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Development of a methodology and modelling toolkit to aid carbon neutrality planning in industrial manufacturing

Thesis presented by

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for the degree of

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Declaration

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Acronyms

AHU	Air Handling Unit
BAU	Business as Usual
CAGR	Compound Annual Growth Rate
CAP	Climate Action Plan
CAV	Constant Air Volume
CCHP	Combined Cooling, Heating, and Power
CCP	Combined Cooling and Power
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
CHW	Chilled Water
COP	Conference of the Parties
COP	Coefficient of Performance
CPPA	Corporate Power Purchase Agreement
CSR	Corporate Social Responsibility
CSRD	Corporate Sustainability Reporting Directive
DSS	Decision Support System
EEM	Emissions Evaluation Methodology
EII	Energy Intensive Industries
EPA	Environmental Protection Agency
EPI	Energy Performance Indicator
ESG	Environmental, Social and Governance
ESOM	Energy system Optimisation Model

ESR	Effort Sharing Regulation
ETS	Emissions Trading Scheme
GHG	Greenhouse Gases
GLSS	Green Lean Six Sigma
HVAC	Heating, Ventilation, and Air Conditioning
HW	Hot Water
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
LIEN	Large Ireland Industry Network
LSS	Lean Six Sigma
MACC	Marginal Abatement Cost Curve
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-criteria Decision-making
MILP	Mixed-integer Linear Programming
NDC	National Determined Contributions
NPV	Net Present Value
PV	Photovoltaic
RES	Renewable Energy Share
SBT	Science Based Targets
SBTi	Science Based Targets Initiative
SDG	Sustainability Development Goal
SEAI	Sustainable Energy Authority of Ireland

SER	Sufficiency Efficiency Renewables
SEU	Significant Energy User
SIR	Savings Return on Investment
SLSS	Sustainable Lean Six Sigma
SS	Six Sigma
TPER	Total Primary Energy Requirement
UML	Unified Modelling Language
UNFCC	United Nations Framework Convention on Climate Change
VAV	Variable Air Volume

Nomenclature

Parameters

$\eta =$ Efficiency

$CAGR =$ Compound annual growth rate

$Carbon\ offset$ = Cost of single carbon credit (€/CO_2e)

$Carbon\ tax$ = Carbon tax (€/tCO_2)

CF = Carbon footprint (tCO_2e)

CTS = Cumulative carbon tax savings (€)

$CCTS$ = Cumulative carbon tax savings (€)

CF = Carbon footprint calculated for baseline year (tCO_2e)

CFC = Cumulative financial cost (€)

CFS = Cumulative financial savings (€)

$COFS$ = Cumulative operational financial savings (€)

COC = Carbon offset cost (€)

$Cost$ = Unit cost of fuel

DR = Discount rate (%)

EB = Emissions balance (tCO_2e)

EF = Emissions factor (tCO_2e/unit)

EO = Energy output

ES = Emissions savings (tCO_2e)

ESS = Energy source savings

FC = Fuel consumption

FCS = Fuel consumption savings

IMP = Implementation cost (€)

NPV = Net present value (€)

$O\&M$= Operations and maintenance cost (€)

OG = Onsite generation

OFS= Operational financial savings (€)

PI = Production increase (%)

P_R= Rated power (kW)

RE = Renewable energy

RES = Renewable energy share (%)

SIR = Savings to investment ratio

SR = Systems ratio

TO = Thermal output (MWh)

TES = Total emissions savings (tCO_2e)

EU = Utility energy

Subscripts:

BAU = Business as usual

dr = Attributed to demand reduction

eff = Attributed to efficiency

ff = Attributed to fossil fuels

HW = Hot water system

i = Energy source

hp = Attributed to heat pump adoption

$boiler$ = Attributed to boiler replacement

$operating\ hours$ = Operating hours of technology

M = Current measure

PV = Present value

re = Attributed to renewable electricity

tp = Time period

$util$ = Attributed to the utility provider

$steam$ = Steam system

oil = Attributed to oil

$elec$ = Attributed to electricity

gas = Attributed to gas

$baseline$ = Baseline value in carbon footprint year

Abstract

The United Nations Sustainable Development Goals emphasises the shift of economies toward carbon neutrality to reduce greenhouse gas emissions. The resulting legislation as well as corporate social responsibility are drivers for industrial decarbonisation. This thesis explores available technical support for Irish industrial organisations targeting decarbonisation and carbon neutrality. An extensive review of the current academic, public, and commercial supports is presented, and three research gaps are identified—open-access, detailed, cross-sectoral methodology with reference to a modelling tool; open-access modelling tool aimed at the organisational level with consideration of demand and supply measures; and a heuristic, bottom-up method of considering interaction effects between emissions-reduction measures based on industrial processes. In response, the overarching aim of this thesis is to develop a methodology and a modelling toolkit with consideration of interaction effects to aid Irish industrial organisations in planning and subsequently achieving carbon neutrality. A further aim is to quantify the financial impact of a carbon neutral industrial sector in Ireland.

A novel decarbonisation methodology based on quality management principles is proposed as a continuous improvement process with reference to a modelling toolkit. It is a nested methodology in which the top tier is a high-level methodology for early-stage planning and the bottom tier is a detailed methodology for in-depth planning. The toolkit comprises a novel high-level modelling tool for early-stage carbon neutrality within the high-level methodology, and a detailed project-based tool for in-depth carbon neutrality planning within the detailed methodology.

The high-level modelling tool uses readily available, site-level data as the model inputs. The model outputs are a five-year carbon neutrality roadmap and financial analysis based on decarbonisation measures in the order of demand reduction; energy efficiency; electrification through heat pumps for hot water loads and electric boilers for steam loads; adoption of renewable electricity; and carbon offsetting of remaining emissions. This modelling tool is intended as a decision support tool for investing in the studies required to pursue more in-depth carbon neutrality planning.

Consequently, this modelling tool progresses the decarbonisation journey at a stage when progress typically stalls owing to lack of information or guidance.

For the project-based modelling tool, the main input is a register of emissions-reduction measures developed through site-specific energy audits, heat studies, and renewable energy studies. This modelling tool bridges the research and development gap between tools aimed at the country/regional level and commercial proprietary software aimed at the organisational level that do not offer structured roadmaps to carbon neutrality. However, validation of the tool through an industry partner case study highlighted the need to consider interaction effects between emissions-reduction measures.

To improve the project-based modelling tool, a novel rule-based method for the resolution of interaction effects between emissions-reduction measures is proposed. It evaluates the emissions source of each emissions-reduction measure and how it reduces emissions. This rule-based method was incorporated into the project-based modelling tool and deployed on three case studies. Results indicate a 43–56% overestimation in emissions abatement in the models without consideration of interaction effects; the results further indicate a substantial financial impact. Thus, this method combats the overestimation of potential emissions reductions in carbon neutrality planning.

A bottom-up financial model of Ireland's industrial sector was developed using the case study models as a basis for scenario analysis of industrial sub-sectors. The potential financial investment required to achieve a carbon neutral industrial sector was calculated as €2-10 billion, which aligns with costs proposed in the Climate Action Plan.

The work presented in this thesis is demonstrated to meet the research objectives; it provides technical support for non-energy-intensive Irish organisations targeting carbon neutrality and assesses the financial impact of decarbonising the industrial sector.

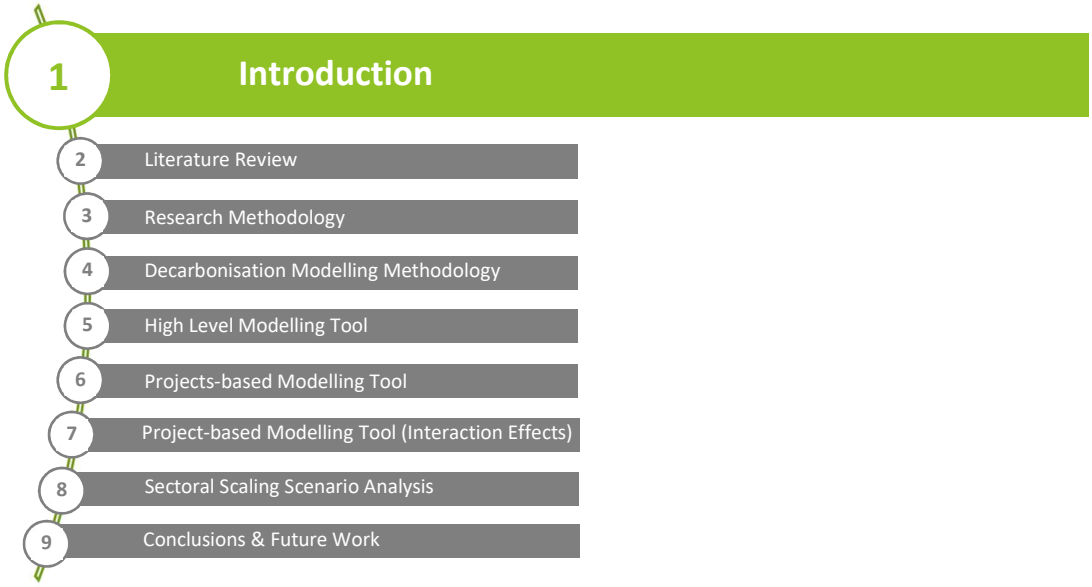
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The aim of this work is to develop a methodology and modelling tool to guide industrial organisations in Ireland to achieve carbon neutrality, and to apply these to case studies to enable the development of a scaled-up model of the industrial sector that can be used to inform national policy. This chapter presents the motivation for this work by detailing sustainability goals and GHG emissions-reduction targets and legislation from a global, European, and Irish perspective. This provides the background and context of this work, from which the research objectives are defined. The overall contributions of this work are set out; these encompass contributions to global sustainability through impact on the sustainable development goals, and academic contributions in the form of a list of publications. Finally, the thesis structure and evolution of the work is presented.

1.1 Research Motivation

The *'safe operating space'* for humanity is cocooned within nine interconnected planetary boundaries of Earth-system processes; these are critical to environmental resilience and stability [1]. There are two core boundaries—climate change and biosphere integrity— and significant change to either of these may *'drive the Earth system into a new state'*. However, the coupling of the planetary processes means that the ramifications of a single boundary breach, even of the non-core processes, are widespread, potentially driving other planetary processes beyond their safe zones and causing abrupt and irreversible damage. By 2022, six of the nine planetary

boundaries had been transgressed [2]. The global average atmospheric CO_2 concentration in 2022 was 417 ppm; this is beyond the safe threshold (350 ppm) and into the zone of uncertainty (350 – 450 ppm) which represents increasing risk to the Earth system [2]. The consequences of this are evident by instances of extreme weather, increasing natural disasters, and conflict resulting from the scarcity of natural resources. From a geological context, this human impact has pushed the Earth system from the stable Holocene epoch towards the Anthropocene epoch which is dominated by human activity [2]. It is clear that Earth is in the midst of an ongoing climate crisis and imminent humanitarian crisis as a result of climate change, and that drastic and urgent action is required to reduce the severity of human impact to stabilise the climate and to support sustainable life. In light of this, the 2030 Agenda for Sustainable Development was officially adopted in 2015 by all United Nations Member States as a global action plan to end poverty, combat inequality, and address climate change by balancing the social, environmental, and economic factors of sustainability. The Agenda comprises 17 sustainable development goals (SDGs), each with a number of specific targets and their appropriate indicators with which to measure success. '*SDG13 Climate Action'* involves taking urgent action to combat climate change and its impacts. Of relevance is '*Target 13.2 Integrate climate change measures into national policies, strategies, and planning'*, where the progress is measured by two indicators, one of which is *'Indicator 13.2.2 Total greenhouse gas emissions per year'*. [3] This target can be directly supported by shifting economies towards carbon neutrality.

Industrial organisations that commit to carbon neutrality are prone to 'green stagnation' whereby progress towards sustainability goals slows or plateaus. In the case of carbon neutrality planning, this is likely to occur between setting emissions targets and achieving them, i.e. in the implementation phase. Up to this point, organisations have been slow to adopt innovative manufacturing strategies, advanced digital technologies, green protocols, and environmentally friendly practices; this forms a barrier to the implementation of decarbonisation measures [4]. Failure to implement these measures results in a large emissions balance that needs to be offset through the purchase of carbon credits. This is an additional cost

that exists solely because of the carbon neutrality commitment, and the financial savings from reducing emissions could be undone by these costs. This highlights the importance of proper planning to ensure that potential decarbonisation measures can be implemented on time and within budget. This level of planning would benefit from emissions and financial modelling in the form of scenario analysis to determine an achievable path to carbon neutrality. Consequently, the motivation for decarbonisation extends to strategic planning and carbon neutrality road-mapping, and this requires updated and relevant technical support and guidance to meet current and increasing emissions targets.

1.2 Problem Statement and Research Questions

It is clear than industrial organisations are increasingly motivated through legislation and CSR to play their part in reducing overall industry sector emissions by targeting carbon neutrality. However, there appears to be no consistent approach for climate neutrality in industrial organisations [5], indicating the scope for a novel methodology. Moreover, a recent study stated that organisational roadmaps should be developed on a case-by-case basis to be effective [6]; this indicates scope for technical support that can capture detailed site data but is aimed at a slightly higher level to be generalisable for applicability across organisations. Consequently, the overarching aim of this work is to support industrial organisations in carbon neutrality planning through the development of a methodology and modelling toolkit. Supporting aims of this work are to implement the modelling tool to provide an evidence base to inform climate policy in Ireland's industrial sector. To support these aims, this thesis addresses the following specific research questions (RQs):

RQ1 – What methodologies exist to support industrial organisations in achieving carbon neutrality?

> **Research Undertaken** – First, standards and certifications relevant to energy management and carbon neutrality were explored, where the latter lead to exploration of the recommended GHG emissions and reporting protocols. Then, Irish certifications applicable to industrial decarbonisation were investigated. Finally, a literature review of decarbonisation roadmaps at

various geographic scales was conducted. From this, requirements for a methodology to aid industrial organisations in achieving carbon neutrality were defined.

RQ2 – What existing mathematical and commercial modelling resources are applicable to individual organisations, and what level of detail do they contain?

Research Undertaken – First, energy modelling tools applicable to all time-horizons and geographic scales were explored to gain a broad understanding. Then, the future-based modelling tools with a focus on techno-economic parameters were explored in more depth, namely carbon/emissions management tools, energy management tools, and energy systems modelling tools. For each tool type, open access tools were explored, as well as commercial software to the extent that was possible. Finally, a literature review was conducted to explore mathematical models that had not been developed further into software or online tools. From this, the requirements for a modelling toolkit were defined to aid industrial organisations in achieving carbon neutrality.

RQ3 – How do existing modelling resources consider the interactions between emissions-reduction measures?

Research Undertaken – Three case studies of industrial manufacturing sites were leveraged as a basis from which to explore the interdependencies or 'interaction effects' between processes, i.e. the way in which an energy or emissions reduction in one process might affect another that of another. First, the industrial processes at each site were analysed to determine typical sources of emissions in terms of equipment and configurations. Then, the relationships between these processes were explored to understand how they interact and how changes in one process might affect another. Each process was further researched to explore other equipment types and configurations that could be used on other sites. Then, carbon footprinting standards and emissions protocols were consulted to round out the research

by seeking additional emissions sources**.** This lead to the development of a rule-based method of incorporating interaction effects in the modelling tool.

Further work was undertaken to deploy the modelling tool considering interaction effects on five studies in the pharmaceutical and medical device sector. These results were scaled using Ireland's Large Industry Energy Network (LIEN), which is made up of 197 member organisations categorised according to industry type, who operate with sustainable management principles. LIEN members have typically already implemented the more obvious and economical emissions-reduction measures, and are currently targeting hard-to-abate projects. The case study organisations are all LIEN members, and thus the savings realised are indicative of other LIEN members. Two scale scenarios were modelled. Scenario 1 comprises the organisations within the same LIEN categories as the case study organisations, and this model is likely to be an adequate representation of these industry sectors. Scenario 2 represents the full LIEN complement, and this was used to quantify the potential emissions and financial impact of achieving carbon neutrality on Ireland's industrial sector.

1.3 Novelty

The research undertaken to address the research questions of this work led to the following novel contributions:

- Development of a methodology to aid non-energy-intensive (non-EII) industrial organisations in achieving carbon neutrality.
- Development of a high-level modelling tool that generates a five-year carbon neutrality roadmap and a 15-year financial analysis to provide a broad indication of the scale of investment required to target carbon neutrality.
- Development of a detailed, project-based modelling tool that generates a carbon neutrality roadmap and financial analysis to show the breakeven point of investment in emissions-reduction measures.
- Development of a methodology to resolve the interaction effects between emissions-reduction measures using a heuristic approach, and inclusion of these effects in the model.

- Quantification of the potential impact of increased targeting of carbon neutrality by the 197 organisations within Ireland's Large Industry Energy Network (LIEN), using two scenarios based on case studies of five manufacturing facilities.

1.4 Contributions

This research yielded novel contributions to global sustainability by progressing the knowledge of industrial carbon neutrality planning, as well as tangible academic contributions in the form of publications.

1.4.1 Sustainable development goals

The methodology developed in this work provides a structured approach to carbon neutrality planning, and the generated output from the modelling toolkit can be used as a knowledge-base for decision-making. In this manner, they are considered to encourage the adoption of certain emissions-reduction metrics, which can be linked to specific targets of the SDGs. Moreover, the industrial sector model can be directly linked to SDG targets. In addition to the overarching 'SDG13: Climate Action' goal, this study addresses 'SDG 7: Affordable and Clean Energy' by promoting energy efficiency and identifying opportunities for renewable energy; 'SDG 9: Industry, Innovation & Infrastructure' by promoting increases in the efficiency of industrial processes; and 'SDG 12 Responsible Consumption' by promoting the efficient use of natural resources. These SDGs and their relationship to the contributions of this work are further detailed in Figure 1.1.

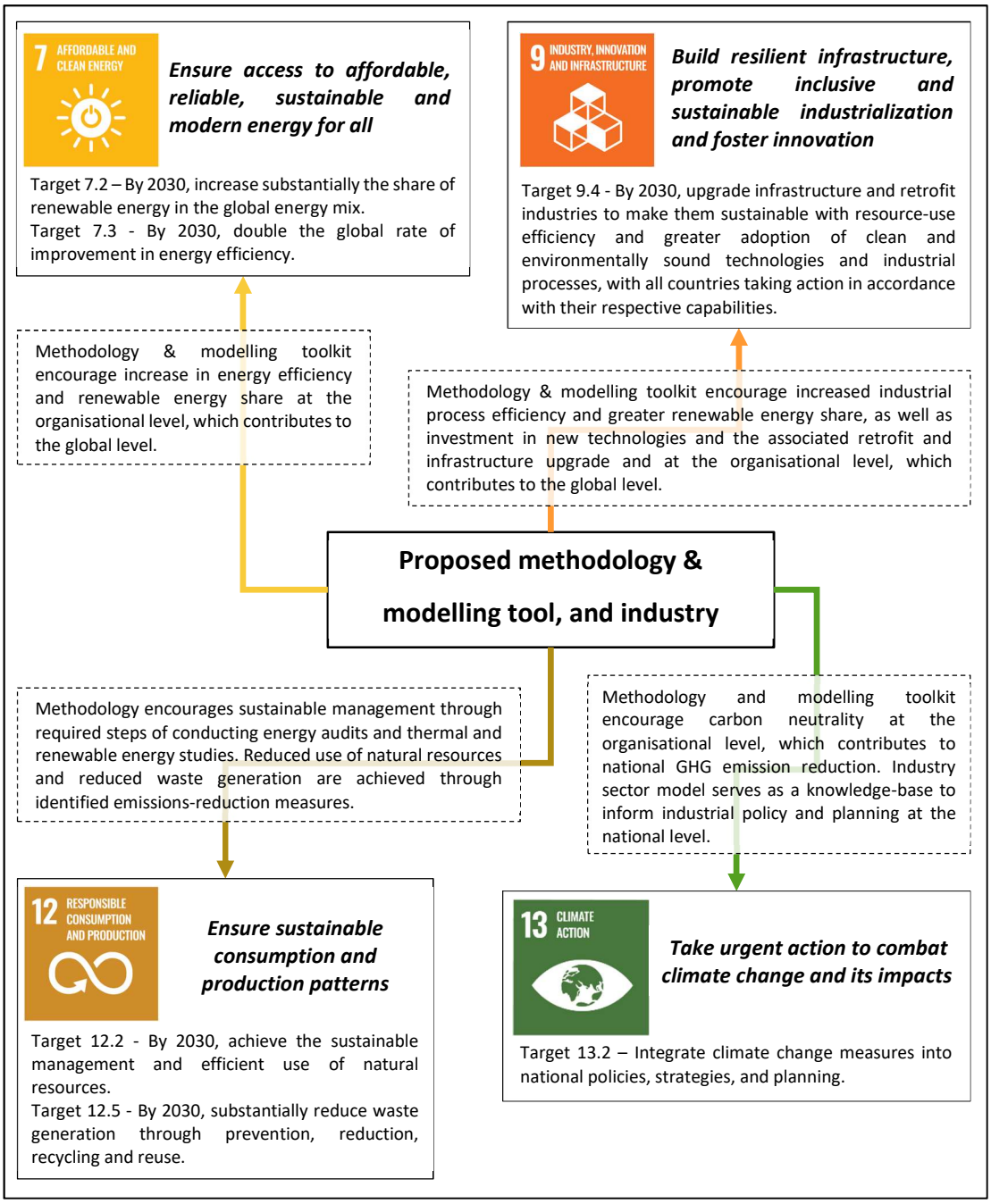


Figure 1.1: Sustainable development goals addressed

1.4.2 Publications

The publications emanating from this research work are as follows.

1.4.2.1 *Journal articles*

- **O'Keeffe, S.**, Clancy, R., O'Sullivan, D., Bruton, K., 2021. Total Site Heat Integration in Carbon Neutral Industrial Manufacturing – A Systematic

Mapping Study. Chemical Engineering Transactions 88, 133-138. https://doi.org/10.3303/CET2188022

- **O'Keeffe, S.**, O'Sullivan, D., Bruton, K., 2022. Methodology for Carbon Neutrality in Industrial Manufacturing. Chemical Engineering Transactions 94, 43-48. https://doi.org/10.3303/CET2294007
- **O'Keeffe, S.**, O'Sullivan, D., Bruton, K., 2023. Development of a Modelling Tool to Aid the Transition to Carbon Neutral Industrial Manufacturing. Journal of Cleaner Production 425. https://doi.org/10.1016/j.jclepro.2023.138604
- **O'Keeffe, S.**, O'Sullivan, D., Bruton, K., 2024. Methodology for the resolution of interaction effects between emissions-reduction measures in carbon neutrality modelling. Energies. Manuscript submitted for publication.

1.4.2.2 *Conference Presentations & Invited Talks*

- The 24th conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction - PRES'2021 – 'Total site Integration in Carbon Neutral Industrial Manufacturing' – Oral presentation
- The 25th conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction - PRES'2022 – 'Methodology for Carbon Neutrality in Industrial Manufacturing' – Oral presentation
- Institute of Civil Engineers Presidential Visit '23 – 'Development of a Methodology and Modelling Tool for Carbon Neutrality in Industrial Manufacturing' – Oral presentation
- Climate Week Rome 2023 – 'Resolving Interaction Effects in Modelling Tool for Carbon Neutrality Manufacturing' – Oral presentation
- MAREI Scientific Advisory Committee Meeting - 'Development of a Methodology and Modelling Tool for Carbon Neutrality in Industrial Manufacturing' – Oral presentation

1.5 Thesis Structure

The remainder of this thesis is organised into the following seven chapters, with each commencing with a short introduction and background to the work presented therein, and culminating with a short conclusions section.

