0	125	D	-100.476	2.62	4.75	10.32
13	15	981.4	90	D	86.661	4.41	37.52	38.23
13	18	1978.9	125	D	114.292	2.96	25.31	12.79
14	17	1947.7	90	D	-52.750	2.76	32.09	16.47
15	19	253.4	90	D	65.310	3.34	6.00	23.67
16	19	855.8	90	D	-54.006	2.80	14.64	17.11
16	20	2456.0	90	D	27.631	1.45	13.22	5.38

```
* PRESSURE RESULTS
  ----------------
```

NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE	NODE	PRESSURE
	MBAR		MBAR		MBAR		MBAR
1	99.18	6	62.76	11	150.00	16	89.64
2	52.38	7	93.06	12	117.75	17	109.21
3	77.94	8	31.52	13	147.80	18	122.50
4	67.10	9	79.93	14	77.13	19	104.28
5	56.89	10	73.82	15	110.28	20	76.42

```
* COST OF NETWORK
```

```
  ---------------
 DIAM  TAG    COST     LENGTH   TOTAL COST
 ----  ---  --------  --------  ----------
              /   M       M
   32   D       1.35     273.1      368.67
   63   D       5.09    6162.6    31367.43
   90   D       6.18   21063.3   130171.42
  125   D      11.72    4027.0    47196.91
  180   D      24.23     363.6     8810.76
                       --------  ----------
                       31889.7   217915.19
COMMAND >* Terminate the SNAP run.
```