- **Chapter 2** presents a literature review, which includes a comprehensive evaluation of existing standards, certifications, academic literature, relevant commercial software related to decarbonisation of industrial organisations, and interaction effects in decarbonisation modelling. The benefits and drawbacks of each offering are analysed. Based on the research questions, four distinct research gaps and objectives are defined within the knowledge areas of methodology (RO1), modelling tools (RO2.1 & RO2.2), and interaction effects of emissions-reduction measures (RO3). This section validates the need for the proposed work and establishes its significance. The identified research objectives are addressed in the subsequent chapters.
- **Chapter 3** outlines the research methodology employed to meet the research objectives defined in the literature review, from the development of a carbon neutrality methodology and associated modelling toolkit to the deployment of a project-based tool to generate an industrial sectoral model for carbon neutrality.
- **Chapter 4** addresses *RO1* and proposes a novel methodology aimed at assisting non-EII industrial organisations in achieving carbon neutrality. This is a nested methodology in which a high-level methodology applicable to early-stage carbon neutrality planning incorporates a detailed methodology as one of its steps. The high-level methodology is briefly discussed, with reference to a high-level modelling tool. Then, an overview of the two quality management strategies underpinning the detailed methodology is provided, and their benefits and contributions are discussed. This detailed methodology is presented graphically, and its five steps are discussed in detail. The fourth step of the methodology entails using a project-based modelling tool developed in this work to generate a carbon neutrality roadmap and financial

analysis; the inputs, function, and outputs of the modelling tool are briefly introduced in this chapter.

- **Chapter 5** addresses *RO2.1* and presents the high-level tool introduced in Chapter 4. First, the modelling tool approach is described graphically and an operational overview is presented. Then, the user and built-in inputs to the modelling tool are presented and the mathematical model underpinning the modelling tool is set out in the form of equations. Finally, a case study is leveraged to test the modelling and the generated outputs are presented.
- **Chapter 6** addresses *RO2.2* and presents the detailed, project-based modelling tool introduced in Chapter 4. The user and built-in inputs to the modelling tool are presented and the mathematical model underpinning the modelling tool is set out in the form of equations. Then, the verification and validation processes used to assess the accuracy and applicability of the modelling tool are described. Finally, the limitations of the modelling tool are discussed and highlighted for second-phase development.
- **Chapter 7** addresses *RO3* and details the progressions of the project-based modelling tool to address the limitations identified in Chapter 6. A heuristic, rule-based method of considering the interaction effects between emissions-reduction measures is presented. Three case studies of medical device and pharmaceutical facilities are leveraged to illustrate the applicability of the modelling tool.
- **Chapter 8** presents a scenario analysis of Ireland's industrial sector based on deploying the project-based modelling tool including interaction effects on five case studies. The case study outputs are scaled to align with the different criteria met by the LIEN organisations to determine the financial impact of achieving a carbon neutral industrial sector.
- **Chapter 9** summarises the work completed and presents a critical analysis and in-depth discussion of the findings. It further provides an overarching conclusion based on the concluding remarks within the previous chapters. It details the contributions of this work and the manner in which they align with the research objectives laid out in Chapter 1. It discusses the limitations of

the developed methodology, modelling toolkit, and industrial sector scenario analysis, and then proposes possible directions for future work arising from these limitations and from further opportunities identified.

The chapters containing the novel contributions of this work are illustrated in

Figure 1.2 as the crucial pillars on which this thesis rests. The research objectives addressed in each chapter are indicated, and the evolution of the thesis is from left to right.

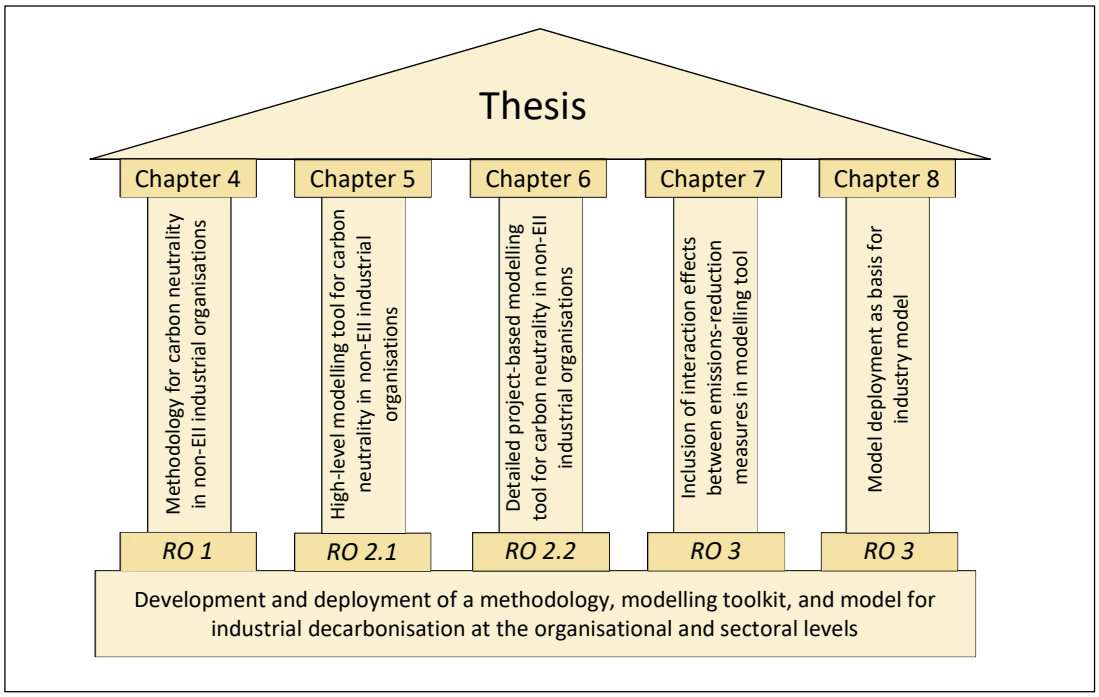
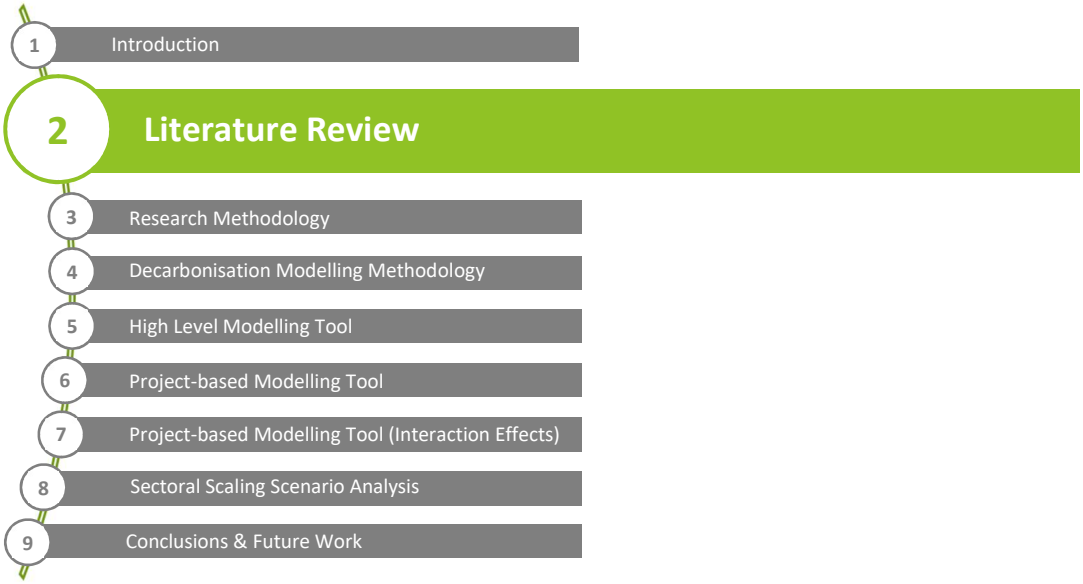


Figure 1.2: Thesis pillars



2.1 Introduction

This chapter investigates existing industrial decarbonisation methodologies and modelling resources. As part of this, current methods of considering interaction effects between modelled emissions-reduction measures are explored. This provides the necessary background and context to address the research questions, define the research gaps, and consequently formulate specific research objectives to define the scope of this work.

The systematic literature review and the traditional (narrative) literature review are two popular, opposing review approaches [7]. Systematic literature reviews provide transparent and reproducible evidence-based reviews. Traditional literature reviews provide a broad overview of the subject area and are more flexible, but may be susceptible to researcher selection bias [8]. A thematic literature review is a form of traditional review that categorises and analyses literature according to recurring themes [9]. The systematic review and the thematic review are the approaches considered in this work, and a comparison of their various features is shown in Table 2.1 as a basis from which to select the more suitable approach.

Table 2.1: Comparison of literature review features

Feature	Systematic Literature Review	Thematic Literature Review
Objective	To answer a clearly defined research question by synthesising literature systematically	To provide an overview of a specific topic by identifying, analysing, and synthesising recurring key themes within relevant literature
Scope	Narrow scope limited to the defined research question	Broad scope based on exploring interconnected themes and relationships
Methodology	Highly structured approach with clear inclusion and exclusion criteria	Flexible, iterative approach in organising literature based on themes
Search Strategy	Exhaustive and heavily documented search strategy using specific, predefined search terms in multiple predefined databases	Literature selected from multiple databases and sources in a less formal approach without the requirement for extensive documentation
Risk of Bias	Low risk owing to the rigorous methodology and search strategy	Higher risk owing to the flexible methodology and subjective search strategy and analysis method
Presentation	Highly structured and standardised presentation of findings	Flexible but logical presentation of findings based on the narrative
Reproducibility	Highly reproducible because of strict inclusion and exclusion criteria and documentation process	Lower reproducibility since the methodology is more flexible and systematic documentation is not required

This work is well-suited for thematic review based on prior knowledge regarding the distinct themes of decarbonisation methodologies based on standards and protocols,

and decarbonisation roadmap generation based on commercial tools. In addition, the systematic review approach was deemed too restrictive since it focusses on academic literature, and this is not the only source of relevant background material for this work. For instance, a review of decarbonisation modelling tools and models, both academic and commercial, is required and this may not be captured in a systematic literature review. Consequently, a traditional literature review was conducted using a thematic approach, and a transparent search strategy was used to combat potential selection bias. The following steps were conducted in the traditional thematic literature review, and this approach is illustrated in Figure 2.1:

1. Define research question – The overarching research question was established based on industry need, and the literature review was conducted to determine if there was a sufficient scientific challenge to pursue an academic study within this field.
2. Identify themes – The literature was analysed to identify relevant, common themes. Two themes were identified, namely decarbonisation methodologies, and decarbonisation modelling tools and models.
3. Organise literature – The literature was categorised into thematic clusters according to the identified themes to provide structure to the literature review.
4. Review and synthesise literature – The literature within each theme was analysed to highlight similarities, differences, and relationships between publications, and to identify trends and gaps. The databases searched are ScienceDirect, Google Scholar, and Scopus, with the following initial search strings designed according to the research themes: ("carbon neutrality" OR "decarbonisation") AND ("industry" OR "manufacturing") AND (“methodology” OR “roadmap” OR “pathway”); ("carbon neutrality" OR "decarbonisation") AND ("industry" OR "manufacturing") AND (“model” OR “tool”). The resulting materials were used as a starting point from which to further explore each theme. Additional searches for standards and policy documents on national, EU, and international standards websites were

conducted. Further web-based searches were conducted for commercial tools not featured in the literature sourced by the previous methods.

5. Refine themes – A review of the literature within the modelling tool theme indicated that the interactions or interdependencies between modelling tool inputs should be explored. The same databases were searched using the search string '("model" OR "tool") AND ("interactions" OR "interdependencies")'. Consequently, the final themes were identified as: decarbonisation methodologies, decarbonisation modelling tools and models; and interaction effects between modelling tool inputs.
6. Identify research gaps – Research gaps were identified, and the literature was analysed for conflicts and trends.
7. Create organisational structure – The themes were analysed from the broadest to the most specialised to create a logical flow and aid comprehension. First, methodologies were analysed as the broadest theme since they may encompass modelling tools; then modelling tools and models were analysed; and finally interaction effects between inputs within modelling tools were analysed as the most specialised theme.
8. Integrate themes – The themes were analysed and integrated into a logical and cohesive discussion to provide a comprehensive overview of the research area, highlighting the key insights and research gaps.

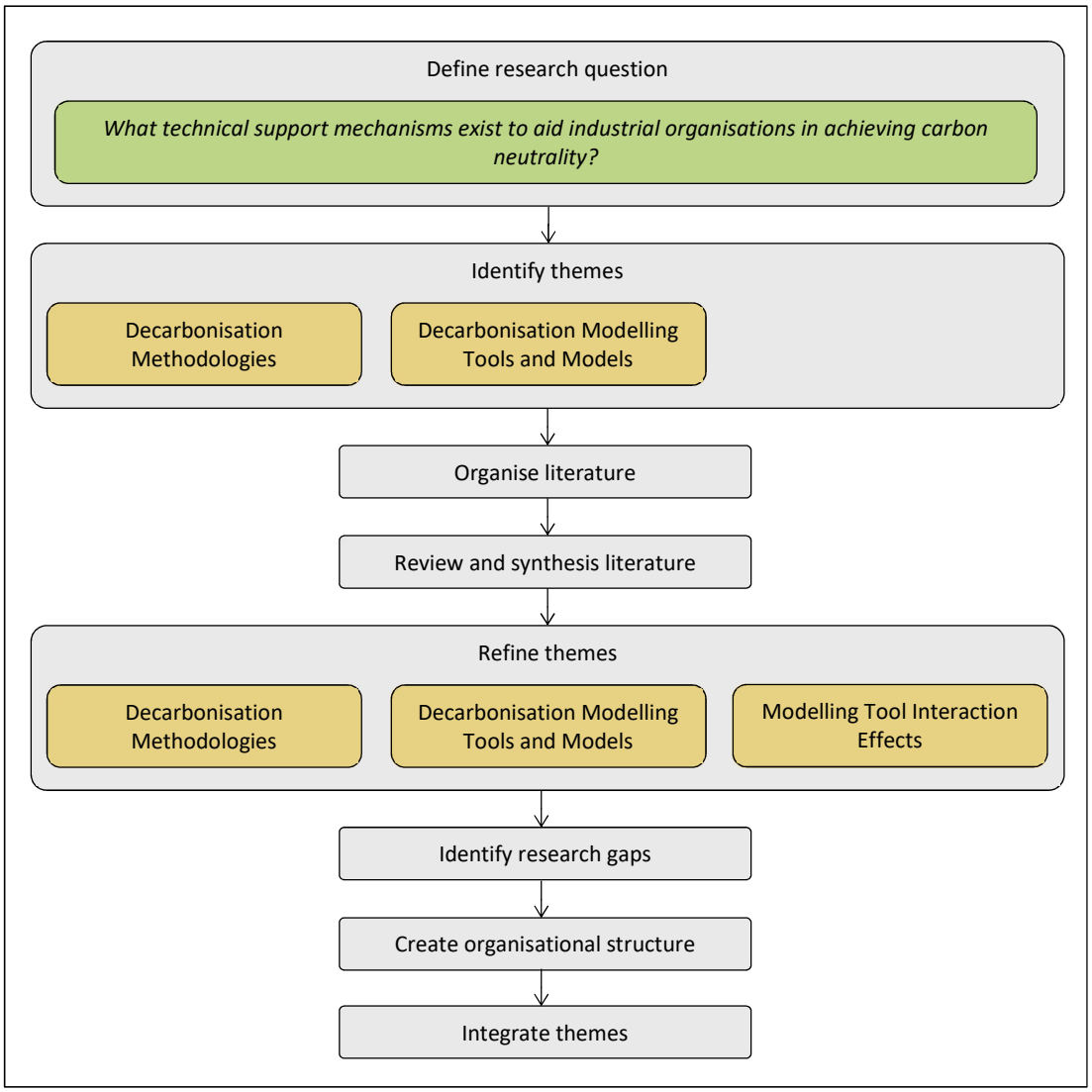


Figure 2.1: Thematic map

The remainder of this chapter is structured as follows. Section 2.2 provides relevant motivation for industrial decarbonisation, a definition of emissions scopes, and a discussion of governing energy and emissions standards and protocols. Section 2.3 presents relevant decarbonisation methodologies. Section 2.4 provides an overview of commercial and open-source energy and emissions modelling tools, and discusses key contributions to the academic literature. Section 2.5 addresses interaction effects in modelling. Section 2.6 discusses software development frameworks in the form of design methodologies and modelling language, as relevant to modelling tool development. Finally, section 2.7 summarises the identified knowledge gaps to position the original contributions of this research and development work around

the scope of existing offerings. The literature review structure and the research questions addressed are shown in Figure 2.2.

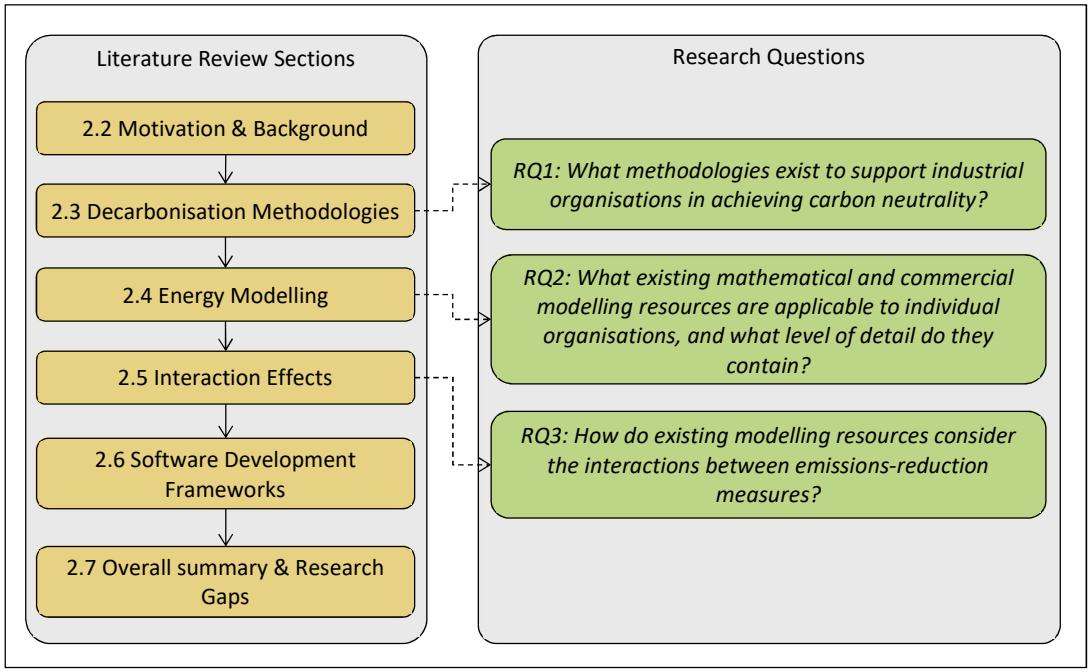


Figure 2.2: Literature Review structure

2.2 Motivation & Background

This section begins by clarifying terms used throughout this thesis. It then provides a strong motivation for industrial decarbonisation from top-down motivation relating to policy to bottom-up motivation on individual industrial organisations. Finally, relevant background with regards to emissions scopes and governing energy and emissions standards and protocols is presented to provide a foundation for subsequent discussions.

2.2.1 Clarification of terms

This section clarifies key terms used within this thesis to establish a common understanding and to ensure consistency.

2.2.1.1 *Decarbonisation*

There is some confusion regarding the definitions of the related terms of carbon neutrality, GHG neutrality, climate neutrality, and net zero [10]. These terms are often interpreted differently or used interchangeably in policies, academic studies and in industry. The IPCC definition limits carbon neutrality to CO_2 emissions,

whereas GHG neutrality encompasses all GHG emissions; the ambiguity of these terms are acknowledged in this report [11]. They further define carbon neutrality and climate neutrality equivalently at the global scale as '*the condition in which anthropogenic GHG emissions are balanced by anthropogenic GHG removals over a specified period*'. The International Standards Organisation (ISO) follows this definition and refers to this state as 'global net zero GHG emissions' [12]. At the organisational scale, the IPCC defines net zero emissions as those under the direct control of the organisation, whereas neutrality includes emissions beyond this boundary [11]. ISO defines carbon neutrality at the organisational level as the abatement of all GHG emissions through emissions-reduction activities and offsetting to compensate for remaining emissions [13]. The difference between carbon neutrality in this context and net zero relates only to the final step on the pathway in which remaining emissions are offset through the purchase of carbon credits. Carbon credits are categorised as reduction credits which involve activities that reduce fossil fuel consumption, removal credits which involve activities that remove atmospheric CO_2, and avoidance credits which prevent the occurrence of an emissions-producing activity [13]. Carbon neutrality allows for carbon offsetting of unabated emissions using any credit type, whereas net zero is more stringent in that all emissions must be reduced where practically possible and only residual emissions can be offset by purchasing removal credits. Consequently, carbon neutrality can be viewed as '*a progressive series of steps on the pathway to net zero*' [12]. This work follows the ISO definitions and addresses carbon neutrality wherein all GHGs are considered.

2.2.1.2 *Modelling resources*

Modelling resources comprise model generators or modelling tools and the models themselves. It should be noted that there is an important distinction between these terms. Modelling generators/tools are sets of mathematical equations and assumptions capable of producing different models based on input data. These model generators/tools can be open- or restricted-access academic equations or code, or proprietary commercial software. The generated models are applicable only to the defined application.

2.2.2 Motivation for Carbon Neutrality

The legislation underpinning the relevant SDG's discussed in chapter 1 and the motivation for targeting carbon neutrality is further discussed in this section from the perspectives of descending geographical scales—global, European, Irish, industrial sectoral, and organisational.

2.2.2.1 *Global Perspective*

The 21st annual United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in 2015 yielded an international treaty on climate change in the form of The Paris Agreement. This was adopted by 196 members to keep '*the increase global average temperature to well below 2 °C above pre-industrial levels*' and to attempt to *'limit the temperature increase to 1.5 °C above pre-industrial levels*'. The Paris Agreement requires participating parties to establish their climate pledges in the form of Nationally Determined Contributions (NDCs), and to update these with increasingly ambitious targets every five years. [14]

At its midpoint in 2023, The Agenda for Sustainable Development has shown slow and disrupted progress and is unlikely to yield success on its current trajectory [15]. In addition, The United Nations Intergovernmental Panel on Climate Change (IPCC) noted in their 2021 report that the global average temperature increase had already reached 1.1 °C above pre-industrial levels, and that drastic and ongoing action is required to limit further warming [16]. The projected emissions reduction based on the current NDCs (prior to COP26) is 7% (2019 baseline) [17]. However, the 1.5 °C global-warming limit requires a minimum emissions reduction of 43% by 2030, and net zero emissions by 2050. At COP 28, Parties were motivated to create considerably more ambitious NDCs in line with this temperature limit, for submission in 2025. [18]

The majority of global emissions (62%) in 2022 were collectively produced by China, the United States, India, the EU27, Russia, and Brazil [19]. However, it is vulnerable nations that are the most severely and disproportionately affected by climate change as they lack the resources to address the impacts thereof. Consequently, it can be argued that the high emitters should bear greater responsibility in reducing global emissions. [20] As such, different regions and nations have varied approaches and

targets in terms of emissions reduction and the transition from traditional to low-carbon energy systems.

2.2.2.2 *European Perspective*

The European Union (EU) submits its NDC on behalf of its Member States, and its climate change response is set out in the European Green Deal, which was launched in 2019 and commits the EU to net zero GHG emissions by 2050. As part of the Green Deal, the ambitious 'Fit for 55' package was later adopted in 2021 as a set of proposals to align the EU's policies with the climate neutrality commitment; five of these proposals were passed into European Climate Law in 2023. The overarching contribution of Fit for 55 is the intermediate legally binding target of 55% GHG emissions reduction by 2030 (1990 baseline). [21]

The EU categorises emissions-producing activities as either part of the emissions trading scheme (ETS) or non-ETS. ETS activities encompass electricity and heat generation, energy-intensive industry (EII), civil aviation, and maritime transport. These are addressed at the EU level through a cap-and-trade system in which organisations must account for their emissions through carbon allowances. These allowances can be traded in the carbon market, where the carbon price is determined by supply and demand market forces. The emissions cap decreases annually to align with the climate targets, increasing the carbon price and incentivising emissions reduction. [22] Non-ETS activities encompass agriculture, transport, the built environment, and small industry. The emissions-reduction targets of these activities are bound by EU Effort Sharing Regulation (EU ESR), and the policies and measures to achieve these targets are determined by the individual EU member states. [23]

More than 40% of Europe's GHG emissions are attributed to the energy and manufacturing sectors [24]. EIIs contribute approximately 64% of the EU's industrial emissions [24]. The European Green Deal highlights the importance of reducing EII emissions as EIIs supply intermediate products to numerous other industries, forming part of their supply chains. They are vital to the European economy [24], and have been the focus of industrial emission reduction. However, GHG emissions of

non-EIIs remain an important part of the industrial sector as the collective savings may be considerable.

2.2.2.3 *Irish Perspective*

As one of its member states, Ireland is subject to EU legislation with regards to climate action targets. Accordingly, Ireland's National Climate Objective is to achieve net zero emissions by 2050, and the following commitments have been made to support this [21]:

- 51% reduction in total GHG emissions by 2030 (2018 baseline)
- Contribute to the collective EU target of 43% reduction in ETS sectoral GHG emissions by 2030 (2005 baseline)
- 42% reduction in non-ETS sectoral GHG emissions by 2030 (2005 baseline)
- Implement measures listed in Ireland's Climate Action Plan 2024 (CAP 24) and beyond

The Climate Change Advisory Council has set Ireland's carbon budgets (allowable GHG emissions) for three consecutive five-year periods to meet the 2030 emissions target and to set Ireland on a path to net zero by 2050. The current total budget for 2021-2025 is 295 $MtCO_2e$, which translates to an average annual emissions decrease of 4.8%. [25] However, these annual reduction targets have not been met, and approximately 47% of the first carbon budget was used up by the end of 2022. Consequently, the required annual decrease has been revised to 12.4%, which can only be met through more drastic action. [26]

2.2.2.4 *Irish Industrial Sector Perspective*

The industrial sector used approximately 45% of its allocated carbon budget by the end of 2022, with a revised required annual emissions reduction of 9.2% for the remaining period [26]. This should be met through industrial action alone as there is no scope within the other sectors to absorb this emissions overshoot. Considering that industry makes up almost 18% of Ireland's energy demand [27] and 10% of Ireland's GHG emissions [21], it is imperative that urgent action is taken to

decarbonise this sector. In light of this, the main targets (excluding those related to construction) laid out in CAP 24 for Ireland's industrial sector are as follows:

- Carbon-neutral heating in industry (50-55% share by 2025; 70-75% share by 2030)
- Reduce fossil-fuel demand through energy efficiency measures in industry (by 2025, reduce to 45% of final consumption

In addition to this legislative motivation for industrial decarbonisation, there is financial motivation in the form of deterrents for high emissions and incentives for emissions-reduction efforts. One deterrent is Ireland's ten-year carbon tax trajectory laid out in the Finance Act 2020 to raise the carbon tax by €7.50 per year until €100 per tonne CO_2 emitted is reached in 2030 [28]. The Irish government offer financial incentives in the form of funding for climate action projects and technologies. Enterprise Ireland is a government organisation that facilitates the Green Transition Fund as part of Ireland's National Recovery and Resilience Plan (funded by the EU) [29]. This fund promotes industrial decarbonisation through financial support of climate planning and emissions-reduction activities. The Sustainable Energy Authority Ireland (SEAI) offers business grants for renewable energy investment, support schemes for energy efficiency projects, tax incentives for energy-saving technology, and contributions to energy audits [30].

2.2.2.5 *Individual Industrial Organisation Perspective*

Individual organisations are required to comply with the environmental and sustainability legislation of the region in which they are based. These policies and associated financial implications in the form of carbon allowances and carbon tax at the global, European, and national level provide top-down motivation on the industrial sector.

Individual organisations are also subject to bottom-up motivation in the form of corporate social responsibility (CSR), consumer demand, and pressure from organisations along the value chain aiming to decrease their value-chain emissions. Each of these motivations have an indirect financial component related to improving

brand image, protecting against loss of sales, and future-proofing supplier contracts, respectively.

2.2.2.5.1 Corporate Social Responsibility

Given Ireland's projected failure to adhere to its carbon budgets and to meet its 2030 emissions targets, mere compliance with national industry regulations is likely insufficient to combat the effects of climate change. To address this, organisations should be urged to surpass legislation and embrace (at least) the environmental aspect of the voluntary initiative of CSR. CSR can be defined as '*the responsibility of enterprises for their impact on society*', and it encompasses four dimensions—the workplace, environment, community, and marketplace [31]. The environmental dimension is the most relevant to this work.

In a 2022 global survey on climate change, sustainability, and CSR, 45% of Irish citizens claimed that CSR influences their purchasing decisions; however, only 13% believe that organisations are seriously embracing CSR [32]. This large gap between the importance of socially responsible corporate behaviour and the trust in delivery of this behaviour indicates a need for organisations to better communicate the tangible sustainable measures taken. On the global scale, the 18-34 age demographic is particularly influenced by CSR (55%) [32]. This value placed on CSR by a younger, more socially conscious consumer base is an indication of its growing importance. Organisations need to act promptly to be a viable green option for these consumers, particularly since certain technological actions may take time to implement because of lagging market and technology readiness.

A particular challenge of CSR is that it is difficult to quantify and it has not until recently been underpinned by policy, making auditing difficult. This has led to virtue signalling by means of greenwashing, wherein organisations make false or misleading claims regarding the environmental impact of their products and/or services. [33]

A 2020 study by the European Commission found that 53.3% of green claims investigated were 'vague, misleading, or unfounded' with 40% lacking substantive evidence. Such claims propagate consumer mistrust and undermine organisations that are ethically and responsibly taking sustainability action. In an effort to combat

greenwashing, the European Commission affected a proposal for a Directive on Green Claims in March 2023. The aim of this directive is to provide a common framework for the comparison and verification of green claims, where these claims are not covered by existing EU regulations. The implementation of a reliable claims system improves consumer trust and thereby imparts a competitive advantage to organisations making valid claims. [34]

In addition, the EU's Corporate Sustainability Reporting Directive (CSRD), set to be to be implemented in a phased-in approach from Financial Year 2024, requires all large and listed companies (excluding micro-enterprises) to report on their environmental and social impact [35]. This initiative allows for greater transparency in sustainability activities and holds organisations more accountable for their actions. This is advantageous for sustainability leaders as it attracts finances by lowering the investment risk and can secure contracts by meeting supply chain requirements. [34]

2.2.2.5.2 Consumer demand

A 2019 study on consumer behaviour found that Irish consumers are environmentally minded, with 41% willing to pay a premium for products that align with their values; this is expected to increase with increasing awareness of the climate crisis [36]. The competitive advantage gained from meeting consumer demand for sustainably made products serves as financial motivation for industrial decarbonisation.

2.2.2.5.3 Value chain organisations

Although it is currently not mandatory for organisations to include emissions generated in their value chains in their carbon accounting [37], the CSRD will require reporting of value chain information in the coming years [35]. In addition, organisations targeting carbon neutrality must include value-chain emissions of individual emissions sources contributing greater than 1% of the total emissions [38]. A 2022 survey of Irish organisations with emissions targets found that value-chain emissions comprised approximately 80% of their total emissions, with *'purchased goods and services'* as the second highest emissions source [39]. Of the 406 companies that set science-based targets in 2022, 96% included value-chain emissions in their carbon accounting [40]. Increasingly, many organisations are future-proofing against tightening regulations by decarbonising their value chain.

This has implications for value chain organisations, where failure to reduce their own emissions may lead to loss of supplier contracts and consequently revenue.

2.2.2.6 *Summary*

There is a two-pronged incentive for industrial decarbonisation in the form of top-down motivation on the industrial sector (principally through the SDGs and more tangibly through Ireland's carbon budgets), and bottom-up motivation on individual organisations; this is shown graphically in Figure 2.3. Both of these forms of motivation are underpinned by a strong financial component—either directly from the cap-and-trade carbon markets in the case of ETS members, and carbon tax savings for non-ETS members; and indirectly from loss of sales and supplier contracts.

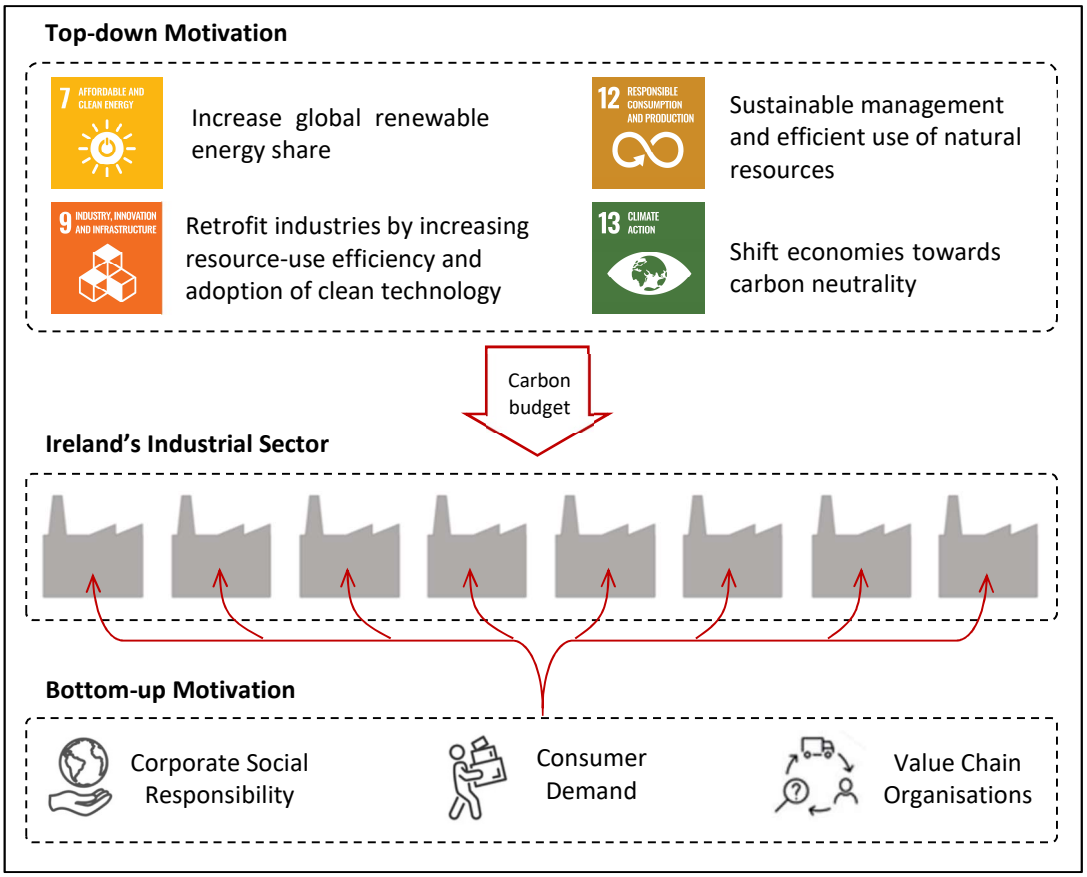


Figure 2.3: Motivation for industrial decarbonisation

Industrial decarbonisation relies on the understanding of the type and category of emissions sources to ensure that the organisations takes responsibility for all relevant emissions. Accordingly, a discussion of emissions scopes is provided in the following sub-section.

2.2.3 Emissions scopes

The Environmental Protection Agency (EPA) of Ireland requires reporting of the emission levels of the six main GHGs stipulated in the Kyoto Protocol, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) [41]. Historically, emissions reduction efforts have been hindered by a lack of accountability as many organisations have been reluctant to consider emissions emanating from their value chains [42]. Since value chain emissions are typically the highest contributor to organisational emissions and the most difficult to define [43], leaving these emissions unmanaged could significantly undermine emissions targets. To address this, the GHG Protocol proposed a classification system in 2001 to group emissions according to their source [37]. The aims were to define organisational boundaries and assign responsibility accordingly, as well as to aid organisations in identifying and managing these emissions. GHG emissions are classified into three categories or scopes. Scope 1 emissions are direct emissions from sources owned or controlled by the organisation. Scope 2 emissions are indirect emissions emanating from the generation of purchased utilities. Scope 3 emissions are indirect emissions associated with the organisation's value chain. The definition and examples of the emission sources are provided in Table 2.2 for each scope.

Table 2.2: Categories of greenhouse gas emissions [37]

Scope	Emission Type	Examples of Emission Sources
1	Direct emissions from sources owned or controlled by the organisation	• Stationary combustion: fuel burned in equipment such as furnaces, boilers, gas turbines • Mobile combustion: fuels burned by motor vehicles, aircraft, ships • Industrial processes: manufacturing, chemical production, oil and gas refineries

		• Fugitive emissions leaked to the atmosphere
2	Indirect emissions	Generation of imported electricity, heating, cooling, steam, compressed air
3	Indirect emissions in the organisation's value chain: upstream - goods and services purchased; downstream - goods and services sold	Employee commuting, business travel, outsourced wastewater treatment, outsourced solid waste disposal, transportation and distribution of goods

This scope definition enables organisations to better understand their emissions sources and to identify broad areas for possible future action, which increases the likelihood of pursuing decarbonisation. Decarbonisation can be guided by relevant standards and protocols, as discussed in the following section.

2.2.4 Standards and Protocols

Different standards apply to the related strategies of carbon neutrality and net zero, where standards for the former have been developed first as a foundation from which to develop the more stringent net zero standard. 'ISO 14068-1:2023 – Climate change management – Transition to net zero – Part 1: Carbon neutrality' provides a framework for achieving carbon neutrality, and is applicable to organisations [13]. The framework specifies commitment to short- and long-term targets as well as a target year by which emissions have reduced to a residual level. The framework specifies the use of a science-based pathway in which emissions reduction within the organisational boundary is prioritised, followed by emissions removal within the organisational boundary, and finally offsetting the remaining emissions. An example pathway is shown in Figure 2.4.

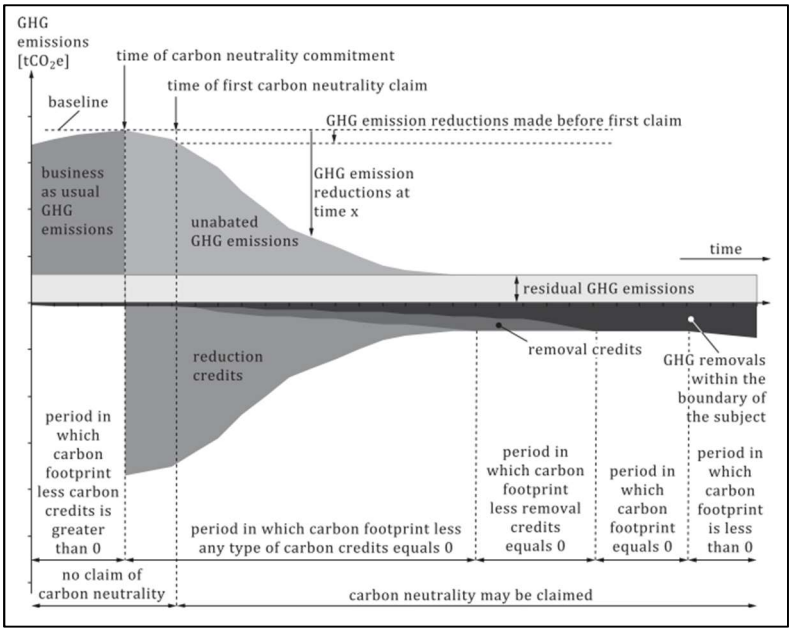


Figure 2.4: Carbon neutrality pathway [13]

'ISO IWA 42:2022(E) – Net Zero Guidelines' provides a set of best practices with which to steer organisations in planning for net zero [44]. The key guidance spans five categories—Levels and Boundaries, Leadership and Commitment, Targeting, Mitigation, and Counterbalancing Residual Emissions. The mitigation guidance focusses on ensuring that an achievable plan is developed in accordance with carbon accounting standards and that sufficient detail is provided with regards to reporting and validating emissions reduction. It encourages early investment in long-term strategies, and specifies that carbon offsetting should be used as a last resort for emissions that cannot be abated by other means. This is high-level guidance rather than detailed technical methodology for achieving net zero. A net zero ISO standard is currently under development to progress and formalise these guidelines, and is due for release at COP 30 in November 2025 [45].

The Carbon Neutral Protocol 2024 offers a framework for organisations targeting carbon neutrality and facilitates a certification program through Climate Impact Partners [46]. The framework comprises a five-step process, in which step 1 involves the definition of the entity to be certified, e.g. organisation, and step 2 involves the calculation of the carbon footprint. Step 3 governs target setting in which a near-term target must be set in accordance with the SBTi, and a long-term target is encouraged. Step 4 involves emissions reduction in the form of the implementation

of emissions-reduction measures and carbon offsetting. The framework promotes the use of expert-based marginal abatement cost curves (MACCs) to evaluate measures for implementation. MACCs are simple and clear visual representations of the trade-off between the economic cost and emissions reduction of various emissions abatement projects relative to a baseline, and thus provide a good overall illustration of the environmental and financial impact of emissions-reduction [47]. Expert-based MACCs present potential projects in ascending order of the net cost of abating one tonne of CO_2 (Figure 2.5). Each project is shown as a single, discrete block, the height and width of which represent the cost and the potential emissions reduction, respectively. The framework offers no further guidance beyond the use of MACCs as the majority of technical guidance in this step relates to carbon offsetting. Finally, step 5 of the framework involves the reporting of the carbon neutrality process for validation, after which the carbon neutral certification is awarded.

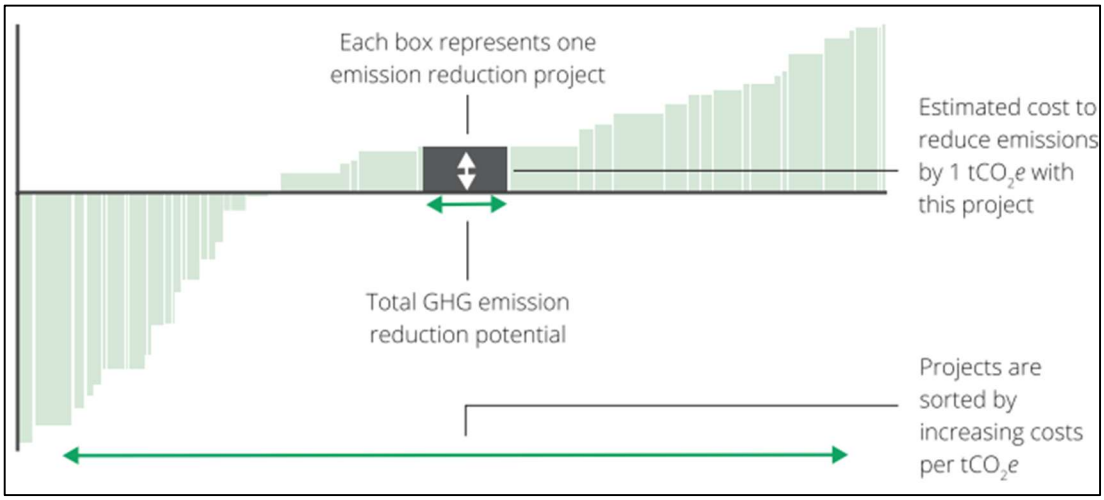


Figure 2.5: Example expert-based MACC [46]

The standards and protocols discussed offer frameworks and guidance, but do not provide a detailed, technical methodology for roadmap development. A framework is a high-level, conceptual structure that provides guiding principles in a flexible approach, whereas a methodology is a prescriptive set of procedures [48]. As such, there are currently no official standardised methodologies for the development of carbon neutrality or net zero roadmaps. However, there are several formal decarbonisation support mechanisms relevant to the reduction of energy consumption and GHG emissions on the global, European, and Irish scale. This refers

to initiatives, campaigns, guidelines, frameworks, standards, and certifications developed or backed by public sector bodies or intergovernmental organisations. These are introduced in the following sub-sections in the order of commitment, management, calculation, target setting, roadmap development, and certification; their relevance to this work is discussed in the summary.

2.2.4.1 *Commitment*

Organisations can make and declare commitments to carbon neutrality by issuing public statements and by further communicating their targets, plans, and progress through environmental, social, and governance (ESG) reports available on dedicated sustainability pages on their websites. In addition, they may pledge their intentions more formally through recognised initiatives or campaigns such as the global Race to Zero and Ireland's Business in the Community (BITC) Low Carbon Pledge.

2.2.4.1.1 Race to Zero

Race to Zero is a global campaign endorsed by the UN that aims to support organisations and other non-state entities in reducing emissions within all scopes, with the overarching target of halving global emissions by 2030 [49]. The campaign is based on a philosophy of transparent member collaboration with the intention that members encourage, support, and empower each other to reach their targets through the sharing of knowledge and resources. Potential members must meet the '5P' criteria of Pledge, Plan, Proceed, Publish, and Persuade. The minimum Pledge criterion for an individual organisation is net zero by 2050, and over 14000 members from 145 countries have made commitments through the campaign thus far. The Plan criterion requires that the decarbonisation plan is published within 12 months; Proceed requires implementation of the plan; Publish requires annual reporting of progress; and Persuade requires organisations to leverage their leadership status to influence others to commit to climate action targets.

2.2.4.1.2 Business in the Community Ireland

BITC is a non-profit organisation driving sustainable change in Irish organisations in support of the transition to a net zero economy [50]. The BITC 'Low Carbon Pledge' is a voluntarily pledge to set SBTs, with the overarching objective to achieve carbon

neutrality. The targets must be set by December 2024, and are based on the full carbon footprint comprising scope 1, 2, and 3 emissions. Organisations require commitment to reduce their direct emissions (scope 1 and 2), contribute to reducing scope 3 emissions within their supply chains, publicly report their progress, and update their emissions-reduction goals in accordance with developing climate science. As of 2023, 70 organisations from eleven industrial sectors have signed the pledge, and half of these signatories have set approved SBTs [50].

These voluntary commitments to decarbonisation require follow through, which can be facilitated by effective energy management to gain understanding of the organisation's energy profile and consumption.

2.2.4.2 *Management*

'I.S. EN ISO 50001:2018 Energy Management Systems – Requirements with Guidance for Use' is a voluntary global standard for energy management in organisations. It details the requirements for the establishment, implementation, maintenance, and ongoing improvement of the energy management system. Specific requirements include the following:

- Development of an energy policy as a framework with which to review the organisation's objectives and energy targets
- Establishment of the organisation's energy objectives, targets, and action plans with consideration of its significant energy uses
- Review of energy consumption and identification of possible energy performance improvements
- Determination of energy performance indicators
- Planning and control of operations associated with the SEU
- Evaluation of energy performance through monitoring, measurement, and analysis of energy data
- Management review of the energy management system to enable a continuous energy improvement cycle

The implementation of an energy management system enables organisations to improve their energy efficiency and reduce their energy consumption in line with

their own objectives. [37] These actions, targets, and information gained are vital to reduce energy consumption, and they provide a good foundation for emissions reduction and contribute to the setting of achievable emissions targets.

2.2.4.3 *Calculation*

Organisational carbon footprints should calculated in accordance with an internationally recognised methodology. The recommended standard, protocol, and guideline are presented in 2.2.4.6 within the context of achieving carbon neutrality.

2.2.4.4 *Target Setting*

Increasing global uptake of corporate net-zero commitments has led to concern over greenwashing through inconsistency in the corporate interpretation of net zero. The Science Based Targets initiative (SBTi) ameliorates this concern by motivating the private sector to set science-based emissions-reduction targets (SBTs) based on the latest climate science aligned with the Paris Agreement. The SBTi Corporate Net-Zero Standard is a global standard that aims to provide a science-based framework for the setting of these SBTs [51]. The four pillars of the standard are the near-term SBT (5-10 year targets), long-term SBT (2050 target of 90% emissions reduction from a 2020 baseline to a residual level), neutralisation of residual emissions (removal and storage of atmospheric carbon), and beyond value chain mitigation (emissions-reduction measures acting outside the value chain). The SBTi proposes the following five-step process for the setting of SBTs [51]:

- Select the base year as a comparison for emissions reduction.
- Calculate total emissions comprising all scope 1 and 2 emissions and mandatory scope 3 emissions.
- Set target boundaries – Near-term SBTs must include a minimum of 95% of scope 1 and 2 emissions to align with the IPCC pathway to limit global temperature rise to 1.5 °C above pre-industrial levels. SBTs must be set for scope 3 emissions only if they comprise 40% or greater of the total emissions; in this case, the relevant SBTs must address a minimum of 67% of the total scope 3 emissions and align with the IPCC 2 °C pathway. Long-term SBTs must

include a minimum of 95% of scope 1 and 2 emissions, as well as 90% of scope 3 emissions, which all align with the 1.5 °C pathway.

- Select the target year for each near-term NBT within a range of 5-10 years, and the long-term target year as any year up to 2050.
- Set SBTs using proposed target-setting methods.

The progression from setting targets to achieving them requires the development of a roadmap that plans the implementation of specific emissions-reduction measures. This development process would benefit from following a comprehensive methodology.

2.2.4.5 *Roadmap Development*

Although the Carbon Neutral Protocol promotes the use of the MACC (Figure 2.5), this is visualisation tool to aid roadmap development, rather than a roadmap itself. Consequently, organisations must currently rely on available guidance and their own experience and knowledge to develop roadmaps in the absence of an established technical methodology. However, the achievement of carbon neutrality as an organisation must be certified against a recognised standard.

2.2.4.6 *Certification*

'ISO 14064-3 – Greenhouse Gases – Part 3: Specification for the verification and validation of greenhouse gas statements' is used for the verification and validation of GHG reduction claims at the organisational level, and details the process from the perspective of the verifier/validator [13]. Although it is not a dedicated certification program for carbon neutrality, it authenticates the claim. As discussed in section 2.2.4.5, the Carbon Neutral Protocol 2024 awards carbon neutral certification to qualifying organisations. However, 'PAS 2060 – Specification for the demonstration of carbon neutrality' neutrality' is the most globally recognised certification standard for carbon neutrality [52]. It requires reporting of all Scope 1 and 2 activities and all Scope 3 activities that contribute more than 1% of the total emissions; activities contributing less than 1% may be excluded provided the total carbon footprint accounts for at least 95% of all emissions. The standard stipulates the following steps for carbon neutrality certification of organisations.

1. Define the boundaries of the organisation to facilitate categorisation of the activities into the three emission scopes.
2. Determine the carbon footprint of the organisation using an internationally recognised methodology. The following three methodologies meet the requirements of PAS 2060 and are recommended within the standard:
    a. BS EN ISO 14064-1 Part 1: Specification with guidance at the organisational level for quantification and reporting of greenhouse gas emissions and removals [53].
    b. GHG Protocol Corporate Accounting and Reporting Standard [37].
    c. UK Government Environmental Reporting Guidelines [54].

    Both the GHG Protocol Corporate Accounting and Reporting Standard and the UK Government Environmental Reporting Guideline are lengthy documents that appear to provide high levels of guidance compared to BS EN ISO 14064-1. Moreover, the GHG Protocol Corporate Accounting and Reporting Standard is the most widely used methodology globally. However, alternative methodologies may be used provided they meet the requirements of PAS 2060.
3. Establish a carbon footprint management plan, and declare commitment to carbon neutrality in compliance with the PAS 2060 specification.
4. Implement measures to reduce the carbon footprint, and determine the effectiveness of these measures.
5. Recalculate the carbon footprint of the enterprise using the chosen methodology to determine the residual GHG emissions.
6. Balance the residual GHG emissions by carbon offsetting, using schemes that meet the requirements of PAS 2060.
7. On achievement of carbon neutrality, validate and declare this achievement in the manner specified in PAS 2060.

The PAS 2060 process for carbon neutrality is illustrated in Figure 2.6, where the carbon footprint management plan is highlighted as the pathway to carbon neutrality. The standard and methodologies include examples of GHG-reduction initiatives—such as energy demand and use and management, fuel switching and

substitution, and waste minimisation [38]. However, they do not provide detailed steps or guidance for emissions reduction, and the development of this plan is the responsibility of the organisation.

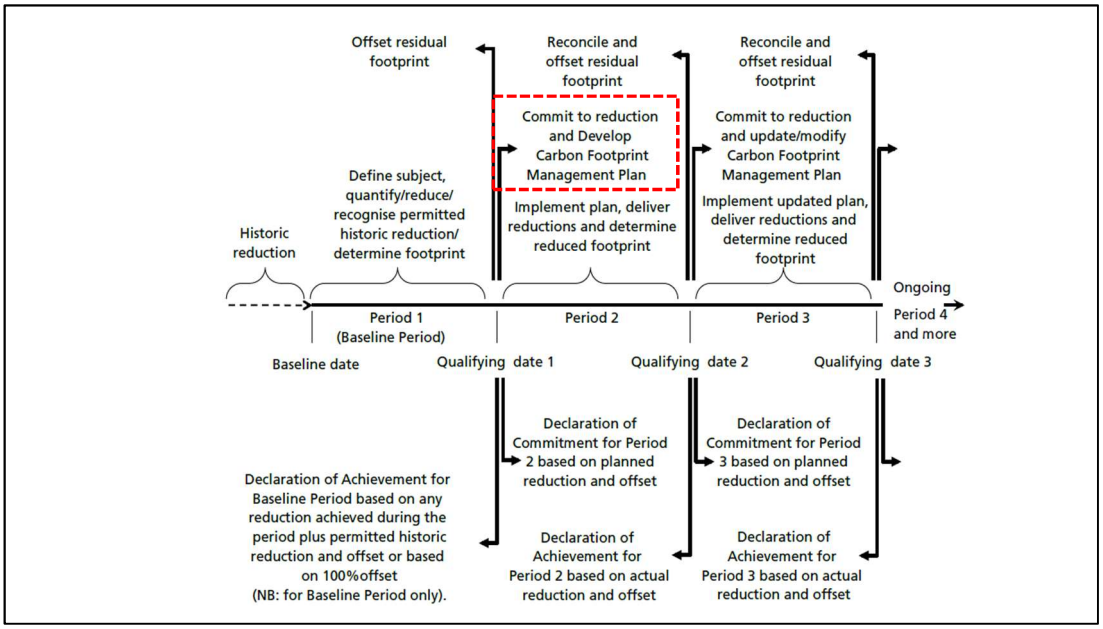


Figure 2.6: Cyclical process for demonstrating carbon neutrality, taking into account permitted baseline period exceptions [38]

2.2.4.7 *Summary*

Existing initiatives, campaigns, guidelines, standards, frameworks, standards, and certifications are vital to a net-zero industrial sector as they provide support for organisations aiming to achieve carbon neutrality or net zero. However, they do not provide a technical, industry-focused, step-by-step methodology for achieving carbon neutrality. Figure 2.7 shows how the current formal decarbonisation support mechanisms aid the process of carbon neutrality in Ireland, and highlights the need for technical guidance in developing roadmaps to deliver results.

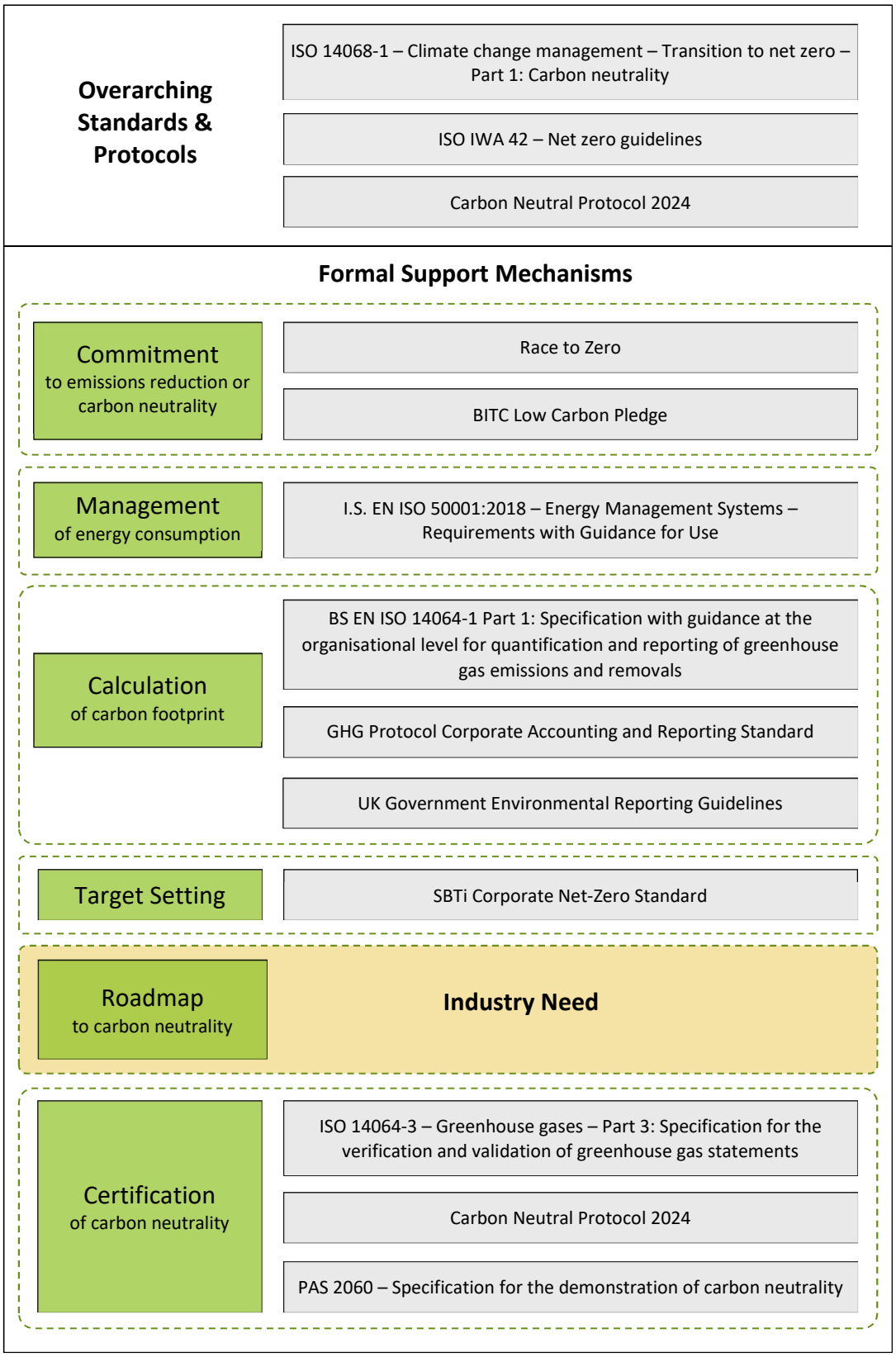


Figure 2.7: Applicability of formal decarbonisation support mechanisms relative to Ireland

2.3 Decarbonisation methodologies for the industrial sector

It is clear from the standards and certifications that there is a policy and industry gap regarding decarbonisation methodologies. This section addresses the following research question to ascertain if there is a sufficient associated scientific challenge:

'*RQ1: What methodologies exist to support industrial organisations in achieving carbon neutrality?'*

The following subsections detail decarbonisation practices and methodologies applicable to the industrial sector, and discuss the associated non-energy benefits.

2.3.1 General measures

There are well-known, independent emissions-reduction measures that can be applied across organisations and industrial sites, such as replacing existing lighting with LEDs, electric cars, employee green travel rewards, and reduced packaging. These are considered to be the easy targets in that they are not specialised measures, and they often form the starting points for decarbonisation. However, these are likely to be standard practice in organisations further along their decarbonisation journey to the point of targeting carbon neutrality. The implementation of these general emissions-reduction measures on a sporadic basis is preferable to following a business-as-usual approach. However, these are independent measures and additional benefit may be derived from exploring management systems that focus on streamlining processes and thereby increasing operational efficiency.

2.3.2 Quality management

Quality management can be described as '*the act of overseeing all activities and tasks that must be accomplished to maintain a desired level of excellence*' [55], and it is supported by various methodologies. Although emissions reduction is not the primary focus of these methodologies, it is often a co-benefit of the process optimisation and waste elimination principles of quality management [56]. ISO 50001 includes some form of quality management is as the energy management standard is based on the continual improvement framework. [57]

Lean manufacturing is a quality management principal aimed at maximising value by minimising waste and improving process efficiency. In 2018, Garza-Reyes conducted a survey of 250 organisations around the globe to determine the impact of the five most popular lean manufacturing tools (Just-In-Time (JIT), autonomation, kaizen/continuous improvement (CI), total productive maintenance (TPM), and value stream mapping (VSM)) on four environmental metrics (material use, energy consumption, non-product output, and pollutant releases) [56]. They found that TPM and JIT had the highest impact in terms of energy reduction, but that VSM was the most widely used lean tool. VSM presents a current state map and an ideal future map based on improved processes, and this graphical scenario representation aids decision making [58]. Various VSM tools that include sustainability aspects have been proposed over the last decade, the latest of which is the 2024 contribution from Silva et al. wherein the Value Stream Mapping for Sustainability (VSM4S) tool was developed [59]. It incorporates a sustainability metric into traditional value stream mapping to extend the impact beyond economic factors. The tool was deployed on a single manufacturing organisation and was found to yield good results.

Six Sigma (SS) is a continuous process-improvement concept based on the principle that process variation may cause errors which present as product defects, and this jeopardises customer satisfaction [60]. It is data-driven approach presented as a step-by-step methodology. Lean Six Sigma (LSS) is a combined approach to continuous quality management in which both waste and defects are minimised to yield improvements in performance, customer satisfaction, and cost [61]. Green Lean Six Sigma (GLSS) incorporates the benefits of each named paradigm, where lean minimises waste, green quantifies the environmental impact, and SS provides a structured methodology. In 2022, Rathi et al. proposed a GLSS framework that incorporates environmental and social sustainability metrics. The current state map is generated using environmental value stream mapping (EVSM) to evaluate waste levels as well as lifecycle assessments and social lifecycle assessments to evaluate the environmental impact and social sustainability, respectively. This framework was successfully applied to a manufacturing organisation and is sufficiently generic to be suitable across the manufacturing sector. [62]

In 2023, Utama and Abirfatin proposed Sustainable Lean Six Sigma (SLSS) as a novel framework to aid sustainable manufacturing performance. Its novelty lies in calculating the manufacturing sustainability index based on relevant sustainability indicators to assess performance, and mapping this performance using sustainable VSM. A case study was leveraged to assess the performance and applicability of SLSS, and it was found to positively impact manufacturing performance. [61]

These quality management tools may improve energy monitoring and management, streamline manufacturing processes, and identify scenarios for energy efficiency, but decarbonisation is not their primary focus. In addition, they target the demand side and they do not consider supply-side solutions such as new technology or renewable energy alternatives.

2.3.3 Energy Hierarchy

The energy hierarchy was developed by the Institute of Mechanical Engineers in 2009 and updated in 2020. It comprises five tiers: (1) Energy demand reduction, (2) Energy efficiency, (3) Utilisation of renewable sustainable resources, (4) Utilisation of other, low-GHG-emitting resources, and (5) Utilisation of resources as we do now [63]. These tiers are organised based on preferred order of use for energy and carbon management, and do not offer detailed steps that can be applied at the organisational level. The 'Sufficiency, Efficiency, Renewables' (SER) framework extends the technological principles of the energy hierarchy to include broader sustainability aspects [64]. It was developed as a multifaceted, holistic approach to the transition to a sustainable energy system, where sufficiency is a non-technological concept of sustainable resource consumption that relates not only to demand reduction, but to resource distribution and management. Efficiency refers to the optimisation of technologies to reduce energy intensity, and renewables refers to the use of renewable energy to reduce reliance on fossil fuel.

2.3.4 Pillars of decarbonisation

The pillars of decarbonisation are complementary actions that form the foundation of deep decarbonisation [65]. Although various sources define different numbers of pillars depending on the level of detail, the Clean Energy Transition Unit defines the

following five pillars of decarbonisation: energy efficiency, clean energy, electrification, clean fuels, and carbon capture [65]. These pillars are interconnected and are not weighted according to potential impact. Consequently, they represent a broad range of core strategies in a systemic rather than structured approach to decarbonisation.

2.3.5 Sector-specific guidelines of energy intensive industries

EIIs comprise steel; chemicals; cement; aluminium; other non-ferrous metals; oil refineries; pulp, paper, and cardboard; glass; ceramics; and other minerals. Given their specific processes and high contribution to sectoral and national GHG emissions, the relevant industry bodies and associations typically offer decarbonisation guidelines to address the unique challenges of each EII. The decarbonisation pathways of sector associations represent bottom-up approaches, wherein they focus on measures specific to the processes in each sector, which may not be applicable outside of the industry. For instance, The European Cement Association's 2050 roadmap focusses on ways to reduce GHG emissions for each of its five parameters/processes (clinker, cement, concrete, construction, and re-carbonation) [66]; however, these are presented as individual steps that can be taken for each process rather than a step-by-step pathway to carbon neutrality.

In addition, academic literature regarding industrial decarbonisation appears to have a strong focus on EIIs. In 2019, Gerres et al. reviewed and compared 40 EII decarbonisation pathways and roadmaps of various countries and associations [67]. They noted that the approaches of the countries differ, but they tend to focus on top-down strategies—such as the German Federal Environmental Agency's proposal to use renewable methane as syngas—that are not specific to industry sectors; however, these pathways typically lack the detailed technology required to achieve the proposed strategies. Johnson et al. analysed and compared 29 EII decarbonisation roadmaps developed for 13 member countries of the Leadership Group for Industry Transition [68]. The evaluation criteria were decarbonisation target, implementation cost, and main decarbonisation measures. They found that most roadmaps address all three criteria from a high level perspective, but lack detail

and prioritisation. In addition, the measures identified require industry-wide adoption to be feasible. Kloo et al. reviewed 14 roadmaps aimed at the decarbonisation of Europe's chemical sector, generated from 2017 to 2023 [69]. They found that there was no consensus on the importance of different strategies, and that the focus was on decarbonisation measures targeting the supply side rather than demand reduction and energy efficiency measures. In 2024, Maghrabi proposed a framework for the continuous performance improvement of thermal-EIIs through the optimisation of energy efficiency [70]. First, a top-down approach is applied to identify performance gaps through peer benchmarking of equipment efficiency and emissions intensity, process design, plant operation and maintenance, and products. Then, design improvement studies in the form of pinch analysis, steam system optimisation, and residual waste heat recovery are conducted to yield recommendations to address the performance gaps identified. Hubner et al. developed a five-step decarbonisation methodology for the ceramics industry [71]. First, decarbonisation goals are set (step 1), and potential emissions-reduction measures are identified through literature research and networking with similar organisations (step 2). These are presented as MACCs, from which the measures are prioritised and then assessed for interactions and adjusted accordingly (step 3); the transformation path is developed based on the chosen measures (step 4). Finally, consensus is sought for the corporate transformation to mitigate any economic barriers to the implementation of the technical roadmap (step 5).

The European Commission investigated the scaling up of innovative technologies applicable to targeting climate neutrality in EIIs. The study was based on 180 installed projects using decarbonisation technologies, where the projects act as demonstrators of the technologies. It was limited to industrial demonstrators funded by EU instruments, and these demonstrators were mapped to the following six technology pathways for climate neutrality [72]:

- Green hydrogen integration – Green hydrogen technologies are represented in most EIIs, and are most prevalent in the steel and chemicals sectors.
- Circularity – This refers to the creation of sustainable closed-loop systems that optimise resource use and minimise waste generation within a value

chain or industrial sector, or across sectors where it is known as industrial symbiosis. Circularity is predominantly represented in the chemicals industry.

- Carbon capture utilisation and storage (CCUS) – CCUS is applicable to EIIs as they are concentrated sources of emissions that are challenging to abate. CCUS exhibits a broad representation across most EIIs, but is most concentrated in the cement sector.
- Energy efficiency – These technologies encompass heat upgrades, waste heat recovery, heat pumps, and the power conversion of waste heat. They are mainly applicable to the steel, non-ferrous metals, and cement sectors, but are present in all EIIs.
- Digitalisation – Digitalisation refers to the transformation of the business model by integrating digital technologies into business processes. It aids decarbonisation through measures such as process optimisation, improved resource management, emissions monitoring. Digitalisation exhibits some crossover with other technology pathways (energy efficiency and electrification), and is most well represented in the steel industry.
- Electrification – Electrification technologies in the context of EIIs refer to the use of electrically powered equipment for industry-specific process traditionally powered by fossil fuels, such as electric steam crackers in the chemical sector and electric arc furnaces in the steel sector. These technologies are predominantly applied to the chemicals and steel sectors.

There are three EU-funded projects relevant to Ireland that act as demonstrators for decarbonisation of EIIs. AAL SEB involves the decarbonisation of high-pressure steam in an aluminium foundry by means of replacement of a gas boiler with an electric boiler. COGNIPLANT is an advanced monitoring and control system applied to industrial plants to manage energy and resources. The REALISE project aims to decarbonise refineries across the EU through CCUS, and has been implemented at an oil refinery in Cork.

There is a strong focus on reducing emissions of EII sectors and this is evidenced by numerous methodologies in academic literature. However, the applicability of these methodologies is restricted to the specific industry it addresses.

2.3.6 Academic contributions at the organisational level

In a 2022 study, Seyfried et al. investigated the climate neutrality approach of 50 industrial organisations, and noted that there is no consistent approach [5]. They found that there is a focus on the transition to renewable energy, with electrification as the most relevant approach; however, there is a financial barrier to the adopting renewable technologies. They concluded that there is limited conversion of the goals into action. Hechelman et al. proposed a universal framework for the development of organisation-specific decarbonisation pathways [6]. This was based on the philosophy that pathways must be developed on a case-by-case basis to be effective. Consequently, they propose a top-down approach informed by brainstorming workshops in which potential emissions-reduction measures are identified. The environmental and financial impacts of these measures are then evaluated further and a MACC curve is derived. The implementation strategy is to implement all measures with a negative avoidance cost, and then evaluate the remaining measures for prioritisation. A further study by Hechelmann et al. conducted in 2023 explored the decarbonisation strategies of manufacturing organisations from a technical and economic perspective [73]. They noted that existing studies either presented theoretical concepts with no foundation of empirical data, or focussed on a single industrial sector. Further investigation in this work agrees with the statements by Seyfried et al. and Hechelmann et al. in that there is a lack of generalisable methodologies, and academic contributions relevant to decarbonisation strategies may yield options for implementation but typically fall short of roadmap generation. In addition, academic contributions are often presented as case study models that have been devloped for specific organisations; these case study models are discussed further in the modelling section (section 2.4.4.2).

Two recent review papers provide a comprehensice overview of relevant existing literature. A 2023 systematic review on deep decarbonisation at the organisational level found yielded 370 papers related to decarbonisation, of which only 49 were categorised as deep decarbonisation responses to climate change. Deep decarbonisation in this context refers to significant emissions reduction, and the search terms were designed to include absolute reduction, carbon neutrality, and net

zero. The remaining papers were categorised as conventional responses which are defined as actions that do not result in CO_2e reductions [74]. Deep decarbonisation responses were only noted from 2014, indicating its emergence as a relatively new research area. Analysis of the literature found the most common themes to be drivers, actions, barriers, and facilitators of decarbonisation. Of particular relevance to this work are actions and facilitators. Actions are categorised as administrative (target setting, data collection and monitoring, and management systems); applicative (energy efficiency, process improvement, product innovation, and renewable energy); communicative (reporting, political activities, and public relations and marketing); and collaborative (company participation, supply chain coordination, carbon trading, and carbon offsetting). Actions in the deep decarbonisation literature predominantly relate to the administrative and applicative categories and focus on sector-specific approaches, but seldom incorporate multiple actions into a cohesive approach. Facilitators are categorised as organisational change (top management commitment, and high ambition); organisational capabilities (knowledge and learning, shared vision, R&D/innovation, long-term focus, and stakeholder engagement); and external support (public policies, synergistic relationships, and public grants and resources). The literature very rarely mentions shared vision, R&D/innovation, and long-term focus despite their importance in facilitating deep decarbonisation. A later study presents a critical review of climate change mitigation strategies at the organisational level and proposes a comprehensive framework for the implementation thereof [75]. The framework comprises six phases as the ideal steps of an organisational climate change mitigation strategy: 'Frame' which defines the goals and scopes; 'Measure' which comprises GHG accounting, 'Analyse' which evaluates the current strategy, 'Commit' which sets targets, 'Implement' which develops a roadmap, and 'Report' which involves monitoring progress and reporting and verification. Existing schemes are evaluated against these steps, subject to the following inclusion criteria: the methodology must be publically available and address at least one of the six phases at the organisational level. A total off 25 schemes were identified, with only 14 applicable to organisations in all sectors (the remaining are strictly applicable to financial institutions). Of these, only nine methodologies include a step for goal

setting and scope definition. Critically, no single scheme adequately addresses all six phases of the organisational climate change mitigation strategy. With the exception of the GHG Protocol, all schemes were presented post-2015, with early offerings focussing on GHG emissions accounting and more recent offerings focussing on emissions targeting. The proposed framework does not explicitly target the industrial sector and there is no reference to a modelling tool or method of generating decarbonisation roadmaps. Two research gaps relevant to this work were identified in this study—the lack of scientific guidance and holistic standards for decarbonisation strategies at the organisational level; and the lack of integration of organisational climate-related actions with broader geographic scales (sectoral, national, and global). Overall, the two reviews discussed highlight that deep decarbonisation is an emerging research field with considerable potential for further exploration and development.

2.3.7 Irish Public Sector Organisational Roadmaps

The public sector contributions to organisational guidance and roadmap development is discussed in the following sub-sections.

2.3.7.1 *Government of Ireland – Organisational roadmap*

The Department of Enterprise, Trade, and Employment of the Irish Government released the 'Roadmap for the Decarbonisation of Industrial Heat' in June 2024 as a guideline for industrial organisations to contribute towards the emissions targets for the industrial sector on the path to net zero. The plan comprises the following five steps, which are recommended to be taken following consultation with a local government enterprise agency for support [76]:

- Assess – Conduct an energy audit of the facility.
- Plan – Create a schedule of decarbonisation projects by prioritising efficiency projects and including fuel switching projects.
- Invest – Implement energy efficient measures, energy efficient design, and fuel switching away from fossil fuels. Electrify heat streams below 150 °C using heat pumps and electric boilers where possible, or make use of biomass or Biomethane.

- Communicate – Report decarbonisation goals and strategy in accordance with reporting requirements, and communicate these to customers and stakeholders.

This roadmap presents a structured plan with detailed measures on how to achieve decarbonisation. However, it is limited to heat and does not address alternative sources of emissions. Moreover, it provides no means of scenario modelling or assessing different implementation options, and relies on the support of local agencies.

2.3.7.2 *Sustainable Energy Authority of Ireland – Organisational roadmap*

The Sustainable Energy Authority of Ireland (SEAI) is currently developing the Emissions Evaluation Methodology (EEM) as a decarbonisation guide for organisations, specifically member organisations of the Large Industry Energy Network (LIEN) [77]. A draft EEM was reviewed for this work, and has been circulated to the LIEN Network. The draft EEM comprises the following five steps:

- Step 1: Establish baseline carbon footprint
- Step 2: Estimate projected carbon footprint – This is based on the business-as-usual scenario taking into account changes in production and activity levels, as well as building and site size.
- Step 3: Set carbon footprint target – This is in the form or percentage reduction in emissions. The target is generally set using a top-down approach based on EU or national targets, carbon budgets, or corporate targets in the case of multi-national organisations.
- Step 4: Develop and implement decarbonisation pathway and actions – The pathway steps in priority are to reduce energy demand, recover thermal energy, and replace fossil fuel energy with renewable energy; there is a concurrent process of redesign which is applied at each step.
- Step 5: Monitor decarbonisation progress – Progress is monitored in a continual process of comparison and corrective action to ensure that the emissions targets are achieved.

The EEM provides a structured methodology for decarbonisation, but does not provide a detailed process for the development and implementation of decarbonisation pathways and actions in step 4, and it does not specifically address carbon neutrality.

2.3.8 Private consultants

Private consultants provide a bespoke service to industrial organisations based on the site's specific operational landscape, energy consumption, and emissions. They leverage their expertise and knowledge of the technical, commercial, and regulatory environment to develop customised decarbonisation roadmaps. They can assist in the evaluation and selection of new technologies that are most suitable for the application with regards to cost, energy consumption, and emissions, as well as provide advice on the integration of renewable energy. From an economic perspective, they can assess the cost-benefit and return-on-investment of identified decarbonisation measures, and provide funding support. Further services may include long-term support through project management at the implementation stage of the pursued decarbonisation measures, and ongoing monitoring and reviewing to enable continuous improvement.

2.3.9 Non-energy benefits

Energy audits yield registers of performance improvement measures, where multiple measures may address the same technology or process. Consequently, a robust and thorough decision-making process is important to ensure optimal investment. The implementation of energy efficiency measures may yield additional non-energy benefits (also termed 'productivity benefits', 'co-benefits', or 'ancillary benefits') which could impact investment decisions if adequately identified, categorised, and quantified [78]. Non-energy benefits have been explored in an industrial context since 2000, where early publications focussed on the identification of these benefits, without classification or quantification. Examples of identified non-energy benefits include lower maintenance [79] and emissions savings [80]. Several investigations have been conducted using case studies to quantify non-energy benefits. Some studies evaluated their effect on the payback period, and found reductions of 32%

[81] and 55% [82]; another study found that non-energy benefits comprised 24% of the total benefits [80]. In 2003, Worrel et al. investigated the non-energy benefits of industrial energy efficiency measures [83] using 77 case studies available in the literature. They found 224 unique non-energy benefits and categorised these benefits as waste, emissions, operations and maintenance, production, working environment, and other. In addition, they proposed a four-step framework for the economic evaluation of these benefits. First the non-energy benefits are identified and described; then, the impact of each tangible benefit is quantified; following this, all assumptions required to determine the economic impacts from the benefits are identified; and finally, the economic impacts of the productivity benefits are calculated. The US iron and steel industry was used as a means to evaluate the framework, based on data available in the literature from 47 energy efficiency measures. Bottom-up energy consumption supply curves (CSCs) were used as the means of evaluation, where the quantity of conserved energy attributed to each efficiency measure is plotted against the cost per energy unit. A baseline curve was constructed for the iron and steel industry using the energy-only cost. A second curve was constructed using the revised cost calculated using the framework to include non-energy benefits. Comparison of the two curves indicates that the inclusion of non-energy benefits doubles the cost-effective potential for energy efficiency measures. However, they noted that the negative impacts should be quantified and included; examples include the risk associated with investment in new technology, additional operator training, and production losses stemming from production shutdown to install new equipment. A 2017 systematic literature review on the additional benefits of investment in energy efficiency measures noted the following highest mentioned benefits within the categories defined by Worrel et al. [78]:

- Work environment – decreased noise, improved worker safety, improved lighting, improved temperature control, reduced need for personal protective equipment, and improved air quality
- Production – improved productivity, improved product quality, improved reliability, increased product output/yields

- Operations and maintenance – reduced production costs, reduce wear and tear on equipment1, reduction in labour requirements
- Waste – use of waste fuels, reduced product waste, reduced waste water, reduced hazardous waste, materials reduction
- Emissions/environment – reduced emissions, reduced dust emissions
- Other – improved worker morale/motivation, decreased liability, improved public image, delaying/reducing capital expenditure

The study noted the importance of the level of quantifiability of non-energy benefits since tangible benefits such as reduced production costs are easy to quantify, whereas less tangible benefits such as an improved work environment are more difficult to quantify but are important. The study proposes a framework to categorise the benefits of energy efficiency measures with consideration of the level of quantifiability (low, medium, high) and the timeframe of the effect of the benefit (short-term, long-term). As such, the framework allows non-energy benefits to inform investment decisions.

In a different strategy, multi-criteria decision-making (MCDM) approaches have been applied in several studies to evaluate energy efficiency projects according to sustainability benefit; however, the majority of these studies address the building, commercial, and public sectors [84]. The most recent and applicable of these studies is the 2024 work by Kshanh and Tanaka in which they proposed a two-stage MCDM methodology for the prioritisation of industrial energy efficiency projects based on the inclusion of sustainability criteria [84]. The first step of the methodology involves determining applicable criteria; this was achieved by refining the criteria most prevalent in the literature by engaging with global energy efficiency experts to score each criterion in terms of applicability and then selecting the highest scoring criteria. The determined sustainability criteria are economic (implementation cost, energy cost savings, fund availability i.e. government grants, and project lifetime); environmental (emissions reduction, water savings, utilisation of clean and renewable energy); socio-political (regulatory requirement, impact on organisational reputation, and impact on employment); and technological (technological availability, impact on maintenance and operation, and implementation time). The

second step of the methodology is the calculation of the criteria weights using a fuzzy analytic hierarchy process (FAHP) applied to qualitative data. The final step of the methodology is the MCDM approach which uses quantitative data to rank the energy efficiency projects. Three industrial case studies were leveraged for validation of the FAHP, and in all cases the economic and environmental criteria proved to be the highest weighted, with relevant sub-criteria of energy costs savings and emissions reduction. One of these case studies, a petrochemical facility, was expanded to test the MCDM approach, and it was found that energy efficiency projects involving operation and maintenance should be prioritised.

This literature on non-energy benefits lists emissions reduction as a co-benefit of energy efficiency measures. However, this work focuses on emissions reduction to the extent of carbon neutrality, which encompasses but is not limited to energy reduction. As such, additional non-energy benefits are valid consequences of some emissions-reduction measures and are important to note. However, the scope of this work is limited to emissions reduction and the financial impact thereof as the driving factors for carbon neutrality. While non-energy benefits are considered to be beyond the scope, this work does inherently includes the following non-energy benefits as identified by Kshanh and Tanaka: implementation cost, energy cost savings, fund availability, emissions reduction, utilisation of clean and renewable energy, and implementation time.

2.3.10 Summary and Research Gap

With such a strong focus on reducing emissions of EII sectors independently, there appears to be a lack of focus on structured, cross-sectoral pathways to emissions reduction that could also address less energy-intensive industries in the manufacturing sector. The energy hierarchy provides a high-level prioritisation of measures for energy management, but detail regarding the achievement of these measures is lacking. Similarly, the SER framework provides high-level guidance, but lacks further detail. The pillars of decarbonisation and general emissions-reduction measures represent independent strategies for emissions reduction rather than structured pathways. Quality management systems yield energy and consequently

emissions reductions as additional benefits rather than the main target, and they do not address supply side measures. Although the SEAI EEM is cross-sectoral and aimed at the organisational level, it is still in development. The Government of Ireland contribution is limited to industrial heat and does not address all potential emissions sources. Private consultants are costly and the investment in bespoke solutions may be a barrier for organisations in the initial stages of carbon neutrality planning. Thus, there is a clear policy gap and industry need which has not been addressed by state or commercial offerings. From a scientific perspective, the academic methodologies reviewed are limited and do not include generalisable modelling tools, rendering them inapplicable to organisations beyond the case studies leveraged. This scientific challenge is further indicated by the lack of robust deep decarbonisation methodologies aimed at the organisational level, as emphasised in two recent review papers; these reviews offer a comprehensive evaluation of existing literature which ensures that all relevant research is included and that the identified research gaps genuinely exist. Critically, none of the methodologies reviewed—with the possible exception of private consultants—include references to modelling tools with which to predict the environmental and financial impact of decarbonisation. As such, no single methodology can currently be followed from the point at which an organisation expresses an interest in carbon neutrality to the point of obtaining an organisation-specific carbon neutrality roadmap and financial analysis. Following a single methodology for the carbon neutrality journey ensures efficiency and consistency in aligning the modelling with the previous methodology steps, thereby reducing potential overlap and mitigating against potentially differing model objectives and user input requirements. Thus, there appears to be a research gap for an open-access, detailed, cross-sectoral methodology with reference to a modelling tool, which is applicable to all stages of carbon neutrality planning at the organisational level in industrial manufacturing. This research gap is illustrated by the comparison of existing tools in Table 2.3, and the following research objective is defined accordingly:

'RO1: Development of a methodology to aid non-EII industrial organisations in planning carbon neutrality'

Table 2.3: Research gap

Tool/Methodology	Stepwise approach	Cross-sectoral	High detail	Publically available	Emissions focus (all sources)	Emissions modelling tool
General measures	×	✓	×	✓	✓	×
Quality management	✓	✓	✓	✓	×	×
Energy hierarchy	×	✓	×	✓	✓	×
Pillars of decarbonisation	×	✓	×	✓	✓	×
EII sector associations	✓	×	✓	✓	✓	✓
Academic methodologies	✓	✓	✓	✓	✓	×
Government of Ireland	✓	✓	✓	✓	×	×
SEAI	✓	✓	×	×	✓	×
Private consultant	✓	✓	✓	×	✓	✓
Research gap	✓					

From this review, it is evident that any proposed methodologies should include modelling tools as a means to generate organisation-specific models.

2.4 Energy Modelling

This section addresses '*RQ2: What existing mathematical and commercial modelling resources are applicable to individual organisations, and what level of detail do they contain?*'

2.4.1 Background

Energy modelling tools in the industrial context address the technical, economic, and social aspects of energy consumption. For the purposes of this work, these are divided into past-, current-, and future-horizon tools according to the time horizon of the generated models. Past-horizon energy modelling tools quantify, characterise, and facilitate the reporting and management of the current impact of the entity being modelled. The most prevalent past-horizon energy modelling tool relevant to this work appears to be carbon accounting software which calculates greenhouse gas emissions from recorded data for a specific past year, and may identify significant

energy users and emitters. The outputs from these past-horizon modelling tools can form the bases for current- and future-horizon energy modelling tools. Current-horizon energy modelling tools include energy management software which monitors energy consumption from current recorded data, predicts energy consumption, and sets performance targets and tracks progress. Future energy modelling tools have considerably longer time horizons in that they predict possible future energy scenarios by simulation of energy systems or by optimisation modelling of various criteria. Carbon and emissions management software straddle the current and future time horizons since they calculate and track current emissions, set long-term emissions-reduction targets, and provide possible solutions. Future-horizon modelling tools in the climate change space can be used to evaluate the effects of implementing measures in response to climate change. The United Nations Framework Convention on Climate Change (UNFCCC) categorises these modelling tools according to their focus and inclusion of broader sustainability facets [85]. Climate change models can be divided into two main areas of focus—predominantly socio-economic models such as integrated assessment models (IAMS) and energy-environment-economy (E3) models; and energy (or energy systems) models which typically prioritise technical and economic parameters [85]. In this work, energy modelling tools are further categorised according to the geographic scales at which they are aimed. The high geographic scales can be considered as global, regional, national, municipal, and clusters; the low geographic scales can be considered as industrial parks and individual organisations. The typical temporal and geographic distribution of the relevant energy modelling tool types is shown in Figure 2.8. (Note that only modelling tool types that consider industrial GHG emissions or the energy system as a whole are mentioned; those that focus on aspects of the energy system—such as the power system and electricity market models—are not considered.)

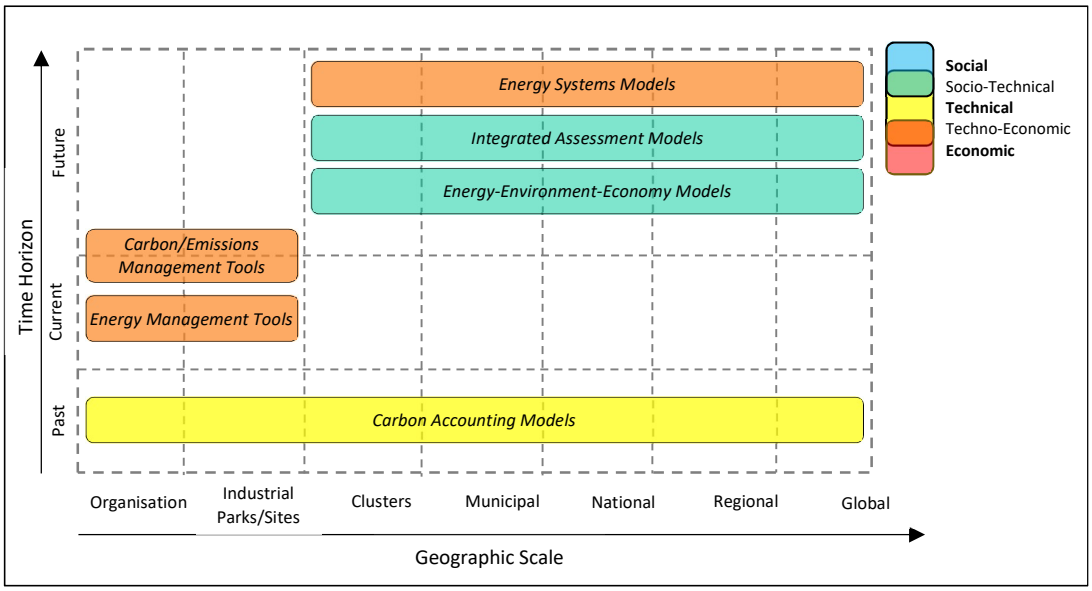


Figure 2.8: Temporal and geographic distribution of energy modelling tools

As a progression from RO1 and in accordance with RQ2, this discussion focusses on current- and future-based modelling tools with a focus on technical and economic aspects since these are the likely the most relevant focus areas for industrial organisations targeting carbon neutrality. Specifically, carbon/emissions management tools, energy management tools, and energy systems modelling tools are explored to determine their applicability at the organisational level and to assess their functionality with regards to carbon neutrality. It should be noted that some model generators/tools discussed in this section are referred to as models in their official names.

The type of modelling tool output varies according to tool function; however, the MACC is often used at the high- and low-geographic scale as it a popular tool for decision-makers to determine the most cost-effective measures to reduce emissions. MACCs can be derived through energy models (top-down approach) or through expert knowledge (bottom-up approach). Model-based bottom-up MACCs are derived from partial equilibrium simulation or optimisation engineering models, and present as smooth, piecewise graphs. Although they are technology oriented, only the absolute emissions reduction is indicated on the graph (i.e. no individual measures are shown). Bottom-up approaches are technology-focussed, and can be further categorised according to their source. Expert-based bottom-up MACCs are heuristic models developed using expert engineering knowledge (Figure 2.5).

2.4.2 Energy Management Tools

Energy management tools encompass energy monitoring and targeting software as part of a continuous improvement cycle (→ Measure → Analyse → Take Action →) to optimise energy consumption and cost [86]. Monitoring involves regular collection of energy consumption data from meters, cost data from utility bills, and data of additional metrics that affect energy consumption. Targeting involves setting energy consumption targets which can be achieved through various techniques, the most effective of which is often multivariate regression analysis based on historical data [86]. The software compares and analyses the actual and targeted energy consumption, and reports to relevant stakeholders in various forms such as control charts, cumulative sum control charts (CUSUM), energy consumption heat maps, and overspend tables. [86]. This feedback provides insight into energy-saving and cost-reduction opportunities, and highlights system inefficiencies and deviations from expected data patterns. Numerous energy monitoring and targeting tools have been developed with this common basic functionality.

2.4.3 Carbon or Emissions Management Tools

Carbon or emissions management tools can be viewed as an extension of carbon accounting tools in that they often include carbon footprinting calculations to use as a baseline for target setting. Additional offerings include setting emissions-reduction targets, tracking progress, and scenario modelling. There are numerous commercial software and tools available, as well as two open-access tools developed by public institutions for use in Ireland; these are discussed in the following sub-sections.

2.4.3.1 *Commercial carbon or emissions management tools*

It should be noted that all commercial platforms are proprietary software and access is through paid subscription or direct appointment of their services. Thus, these tools could not be explored fully, and consequently the level of detail in the calculations of the generated outputs is unclear. The following discussion is based on available information. A 2024 article by the sustainability data hub 'KnowESG' listed the following as the top sustainability platforms: Persefoni, Microsoft Cloud for Sustainability, Salesforce Net Zero Cloud, IBM Environmental Intelligence Suite,

Sphera, and Sinai Technologies [87]. Amongst other products, Persefoni offers the 'Net-Zero Navigator' for decarbonisation management [88]. This generates decarbonisation pathways in line with custom or SBTi targets based on industry type, emissions data, and decarbonisation targets. These pathways appear to use generic decarbonisation measures specific to each industry. The Microsoft Cloud for Sustainability comprises tools to '*enable ESG data intelligence, deliver sustainable IT systems, improve ESG performance, and unlock sustainable growth*' [88]. Relevant functions include carbon accounting of scope 1, 2, and 3 emissions; setting of emissions targets; and monitoring of decarbonisation progress. Scenario modelling is offered to forecast the emissions impact of various actions. Finally, sustainability insights are offered in the form of comparison of an organisation's most recent energy and emissions data with that of previous years, as well as benchmarking against similar organisations. The functionality does not appear to extend to the generation of decarbonisation pathways. The Sphera platform offers ESG reporting through corporate sustainability software, and carbon accounting through environmental accounting software [89]. However, neither of these appear to address decarbonisation. Salesforce's Net Zero Cloud platform facilitates the setting, of science-based targets; carbon accounting of scope 1, 2, and 3 emissions; emissions forecasting; and scenario analysis based on user-defined percentage reductions of emissions-producing activities. The relevant IBM platform is the IBM Envizi ESG Suite which offers emissions management, ESG reporting, and decarbonisation [90]. The decarbonisation feature includes automatic utility data capture, emissions management and monitoring, and sustainability benchmarking. In addition, it offers ESG forecasting using a range of planning tools applicable to different stages of planning, although the structure and output of these tools is unclear. Sinai Technologies claims to have developed '*the world's first decarbonisation platform that goes beyond the standard GHG emissions inventories and reporting offered by other GHG emissions management software providers*' [91]. This claim is supported by the 2021 award of World Economic Forum technology pioneer [92]. The platform offers a set of five tools aimed at organisations—'inventories' assists with the measurement and reporting of scope 1, 2, and 3 emissions; 'baselines' forecasts and compares emissions trajectories of the business-as-usual scenario and the

decarbonisation targets; 'low-carbon scenarios' explores decarbonisation opportunities and the cost thereof; 'carbon pricing' determines the organisation's internal carbon price for financial modelling; and 'value chain management' facilitates the collection of primary scope 3 emissions from upstream and downstream sources and uses global databases to estimate unknown values. SINAI Technologies clearly offers useful decarbonisation data from which to make informed business decisions. However, the most relevant modelling tool to this work is the low-carbon scenario modelling for emissions reduction, the output of which is a MACC from which it appears the user is required to select decarbonisation opportunities.

2.4.3.2 *Open access tools*

In 2021, the Government of Ireland launched the Climate Toolkit 4 Business, an open-access online initiative aimed to support business in their climate action endeavours. The toolkit uses the average annual electricity and gas consumption, refuse weight, vehicle fuel volume/cost and business flight details, and water consumption to calculate the carbon footprint. It then provides an action plan of emissions-reduction measures, and the user manages the implementation of these measures through the user portal, where links to further relevant information is provided. However, these recommended measures are generated from a master list of 22 predefined, high-level measures typical to Irish business sectors. Consequently, this is an entry-level toolkit with the goal of introducing and promoting climate action at the organisational level. [93]

The SEAI released an Excel-based tool for its LIEN members in 2023, with a dual function of reporting as part of the LIEN programme and emissions evaluation to generate a decarbonisation plan. The reporting section of the tool requires inputs for energy performance, savings, and end use to feed into the LIEN annual review. There are two input sections for the decarbonisation plan. 'Energy Growth' captures the effects of facility or production expansion in terms of the energy (fuel) type and additional quantity to calculate the business-as-usual emissions scenario. 'Savings' captures the organisation's decarbonisation projects; these are input according to the energy type, energy savings quantity, and project category. The category options

are: Reduce (Energy Conservation), Reduce (Energy Efficiency), Recycle (Heat Recovery), Refuel (Fuel Switching), and Refuel (Renewable Energy). The energy growth and savings inputs are used to generate a decarbonisation plan which graphically indicates the emissions reduction attributed to each category in the form of line and waterfall graphs. This decarbonisation tool is limited to energy and emissions and provides no indication of the financial impact. [94] It should be noted that this tool is not publically available outside of the SEAI LIEN members and that it was released after the methodology and modelling tool papers emanating from this work were published. Any similarities can be viewed as validation of this work and as an indication of the important and relevance of this study area.

2.4.3.3 *Summary*

A comparison of the proprietary and open-access carbon and emissions management tools is shown in Table 2.4 in terms of the decarbonisation pathway generation capabilities. Approximately half of the tools evaluated do not generate decarbonisation pathways; the data visualisation and scenario modelling yield insights to inform user decision-making. The tools that do offer pathway generation are typically based on generic emissions-reduction measures, which is a high-level approach that may not be suitable beyond an entry-level exploration of carbon neutrality. The LIEN tool is deemed the most applicable although there is no consideration of financial impact of the pathway generated. Thus, decarbonisation pathway generation at the organisational level can be viewed as limited in existing tools. Modelling tools aimed at higher geographic scales are worth exploring to gauge their functionality and applicability at the organisational level.

Table 2.4: Comparison of decarbonisation pathway generation in carbon and emissions management tools

Tool	Accessibility	Decarbonisation pathway description
Persefoni Net-Zero Navigator	Proprietary software	Pathway generation based on generic measures specific to each industrial sector

Microsoft Cloud for Sustainability	Proprietary software	No pathway generation; focus on carbon accounting, setting of emissions targets and monitoring progress
Sphera	Proprietary software	No pathway generation; focus on ESG reporting and carbon accounting
Salesforce Net Zero Cloud	Proprietary software	No pathway generation; focus on carbon accounting, setting of emissions targets, monitoring progress, and scenario analysis
Sinai Technologies	Proprietary software	Scenario modelling output as a MACC from which the user selects decarbonisation measures
IBM Envizi ESG Suite	Proprietary software	ESG scenario modelling and forecasting; the tools used and generated output are unclear
Climate Toolkit 4 Business	Open access	Pathway generation based on generic high-level measures
LIEN decarbonisation tool	Open access	Pathway generation based on user input; does not consider financial impact

2.4.4 Energy Systems Modelling

Energy system models are simplified, quantitative representations of complex energy systems, developed using mathematical equations, unique data, and assumptions [95]. The modelling tools used to generate these models encompass a broad range of public, commercial, and academic contributions. Energy system modelling tools and models can address either the complete energy system or focus on a single or multiple energy sectors (electricity, transport, residential, commercial, industry, or agriculture). They can be characterised according to various parameters, including:

1. Technological detail – The level of technological detail in a model can be described as bottom-up, top-down, or hybrid. Top-down approaches are more general with a broader focus and consider macroeconomic variables in a decomposition approach. Their low level of technological detail means that

they are best-suited as an assessment tool for the socio-economic impact of energy and climate policies. Bottom-up approaches are technologically explicit with narrow focus of a specific subsystem, and can expand upwards to include more of the system in a composition approach. They do not consider macro-economic impacts, and thus are best suited as energy planning tools. Hybrid approaches encompass both top-down and bottom-up approaches, either by linking or integrating models, to provide a holistic view of future energy systems. [96]

2. Modelling tool structure – Pfenninger et al. categorised energy systems models into four groups, namely energy systems optimisations models, energy systems simulation models, power systems and electricity market models, and qualitative and mixed-methods scenarios [97]. The most prevalent structures are optimisation and simulation models. Optimisation models are highly structured models that numerically optimise an objective function within a set of constraints, whereas simulation models predict system behaviour based on various scenarios. Energy systems optimization models (ESOM) are partial equilibrium models that generate least-cost pathways for energy systems; they model possible energy futures to provide insight to inform policy and guide energy system development. Simulation models of energy systems show the response of the energy system to predefined inputs to aid understanding of system operation. [98]
3. Geographic scale – Model generators/tools are applicable to a range of geographic scales—global, regional, national, municipal, clusters, and individual project—with some targeting a single scale and others applicable to multiple scales. Individual energy system models are applicable at the particular scale defined by the project scope and input data.

Numerous simulation and optimisation modelling tools, models, and commercial software have been developed for scenario modelling and decarbonisation pathway generation for a range of energy sectors. For the purposes of this work, relevant contributions are discussed in the following sub-sections according to their geographic scale. At the high geographic scale (global, regional, national, municipal),

energy system models form an evidence base to aid policy- and decision-makers in short- and long-term energy system planning as part of the sustainable energy transition to achieve net zero emissions. At the low geographic scale (individual projects or project clusters), energy models are an effective support tool to provide insight for decarbonisation goal-setting and to generate decarbonisation pathways.

2.4.4.1 *High geographic scale*

The majority of existing modelling tools and generated models appear to address the higher geographic scale at the global, regional, country, and municipal levels. The UNFCCC highlights the following energy models: MARKAL, Model for Energy Supply Strategy Alternatives and their General Environment (MESSAGE), Prospective Outlook on Long-term Energy Systems (POLES), Price-Induced Market Equilibrium System (PRIMES), Strategic Assessment Framework for the Implementation of Rational Energy (SAFIRE), Very Long-term Energy Environment Model (VLEEM), and World Energy Model (WEM), as well as a number of models that are applicable to specific non-European countries [99]. In 2021, Plazas-Nino et al. conducted a systematic literature review on optimization modelling of national energy systems, and found the five most popular optimisation frameworks and modelling tools globally to be MARKAL, The Integrated MARKAL EFOM System (TIMES), MESSAGE, Open Source Energy Modelling System (OSEeMOSYS), and Global Energy System Model (GENeSYS-MOD) [100]. All studies modelling Ireland's energy system used TIMES. Although this study focussed on national energy systems, many of the modelling tools are applicable at the regional and global levels. A 2010 systematic review of energy systems models highlighted an additional simulation modelling tools for discussion—the Low Emissions Analysis Platform (LEAP) [101]. Fattahi et al. analysed 19 energy system models in terms of capability to model the transition to a low-carbon energy future [102]. They used multi-criteria decision analysis with the criteria of 'technological detail and learning, temporal resolution, spatial resolution, social parameters, modelling methodology, data source, accessibility, and application'. The five highest scoring models are PRIMES, Renewable Energy Mix (REMix), the MARKAL family of models, METIS, and Energy System Simulation (ENSYSI). Other notable modelling tools developed for use at the high geographic

scale include EnergyPLAN and the MACC, as well as the National Energy Modelling Framework (NEMF) developed specifically for Ireland [103]. Some of the optimization and simulation energy systems models mentioned are not applicable beyond the country for which they were developed; only the current modelling tools and generated models most relevant to Ireland for energy systems modelling at the high geographic scale are discussed further in the following sub-sections.

2.4.4.1.1 EnergyPLAN

EnergyPLAN is a simulation energy systems modelling tool that was designed for energy systems with high renewable energy shares, with the majority of case studies centred in European countries [104]. It targets the national scale, although it is applicable at other geographic scales from municipal to regional. It forms the basis of Heat Roadmap Europe, which is study of the decarbonisation of Europe's heating and cooling sectors [105].

2.4.4.1.2 LEAP

LEAP is a simple, accounting framework modelling tool with low data requirements that is predominantly used for simulation, although the latest versions supporting optimisation modelling [106]. LEAP has been used in over 190 countries, from the municipal up to the global scale over the medium- to long-term [106]. Locally, the LEAP Ireland 2050 Model was developed using the LEAP software to create policy-guided scenarios as an aid for climate policy decision-makers [107].

2.4.4.1.3 Marginal abatement cost curve

The MACC is an approach rather than a modelling tool, where each MACC is an individual model specific to its application. MACCs are applicable at any geographic scale, depending on the scope of the modelling tool or expert knowledge from which they are generated. Jiang et al. conducted a systematic review of MACCs from 1993 to 2018, and found that the following geographic breakdown: global (29.4%), country (46.9%), region (2.8%), with the remainder comprising intra- and international curve comparisons [108]. The most well-known MACCs at the high geographic scale are the expert-based MACCs developed by McKinsey & Company in 2007 and updated since—a global curve and 14 country curves [109]. From the Irish perspective,

McKinsey's MACCs form the modelling foundation for Ireland's Climate Action Plans [110].

2.4.4.1.4 MARKAL/TIMES

The MARKAL/TIMES family of model generators were developed by collaboration between The Energy Technology Systems Analysis Program (ETSAP) and the International Energy Agency (IEA). The TIMES model generator is the current version and the successor to the MARKAL model generator. TIMES is a bottom-up ESOM tool that generates models of possible energy futures based on different scenarios, either to meet a defined carbon budget or emissions target or to analyse the effects of implementing specific policies. It is a partial equilibrium model that uses linear programming in a combined technical and economic approach to meet the objective function of minimising loss of surplus. TIMES has been used to generate energy system models at the global, regional, national, and municipal levels to aid policy-making. Locally, the Irish TIMES Model was developed during the period 2009 – 2017 to provide an evidence base to inform climate and energy policy [111]. This evolved into The TIMES-Ireland Model (TIM) in 2021 to address tightening decarbonisation ambitions and to include technological progress and improvements in energy systems modelling strategies [112].

2.4.4.1.5 MESSAGE

MESSAGE is a bottom-up, optimisation modelling tool for energy systems planning, evaluation of energy policy, and scenario modelling over the medium- to long-term at the global, regional, and national scale. It has a particular focus on green technologies. MESSAGE has been used in the Global Energy Assessment, and it is one of six models used in the development of the Intergovernmental Panel on Climate Change (IPCC) global emissions pathways. [99]

2.4.4.1.6 METIS

METIS was developed by the European Commission's Directorate-General for Energy as an in-house modelling tool to simulate the short-term operation of the European energy system. It can be applied at the regional, national, and multinational levels for hourly simulations of the electricity, gas, hydrogen, and heat systems; and the energy markets. [113]

2.4.4.1.7 OSeMOSYS/GENeSYS-MOD

GENeSYS-MOD as the successor to OSeMOSYS is an open-source, bottom-up, cost-optimisation modelling framework that focusses on three sectors—energy, heat, and transportation. It generates long-term, low-carbon scenarios for a wide geographic scale, from the household to the organisational to the global geographic level. [114]

2.4.4.1.8 NEMF

NEMF was developed by the Sustainable Energy Authority Ireland (SEAI) to model Ireland's energy system and inform national policy. It combines a top-down macro-economic model and bottom-up sectoral energy models to project energy supply and demand based on different scenarios [115]. NEMF has contributed to numerous national studies, including heat studies, the development of decarbonisation pathways, the EPA's emissions projections, and Ireland's National Energy and Climate Plans [103].

2.4.4.1.9 POLES

POLES is a global, partial equilibrium, simulation modelling tool that has been in use for over two decades to develop long-term scenario models of energy supply and demand and emissions levels [104]. POLES-JRC is the latest evolution of the tool, developed through funding by the European Commission's Joint Research Centre [104]. It has a global, regional, and national scope, encompassing 66 regions composed of 54 countries [104]. It is decomposed into sectors, with the industrial sector comprising four areas, the first three of which are energy-intensive industries—iron and steel, chemicals, non-metallic minerals, and other industry (other manufacturing, mining, construction) [104]. An area of particular relevance is the modelling of the adoption of new technologies [99]. POLES was used to generate all projections in the European Commissions' World Energy Outlook 2050 [116] and its Global Energy and Climate Outlook 2022 [104].

2.4.4.1.10 PRIMES

PRIMES is a hybrid, partial equilibrium model that simulates market equilibrium to predict energy balances for Europe as a region and for individual countries at the national level [117]. It forms part of the model suite used by the European Commission, with a particular focus on policy impact and emissions trading [118]. It

has contributed to the 'formulation' policy cycle within the 'climate action', 'energy', and 'transport' policy areas [118]. In addition, PRIMES is the modelling foundation for the EU Reference Scenario 2020, in which it is used to project a possible future outlook of the EU energy and transport systems, and emissions levels [119]. PRIMES comprises a number of modules that can function independently on the sector level. Of relevance is PRIMES-Industry, which encompasses ten industrial sectors (predominantly energy-intensive industries) that are further divided into 31 sub-sectors based on processing type. The module offers 234 energy process technologies and 22 fuel options, and considers new technologies, energy efficiency, heat recovery, electrification, and alternative fuels to solve for the energy system for each sector. [119]

2.4.4.1.11 WEM/ETP/GEC

WEM was the first modelling tool developed by the International Energy Agency (IEA) to simulate energy markets. This was followed by the development of the Energy Technology Perspectives (ETP) bottom-up modelling tool with a high technology focus; this was used as a complementary approach rather than a replacement. The current approach in all IEA publications is the Global Energy and Climate (GEC) model—a bottom-up, partial-optimisation, WEM-ETP hybrid modelling tool for long-term sectoral, national, regional, and global scenario modelling. [120]

2.4.4.1.12 Summary

A comparison of the energy systems modelling tools and models applicable to the high geographic scale is shown in Table 2.5.

Table 2.5: Comparison of modelling tools and models at the high geographic scale

Tool	Modelling Tool Type	Generated Models
EnergyPLAN	Simulation	Heat Roadmap Europe
LEAP	Simulation & Optimisation	LEAP Ireland 2050 Model
MACC	n/a	McKinsey MACC in Ireland's Climate Action Plans

MARKAL/TIMES	Optimisation	The TIMES-Ireland Model
MESSAGE	Optimisation	Global Energy Assessment; IPCC Global Emissions Pathways
METIS	Simulation	European Commission system models
OSeMOSYS/GENeSYS-MOD	Optimisation	Various low-carbon models
NEMF	Simulation	EPA emissions projections; National Energy & Climate Plans
POLES	Simulation	European Commissions' World Energy Outlook 2050; Global Energy and Climate Outlook 2022
PRIMES	Simulation	EU Reference Scenario 2020
WEM/ETP/GEC	Optimisation	International Energy Agency models

2.4.4.2 *Low geographic scale*

The low geographic scale deals with individual projects or sites. Within the context of this work, this refers to modelling tools and models developed for industrial parks and individual industrial sites. In addition to some of the modelling tools discussed in the previous section, the following are applicable at the low geographic scale. (Note that these are academic models since developed software at this scale is discussed in section 2.4.3 as it is typically marketed as carbon- or emissions-reduction software.) Ayoub et al. developed a framework to generate decarbonisation roadmaps applicable to estates comprising individual commercial sites [121]. It is presented as a case study of 60 supermarkets in the UK, where the electricity and natural gas consumption and profiles are the primary model input to form the database. Technology replacement scenarios are modelled in the form of photovoltaic and combined heat and power systems. Then, a mixed-integer linear programming (MILP) optimization model is used to generate the optimal overall investment plan for the estate over the specified time period; the plan details the technology replacement for each supermarket. The framework includes a high-level tool in which emissions reduction measures are limited to technology replacement

(PV and CHP only), with no consideration of energy efficiency projects. Moreover, it is not aimed at individual sites, and as such the significant energy users and alternative measures to address the associated emissions are not identified. Wei et al. developed a roadmap to carbon neutrality and an MILP optimisation model for industrial parks, based on energy, economic, and environmental analyses [122]. The optimisation model considered ten typical carbon emissions neutralisation schemes and found that the optimal scheme is based on electrical generation from the power grid and PV panel, and heat from natural gas. However, case studies of industrial parks in various locations showed that the generalisation of the optimal model is limited as a result of poor solar radiation in some areas. They recommend using a weighting system for cost and emissions in future research to optimise the solution. A 2023 study explored the decarbonisation strategies of manufacturing organisations from a technical and economic perspective [73]. It noted that existing studies either presented theoretical concepts with no foundation of empirical data, or focussed on a single industrial sector. In response, an in-depth analyses of eight manufacturing organisations was conducted to develop decarbonisation pathways based on MACCs. The study concluded that MACCs are a good tool with which to prioritise emissions-reduction measures and that the approach used is generalizable globally to organisations in all industrial sectors. However, the decarbonisation strategy for each case study was developed over 40 days, and it is acknowledged that an automated approach might be required. The academic literature reviewed comprises either modelling tools that do not consider demand side measures, or organisation-specific models developed on a case-by-case basis; these are summarised in Table 2.6. No mathematical models pertaining to the generation of decarbonisation roadmaps were found; this is in line with the 2023 study by Hechelmann et al. that stated models should be generated case-by-case to be effective and implementable [6].

Table 2.6: Summary of academic models applicable to the low geographic scale

Study	Description	Applicability & Reason
Ayoub et al. [121]	Modelling tool (MILP optimisation)	Not applicable as only considers supply side measures in the form of technology investment
Wei et al. [122]	Modelling tool (MILP optimisation)	Not applicable as only considers supply side measures in the form of technology investment; specific to industrial parks
Hechelmann et al. [73]	Models	Not applicable as organisation-specific

In addition, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories emphasises that modelling accuracy is improved when based on national data, assumptions, and context [123]. As such, decarbonisation planning tools developed for global use may not applicable to all countries owing to differing regulations and policies, emissions factors, and the readiness level and availability of decarbonisation technologies [124].

2.4.5 Summary and Research Gap (Modelling Tool)

The existing simulation and optimisation modelling tools most applicable to industry in Ireland are shown at their target geographic levels in Figure 2.9 to set the scene for the current carbon/emissions management and energy systems modelling. The majority of tools shown are designed for energy systems at the high geographic scale, where the abatement options are broad sector- or system-based abatement options. While some of these modelling tools also function at the organisational or site level, they may be overly complex and cumbersome and lack the required detail (site- or project-specific abatement options) for the site level. Thus, they may be considered as not explicitly relevant to individual industrial sites. Academic contributions are limited to case study models and to modelling tools that do not consider demand side emissions reduction measures. As a result, only proprietary commercial carbon and emissions management tools, and the relatively simple Irish Government and SEAI tools are considered applicable at the site level. National tools provide greater

accuracy owing to their country-specific context. However, the Irish tools lack the capability to perform financial analysis to determine the required investment costs and the potential financial savings attributed to the implementation of emissions-reduction measures. Thus, the literature review indicates that there is a lack of open-access modelling tools aimed at the site level that support a high level of detail to include site-specific industrial processes and equipment. Consequently, the following research objectives are defined:

RO2.1 - Development of a high-level modelling tool to aid non-EII industrial organisations in early-stage carbon neutrality planning

RO2.2: Development of a detailed, project-based modelling tool to aid non-EII industrial organisations in planning carbon neutrality

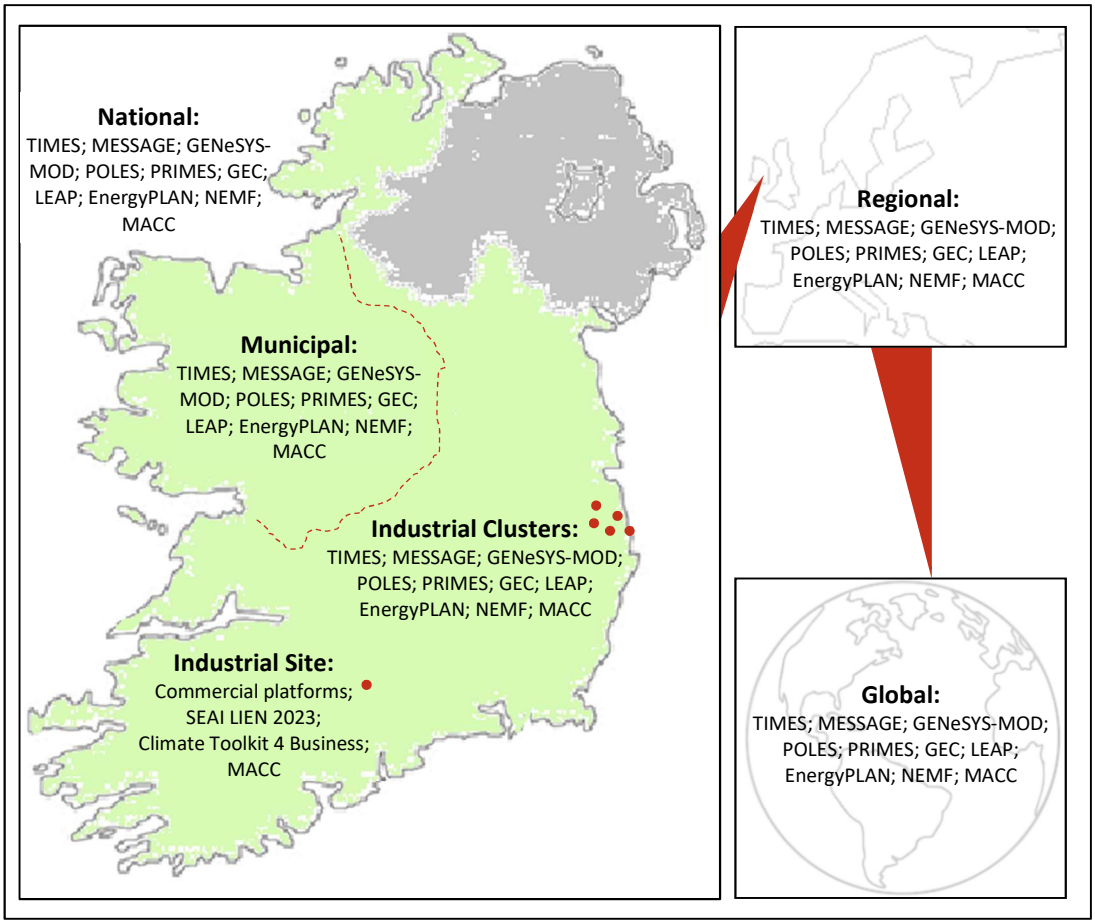


Figure 2.9: Modelling tool geographic levels

Although emissions-based modelling tools showcase the financial and environmental effects of implementing a set of individual measures, the interactions between these

measures can exert considerable influence and drastically affect the results. Thus, methods of resolving interaction effects should be explored.

2.5 Interaction Effects

Lack of consideration of interaction effects between emissions-reduction measures in carbon neutrality planning can lead to the overestimation of potential emissions reduction, resulting in an unexpectedly high emissions balance. This section addresses '*RQ3: How do existing modelling resources consider the interactions between emissions-reduction measures?*'

2.5.1 Background

Inputs to mathematical models may interact with each other to strengthen or weaken the effect of subsequent measures and the model output. The clarification of these interaction effects aids understanding of the relationships between model variables and their effect on the model output. The method of dealing with these interactions is well-documented in prediction modelling, but less so in other types of modelling. The following sub-sections present methods of addressing these interaction effects in prediction models and in the simulation and optimisation models discussed in section 2.4.

2.5.2 Predictive Analytics

Predictive analytics is a statistical approach in which patterns in existing data are analysed to predict future outcomes, and predictive models are the functions that describe these relationships. Predictive models comprise independent predictor variables and a dependent response variable, where the direct influence of the predictor variables on the response variable is known as a 'main effect'. Prediction models can be categorised as classification models which are qualitative and output categorical variables, and regression models which are quantitative and output numerical variables. In multivariable regression modelling, there may be relationships between predictor variables, whereby one predictor variable influences the extent of the impact of another predictor variable on the response variable; this is known as an 'interaction effect'. These interaction effects can result in a

moderation or enhancement of the impact of the predictor variable. Interaction terms are typically only included in the final model if they are statistically significant and they increase the coefficient of determination of the model. The multivariable regression model including interaction effects can be expressed as follows. [125]

$$\hat{y} = a + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \underbrace{\beta_{12} x_1 x_2}_{\text{Interaction term}} + \cdots + \underbrace{\beta_{k-1,k} x_{k-1} x_k}_{\text{Interaction term}} + \varepsilon \qquad \textit{Eq. 1}$$

Where:

$\hat{y}$ = expected y-value

a = y-intercept

β = regression line slope

x = predictor variable

k = number of predictor variables

ε = error term (difference between the estimated and actual y-value)

2.5.3 Interactions in Simulation and Optimisation Models

In the context of this work, simulation modelling replicates individual emissions-reduction measures in a user-defined order and quantity, and optimisation modelling determines the best order and quantity of the measures according to the user-defined optimisation criteria. The input data for both the simulation and optimisation models is theoretical since the measures have not yet been implemented. Thus, the interactions between measures are not intrinsic to the model and there is no generic mathematical method of considering the interaction effects. Lack of consideration of interaction effects yields inaccurate results in simulation modelling, and may result in lesser pathways being presented as the optimal pathway in optimisation modelling. High-level energy system models such as those mentioned in section 2.4.4.1 are likely to have similar functionality with regards to the inclusion of interaction effects. As an example, the MARKAL/TIMES models appear to consider at least the following types of interactions [126] [126]:

- Technological – Interaction effects are considered where existing technologies are replaced by new technologies and where multiple technologies are complementary. In addition, the modelling tool has a

'learning by doing' approach where cost decreases with increased adoption of technology as a result of a greater experience base.

- Economic – Market dynamics are considered to account for supply and demand effects, and the relationship between economic growth and energy demand is discerned.
- Sectoral – Sectors are integrated to account for interactions between measures in different sectors.
- Temporal – Path dependency is taken into account, and short- and long-term effects are differentiated.
- Geographical – The geographical region is considered to determine the applicable policies and the relevant availability of resources.

2.5.4 Interactions in Carbon or Emissions Management Tools

Neither of the Irish Government contributions consider interactions between emissions-reduction measures. Climate Toolkit 4 Business offers high-level, generic measures and these are presented independently. The SEAI LIEN 2023 tool categorises measures input by the user and assimilates the emissions savings into a decarbonisation waterfall with no adjustment. The level of detail in commercial tools is unclear owing to their proprietary nature; however, most of the tool explored in section 2.4.3 do not generate pathways and thus the consideration of interaction effects is not relevant.

2.5.5 Interactions in Academic Contributions

MACCs are a widely used approach with which to prioritise decarbonisation measures [127]. Model-based MACCs are typically presented as pathways and include interaction effects to the extent considered in the models from which they are generated [128]. In contrast, expert-based MACCs typically represent individual emissions-reduction measures rather than pathways [128]. They allow users to visualise the cost and emissions abatement potential of each measure individually to aid decision-making regarding implementation. However, in practice, these individual measures interact to affect the abatement potential of subsequent measures, and ignoring this can lead to double-counting of emissions reduction

[128], as shown in Figure 2.10. Further, they represent a specific point in time and thus do not consider temporal dynamics [128]. The reviewed MACC-based studies applicable at the organisational level consider interaction effects between measures on a case-by-case basis by in-depth analysis combined with expert knowledge [6][73]. However, these studies and others highlight the importance of considering interactions effects in MACCs [71][129] [127].

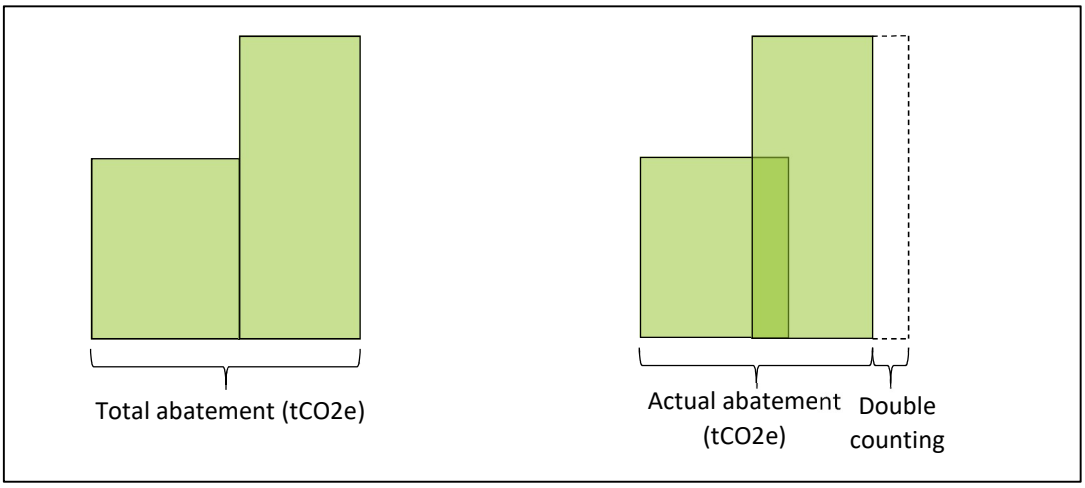


Figure 2.10: Interactions in expert-based MACCs

Hu et al. proposed a methodology of ranking and selecting potentially interacting measures in MACCs by tackling it as a multi-criteria decision-making problem (MCDM) [127] using the criteria of cost and emissions abatement. Sets of correlated measures are created and all combinations are ranked using a multi-objective ranking algorithm to determine the best set of measures to be implemented.

2.5.6 Summary and Research Gap (Interaction Effects)

Resolution of interaction effects within models mitigate the risk to model validity, and sufficient understanding of the subject field is required to incorporate these interactions. The extent of inclusion in modelling tools varies and is not clear for each emissions management and energy system modelling tool explored in this work.

Table 2.7: Summary of interaction effects

Modelling tool	Interactions considered
Predictive analytics	Mathematical model
Optimisation/ Simulation	No inherent consideration
Energy systems models	Technological, economic, sectoral, temporal, geographical
Commercial Carbon/Emissions management software	Not relevant as no roadmap generation, or unclear
Open access Carbon/Emissions management software	Not considered
MACC-based models	Case-by-case
Hu et al. [127]	MCDM

Critically, no heuristic, bottom-up, universal methods of considering interaction effects based on characteristics of industrial processes have been found in the literature or open access models. In response to the lack of or unknown extent of consideration of interaction effects from a practical perspective, the following research objective is defined.

'RO3: Development of a method for the resolution of interaction effects between emissions-reduction measures in a modelling tool to aid non-EII industrial organisations in planning carbon neutrality'

With the establishment of the functionalities and the roles of the modelling tools within the modelling toolkit, it is important to consider software development frameworks as a means to support and communicate the design, implementation, and testing of these tools.

2.6 Software development frameworks

Software development can be framed by recognised design and communication strategies to manage and articulate the process effectively, as well as artificial intelligence (AI) approaches to develop algorithms. Accordingly, software design methodologies, AI approaches, and modelling languages are discussed in the following sub-sections.

2.6.1 Software design methodology

This section compares the existing software design methodologies and discusses the reasoning behind the choice of methodology for the modelling toolkit development.

2.6.1.1 *Comparison of methodology types*

There are two software development methodology types—heavyweight and lightweight. Traditional heavyweight methodologies are highly structured and systematic. These methodologies are driven by the software requirements, which are defined upfront, and a detailed plan of sequential project steps is designed and followed, with minimal changes. High levels of documentation are required and the development process is efficient, predictable, and highly controlled. Heavyweight methodologies are process-focused and the success of projects developed using these methodologies is determined by the extent to which the project plan has been followed. Lightweight methodologies are becoming increasingly popular since they are flexible with a short planning phase and they have low documentation requirements. Since they are not highly structured, project steps can be completed in parallel. These methodologies are user-focused, where user feedback after development iterations can be incorporated quickly to adjust requirements and priorities. [130] The success of projects developed using lightweight methodologies is determined by business value [131].

Akbar et al. compared heavyweight and lightweight methodology types using the six-pointed star model of project management which considers the factors of scope, schedule, budget, risk, resource, and quality [132]. They found that lightweight methodologies are preferable for small-scale projects, and heavyweight methodologies are better suited to medium- and large-scale projects.

2.6.1.2 *Project characteristics and requirements*

The modelling tool development of this work can be classified as a project with a small project team since there is a single developer, and thus heavy documentation and a highly structured approach are not required as a form of team control. Software development needs to be rapid to meet the timeframe of this work. In addition, it needs to be flexible in response to changing trends and legislation

regarding carbon neutrality, as well as to maintain novelty in response to any similar developments emerging in the academic space. High user-feedback is required since this project is being conducted in conjunction with an industry partner who has provided data for use as a case study; there should be an iterative approach where each iteration produces a functional model which can then be improved based on user feedback. For these reasons, a lightweight methodology is more suitable for the project.

2.6.1.3 *Comparison of lightweight methodologies*

There are numerous lightweight software development methodologies; five popular methodologies are described and compared in Table 2.8 [130], and the reasons for their applicability to this project are discussed.

Table 2.8: Comparison of lightweight software methodologies

Methodology	Description	Applicability & Reason
Feature-Driven Development (FDD)	Simple method comprising five processes, conducted incrementally: develop overall model; build feature list; plan by feature; design by feature; build by feature [130]. Method is aimed at large development teams of up to 100 developers [133].	Medium Applicability: FDD is not ideal for small project teams as in this project. It focusses on defining the features upfront.
Test-Driven Development (TDD)	Iterative method that prioritises development of test scenarios, where initial code is tested and only further developed if the test fails. Repeated testing against each iteration yields high-quality code [130].	Low Applicability: The learning curve involved in this approach and the process itself may slow code development; it is unnecessarily time-consuming to develop high-quality code for each step when requirements may change in future steps.
Dynamic System	Uses a rapid application development approach that	Medium Applicability:

Development Method (DSDM)	prioritises the project resources (cost, time) and quality, and provides software functionality within the predefined resources [130]. Method is aimed at large development teams of up to 100 developers [133].	DSDM is not ideal for small project teams as in this project.
Scrum	Iterative method that is highly responsive to changing customer needs. The development phase is divided into sprint cycles, where each cycle adds incremental value and outputs a functional product [130]. Scrum is aimed at small development teams, ideally less than 10 developers [133].	High Applicability: Project approach is to develop functional models that increase in functionality with each iteration, which is in line with the sprint cycles of the scrum method. The scrum responsiveness to changing customer needs is required since the software requirements may change based on ongoing academic research and the industry partner's feedback. Scrum is aimed at small development teams, which suits the single developer of this project.
Extreme programming (XP)	Iterative method with short cycles, based on two core processes: pair programming (one developer reviews code as another writes); and refactoring (code is continuously improved and simplified after unit testing [130]). XP is aimed at small development teams of less than 10 developers [133].	Low Applicability: This project has a single developer and cannot facilitate pair programming.

The scrum methodology is deemed to be the most applicable for the project owing to its flexibility, customer focus, regular output of functional models, and project size. A simple scrum process is shown in Figure 2.11, with the following steps:

- Planning – A product backlog is created in the planning stage to capture the desired functionality set of the tool. Scrum works on an iterative process of developing each functionality in turn in dedicated sprints. Sprint planning involves organising the functionalities into scrum sprints.
- Implementation – The sprint tasks are executed in the implementation phase.
- Review – The software is demonstrated and compared through user acceptance testing to determine if the desired functionality has been met.
- Retrospect – A development team meeting is held to reflect on and assess project and team performance.

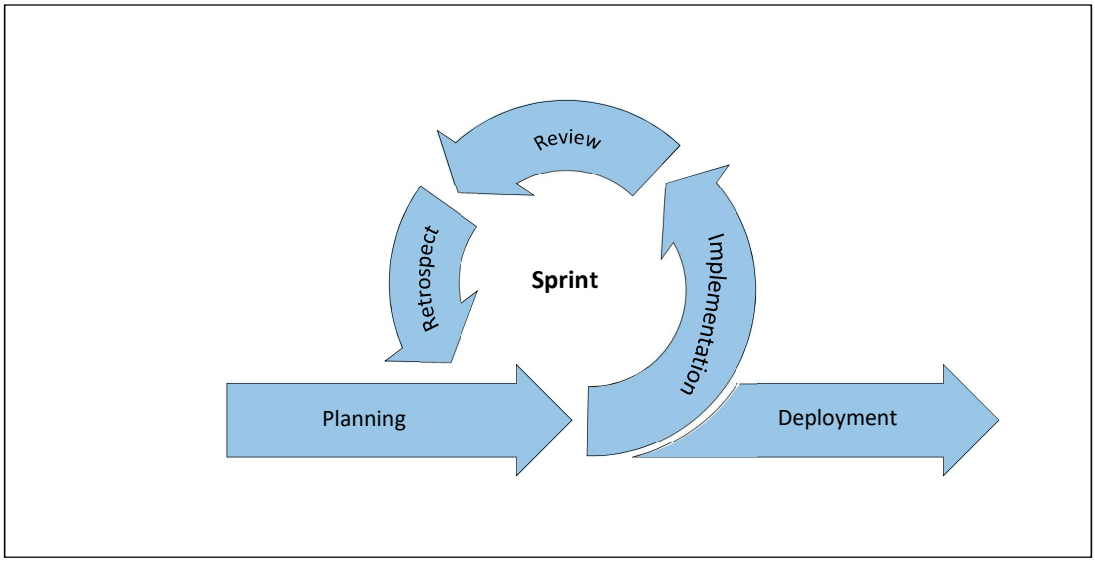


Figure 2.11: Scrum development process

Although software design methodologies provide a structured approach to managing software design, additional approaches are required for algorithm development where AI is used, such as in modelling complex interaction effects between emissions-reduction measures.

2.6.2 AI approach

AI systems can be classified as rule-based or machine learning systems [134]. Rule-based systems follow a knowledge-based approach reliant on expert analysis of the

system to be modelled. A fixed rule set is generated from this expert knowledge, and the system uses it as the foundation from which to perform only the required tasks. Rule-based systems are easily interpretable and are suitable for applications with basic data that require consistent and predictable results delivered with high precision. Rule-based systems are modular which allows for easy scalability and maintainability of the model; and they are customisable whereby rules can be changed or added as new insights are gained, rendering the model flexible and adaptable. In contrast, machine learning systems learn from data by analysing patterns, and they make decisions or predictions based on historical data without the requirement for explicit input for each new task. They are suitable for applications with complex datasets where rules are not easily definable. A rule-based system approach is chosen for this work since the input data is basic and is input explicitly for each task.

The benefits of using a software design methodology in conjunction with an AI approach are enhanced by the use of a software modelling languages to effectively communicate the tool design and functionality.

2.6.3 Modelling language

There are several modelling languages that used in software development. For the purposes of this work, Unified Modelling Language (UML) is selected as it is the industry standard method of describing software and systems development in software engineering [135]. It is a formal, concise, and comprehensive visual language comprising various diagrams that represent the static and dynamic structures of the system [136]. The level of detail of UML required depends on the project, with agile software development methodologies typically using UML 'as a sketch', i.e. using simple diagrams to illustrate the main parameters of the system [136]. Kruchen developed a UML '4+1 View Model' to represent a software architecture from various perspectives (Figure 2.12) [137]. It has four concurrent views—logical, development, process, and physical—and includes scenarios (general use cases) as an additional view that serves as a guide to the four concurrent views and as a validation of the model.

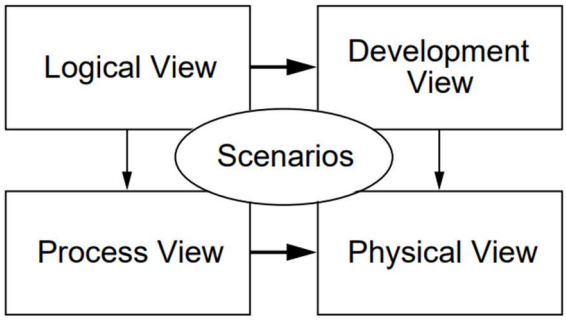


Figure 2.12: 4+1 View Model [137]

Table 2.9 describes the function of each view and the perspective from which it is presented. Although some view can be illustrated by a number of diagrams, the use of all diagrams was deemed unnecessary based on the scope of this work and its software methodology. Thus, the most common or most suitable diagram for each view was chosen as indicated in the table, and these are discussed in the following sections.

Table 2.9: 4+1 View Model description

View	Function [136]	Perspective [137]	Diagram
Logical	Describes the system's functional requirements	Developer	Class
Development	Serves as a software management aid in describing the static behaviour of the system in terms of the organization of the system parts	Programmer	Package
Physical	Describes the physical arrangement of system components and their interactions	System engineer	Deployment
Process	Describes the dynamic behaviour of the system—system processes, information flow, and non-functional aspects	Software integrators	Activity

Scenario	Describes the system functionality, and validates all other views	End user	Use case

The class diagram in the logical view represents the static structure of a system, where a class is a group of objects with the same features. Each class is shown along with its attributes (data or properties of the class), its operations (services available for request), and the relationships between the classes. The class diagram is a fundamental UML tool for software developers since it can be used to convert between the model and code [138]. The package diagram in the development view is a structure diagram that represents the arrangement of the elements of the model, and is typically used to simplify complex class diagrams [136]. The deployment diagram in the physical view is a structure diagram that models the execution architecture of a system by illustrating the physical arrangement of the hardware (devices or processors), the software deployed on it (artefacts), the elements that the software implements (components), and communication links in the system [136]. The activity diagram in the process view is a popular UML diagram that models the dynamic behaviour of a system by illustrating the flow of control of business processes; it typically represents high-level processes, and is thus not highly technical and communicates to a broad audience [136]. The diagram is formatted in a similar manner to a flowchart, with swim-lanes for each object and its associated activities and arrows to indicate the flow of control between objects [139]. In the scenario view, the use cases of a system represent the system's high-level functional requirements which are the drivers for tool development. Use case diagrams graphically present the system interactions with its users as a form of communication of the system's dynamic behaviour. These diagrams facilitate the identification of superfluous requirements that can be removed, and gaps where additional requirements should be included, and are thus beneficial as a first step to aid system design. The users of a system are known as its actors, which are any entities (people, organisations, external systems) that act in the system. [136]

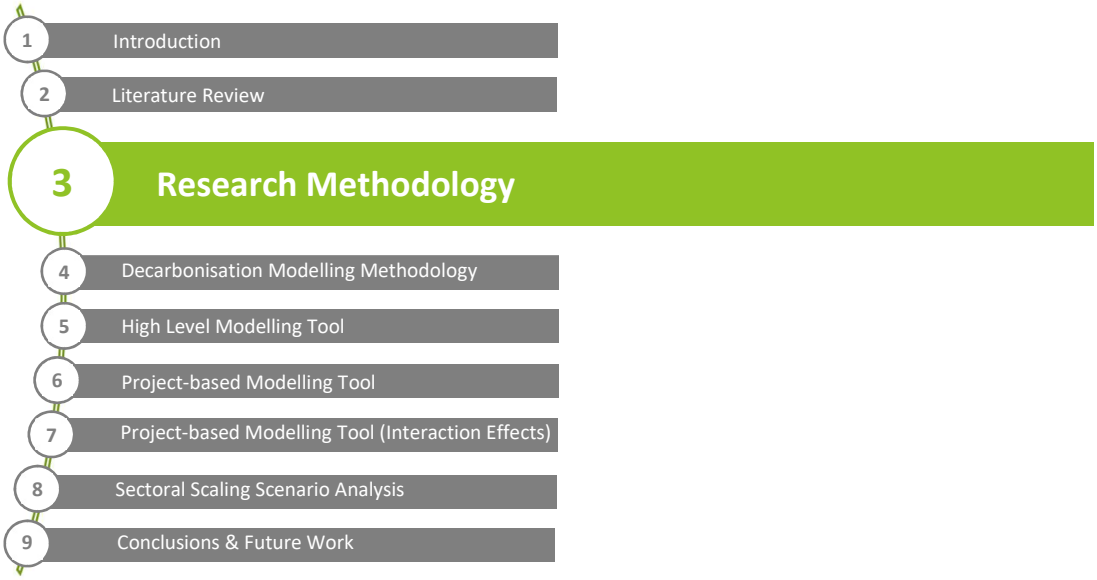
The choice of software design methodology, modelling language, and AI approach supports the development of the modelling toolkit proposed in this work.

2.7 Overall Summary & Research Gaps

Deep decarbonisation is an emerging research field with considerable opportunities for future exploration and development, and it is clear that technical support is required for non-EII organisations targeting carbon neutrality. A review of relevant literature in response to the research questions identified three research gaps (methodology, modelling tools, and interaction effects), from which the research objectives were defined. RO1 addresses the lack of practical methodologies at the organisational level that include a modelling toolkit. RO2.1 guards against green stagnation through the development of an entry-level modelling tool that highlights the potential emissions and financial outcomes of investing in more detailed carbon neutrality exploration. RO2.2 addresses the lack of open-access, detailed modelling tools applicable to non-EII industrial organisations across different industrial sectors. RO3 mitigates the risk of overestimating potential emissions reductions in carbon neutrality planning through the development of a method for the resolution of these interaction effects. These ROs are discussed in further detail in the following chapters, as shown in Table 2.10. As a progression of RO3, chapter 8 presents an industrial sector model based on the scaling of the five case studies leveraged to highlight the collective impact of industrial decarbonisation.

Table 2.10: Literature Review Overview

Research Question	Research Gap	Issue addressed	Research objective	Ch.
RQ1 – What methodologies exist to support industrial organisations in achieving carbon neutrality?	Open-access, detailed, cross-sectoral methodology with reference to a modelling tool	Lack of practical methodologies that included a modelling toolkit	RO1 – Development of a methodology to aid non-EII industrial organisations in achieving carbon neutrality	4
RQ2 – What existing mathematical and commercial modelling resources are applicable to individual organisations, and what level of detail do they contain?	Open-access modelling tool aimed at the organisational level with consideration of demand and supply side measures	Green stagnation in the project implementation phase	RO2.1 – Development of a high-level modelling tool to aid non-EII industrial organisations in early-stage carbon neutrality planning	5
		Lack of open-access modelling tools applicable to industrial organisations	RO2.2 – Development of a detailed, project-based modelling tool to aid non-EII industrial organisations in carbon neutrality planning	6
RQ3 – How do existing modelling resources consider the interactions between emissions-reduction measures?	Heuristic, bottom-up, universal method of considering interaction effects based on industrial processes	Overestimation of potential emissions reductions in carbon neutrality planning	RO3 – Method for the resolution of interaction effects between emissions-reduction measures in a modelling tool to aid non-EII industrial organisations in planning carbon neutrality	7



3.1 Introduction

The literature review presented in Chapter 2 indicates that greater technical support is required to assist non-EII industrial organisations at all stages of carbon neutrality exploration and planning. The research objectives are defined based on the research questions and the research gaps determined from the literature reviewed. To meet these research objectives and to overcome the research barriers, it is important that the research is developed in a systematic manner. A research methodology outlines the research philosophy, provides a structured roadmap of the work, and ensures focus on the defined research objectives to limit the research scope [140]. This ensures that the work is conducted with scientific rigour and that it is replicable. This chapter presents the research methodology followed in this work.

3.2 Proposed Research Methodology

There are three main research philosophies that are used to design studies, and these are categorised by the manner in which data is collected, analysed and used. A quantitative research methodology is a precise and replicable empirical approach that involves the collection and analysis of numeric data to test hypotheses. A qualitative research methodology is a subjective approach that aims to investigate complex phenomena, and is based on participant experience using interviews, case studies, and focus groups. A mixed-methods research methodology is a comprehensive, hybrid approach with both qualitative and quantitative

characteristics; it allows the approach to be tailored to the specific need of each stage of the work. [140]

The proposed research methodology is a mixed-methods methodology that aligns with the research objectives and is built within the framework of the chosen mixed-method research philosophy as well as the scrum software development methodology detailed in section 2.6.1.3. The proposed six-step methodology is shown graphically in Figure 3.1, where the qualitative and quantitative activities are indicated for each step. The first step is information gathering which is achieved through the quantitative approach of discussions with industry partners to asses user need from a practical perspective, as well as a quantitative review of relevant literature and existing modelling tools to define the user and technical requirements of the methodology and modelling toolkit. The research objectives are then defined based on these two sources of information. The second step of the research methodology is the development of a methodology for carbon neutrality which includes the development of a modelling toolkit (RO1). The methodology is structured according to quality management principles and is considered a qualitative process as it is a descriptive tool that maps a scientific process but does not directly involve numerical operations. This naturally progresses to the development of the modelling tools within the modelling toolkit, which follow the scrum software development methodology. In each case, the Planning phase is quantitative as it involves the numerical process of assessing work capacity based on the time available. The Implementation phase is a quantitative execution of the tasks through the numerical process of developing the mathematical models and then encoding them into Python, to create the modelling tool. The Review phase is a mixed-method approach where verification is quantitative and involves code review to determine accuracy, whereas validation is qualitative since it determines applicability by comparing the generated output to the expectations of the industry partner. The Retrospect phase is a qualitative process of development team feedback, which in the case of this work is a self-assessment and feedback from the academic supervisor. The third step of the research methodology represents the high-level modelling tool (RO2.1) which aims to provide science-based motivation for organisations to pursue carbon neutrality through more detailed modelling. The

fourth step represents the more detailed, project-based modelling tool (RO2.2). This leads to the fifth step in which a method for the resolution of interaction effects within the project-based model is developed to enhance its applicability (RO3); this modelling tool has a stricter validation process whereby three case studies are used. In the final step, these case studies are leveraged in a quantitative criteria-based approach to develop a scaled-up model of Ireland's industrial sector. LIEN organisations are classified according to industrial sector and grouped according to various criteria, which are used to scale up the scale studies.

3.3 Methodological Limitations

The proposed research methodology is subject to limitations and potential weaknesses. The information gathering step was constrained by the limitation of the industry collaboration to the pharmaceutical and medical device sectors. The industry need provided a practical basis from which to determine the tool requirements and to design the tool. In addition, the modelling toolkit was validated using limited case studies from the same industry sectors, and consequently this may not have fully assessed the tools for applicability in all industrial sectors. As such, sample bias may have been introduced, although this was mitigated with a literature review to provide an in-depth, comprehensive perspective.

3.4 Thesis Structure

The remainder of the thesis is structured according to the steps of the research methodology as follows: chapter 4 outlines the development of a carbon neutrality methodology in accordance with step 2 and introduces the modelling toolkit; chapter 5 describes the high-level modelling tool as per step 3; chapter 6 describes the project-based modelling tool (step 4); chapter 7 describes the progression of the project-based tool to include interaction effects (step 5); chapter 7 explains the process of model deployment to build up an industrial sector model based on case studies and scenario analysis (step 6).

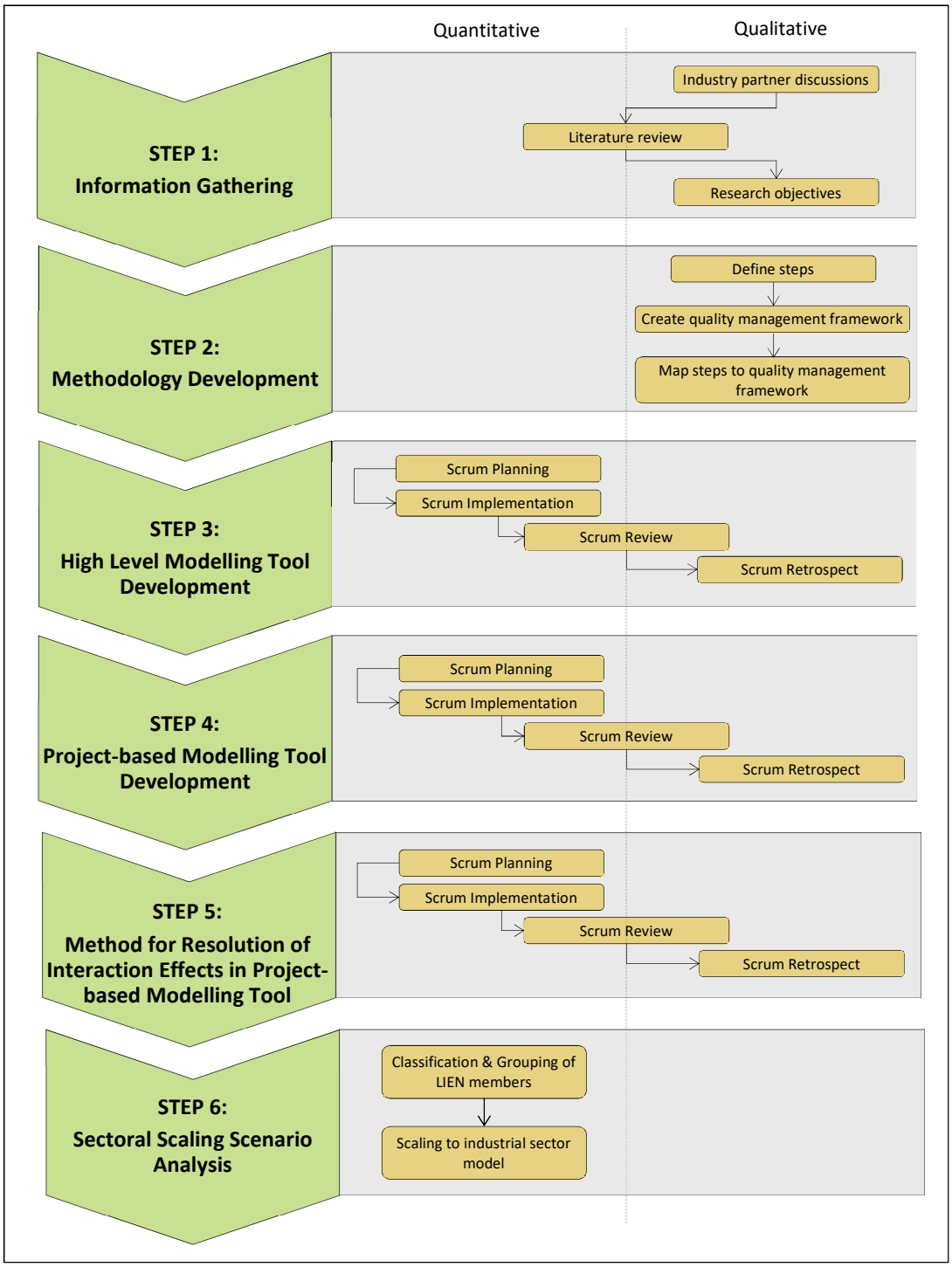
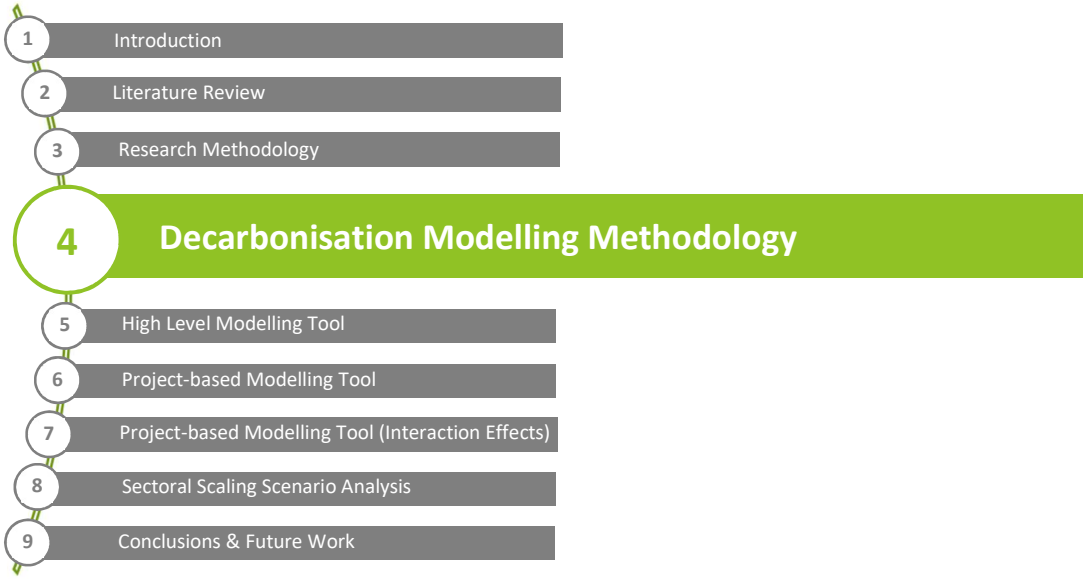


Figure 3.1: Proposed research methodology



4.1 Introduction

The literature review presented in Chapter 2 highlights the lack of comprehensive methodologies to facilitate the delivery of industrial carbon neutrality. Accordingly, this chapter addresses the following research objective:

'RO1 - Development of a methodology to aid non-EII industrial organisations in achieving carbon neutrality.'

This chapter proposes a methodology to facilitate the delivery of carbon neutrality, which can be applied at the organisational level across industry sectors and includes a modelling toolkit to assist in the generation of roadmaps and financial analyses. For broad applicability, the methodology must cater to organisations at different stages of the carbon neutrality journey with different budgets and energy management strategies. Organisations in the initial stages of carbon neutrality exploration or planning may have limited energy data available, which acts as a barrier to following in-depth decarbonisation approaches or using advanced modelling tools; these organisations would benefit from high-level guidance. In contrast, organisations with commitments to carbon neutrality may have approved budgets as well as advanced energy measurement and monitoring management systems in place; these organisations require detailed technical guidance and financial analysis. Consequently, the proposed methodology is a nested methodology presented as a

flowchart where the top tier represents the high-level approach (described in section 4.2) and the bottom tier represents the detailed approach (discussed in section 4.3).

4.2 Proposed High-level Methodology

The purpose of the high-level methodology (Figure 4.1) is to provide guidance for organisations at the exploratory or initial stages of carbon neutrality planning. This is achieved through the use of a high-level modelling tool as the first step of the methodology. There are no prior steps since readily available site-level data is entered into the tool and no additional preparation is required. A carbon neutrality roadmap and financial analysis are generated based on a generalised set of demand reduction and energy efficiency projects, as well as recommended technologies for thermal loads and renewable electricity which have been deemed viable for the site based on data provided. This provides an indication of the emissions reduction and financial impacts of targeting carbon neutrality. The intention is that this motivates organisations to invest in activities to gather the data required for more detailed planning. If the output of the high level tool does not provide sufficient motivation to continue with the detailed methodology, then the process reaches an end. Conversely, if this motivation is sufficient, the detailed methodology is then followed. This entails gathering more detailed data and conducting site-specific studies to use as inputs into a more detailed, projects-based modelling tool which generates an organisation-specific carbon neutrality roadmap and detailed financial analysis.

4.3 Proposed Detailed Methodology

The proposed detailed methodology aims to facilitate the reduction of the carbon footprint of organisations through a number of steps including the implementation of emissions-reduction measures. Emissions reduction is an ongoing process involving continual measurement and monitoring of energy and emissions data as measures are implemented. As such, it can be viewed as a continuous process improvement approach, which would benefit from using a proven quality management methodology as a basis. A review of potential approaches and the proposed detailed methodology are discussed in the following subsections.

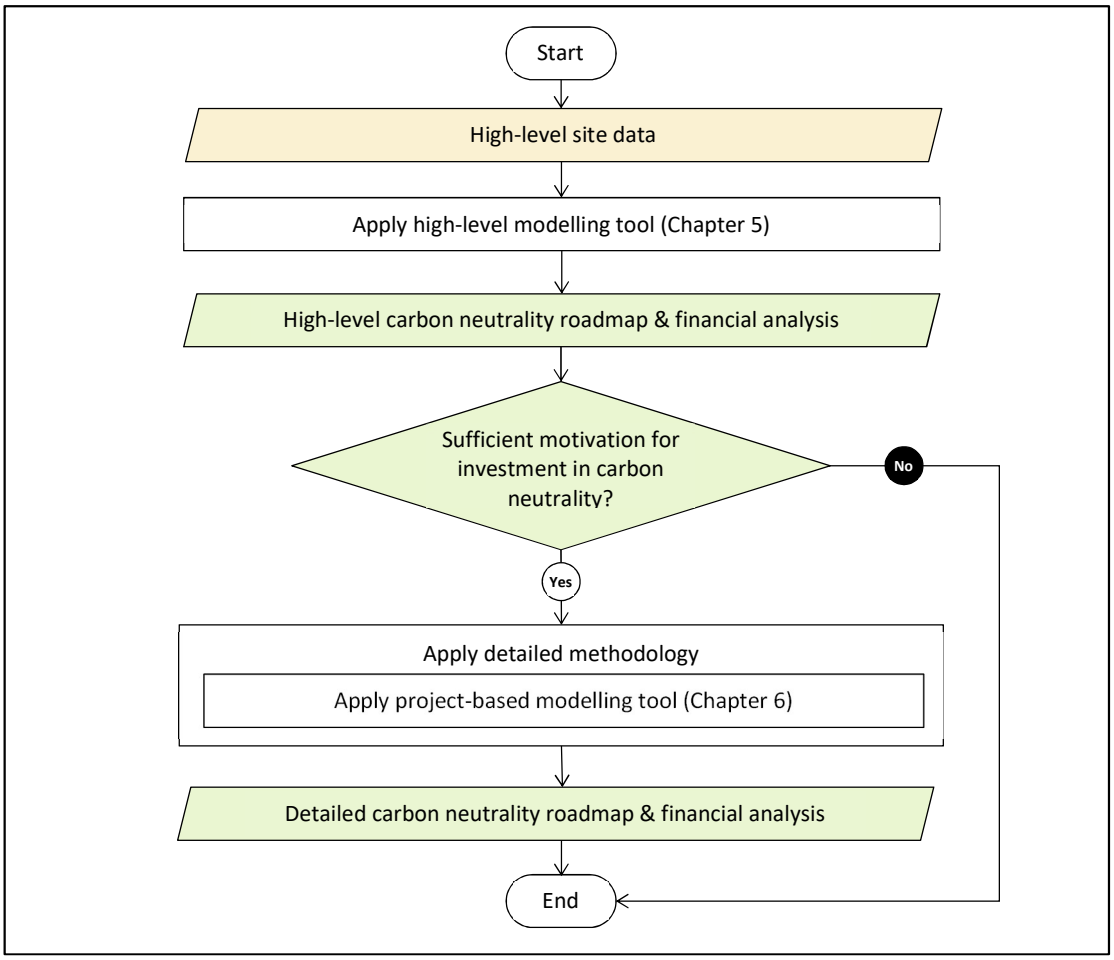


Figure 4.1: High-level methodology

4.3.1 Review of potential approaches

A comparison of the continuous improvement management paradigms introduced in section 2.3.2 is shown in Table 4.1. The lean and green paradigms are based on sets of principles pertaining specifically to process and environmental waste, respectively, and are not directly applicable to emissions reduction. In addition, they are less focussed on continuous improvement than SS [61]. The dominant SS methodology is DMAIC which is an improvement model for existing processes. It consists of five interconnected phases—Define, Measure, Analyse, Improve, and Control—which are structured as a step-by-step methodology. DMAIC has been applied to various quality management paradigms (SS, LSS, GLSS, and SLSS) including those that consider environmental aspects, indicating that it is easily adaptable and appropriate for this work. Consequently, the proposed carbon neutrality methodology is adapted from the traditional DMAIC methodology.

Table 4.1: Comparison of continuous improvement quality management paradigms

Quality management paradigm	Description	Methodology
Lean manufacturing	Focus on process waste reduction in seven identified waste streams (overproduction, rework, inventory, motion, conveyance, over-processing, waiting) [60]	Lean principles
Green manufacturing	Focus on environmental waste reduction through reductions in water, air, and land pollution; waste at source; and risk to humans and other species [141]	Green principles
Six Sigma	Structured approach focussing on reducing process variation, thereby decreasing costs and improving product and service quality. [60]	DMAIC
Lean Six Sigma	Combined approach that minimises process waste and defects	DMAIC
Green Lean Six Sigma	Combined approach that minimises process and environmental waste and defects	DMAIC
Sustainable Lean Six Sigma	Combined approach that minimises process and environmental waste and defects, and incorporates sustainability indicators [61]	DMAIC

4.3.2 Proposed Adapted DMAIC Framework

The novel adaptation of the traditional DMAIC framework is illustrated in Figure 4.2, where the inner ring represents the DMAIC steps in the traditional method, and the outer ring represents the proposed method. The application of the steps is described for each method, and discussed in further detail in the following subsections.

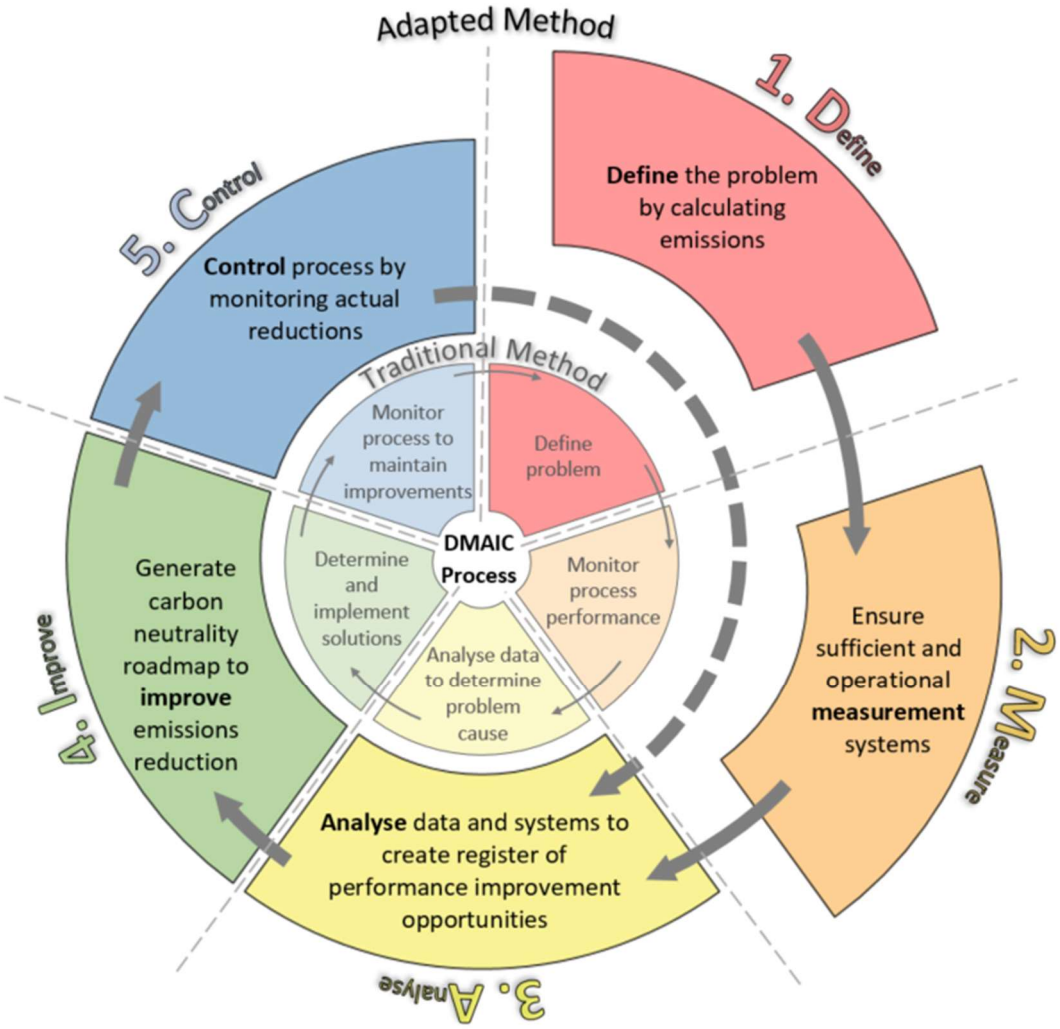


Figure 4.2: Graphical comparison of traditional and adapted DMAIC process

4.3.2.1 *DMAIC Define*

In traditional DMAIC, the problem is defined in this step as a qualitative input [142]. In the adapted approach, the qualitative problem is known to be the organisation's use of emissions-generating energy sources as this is the driver for following the methodology. Instead, this step in the proposed approach involves defining the extent of the problem as a quantitative input, i.e. the calculation of the carbon footprint.

4.3.2.2 *DMAIC Measure*

In traditional DMAIC, this step represents the measurement of the process performance [60]. The proposed approach uses this step to ensure that the metering and monitoring systems are sufficient and operational, which includes checking that

all relevant energy users are sub-metered, and that these meters are operational and are able to record data with the optimal granularity for the process.

4.3.2.3 *DMAIC Analyse*

In both the traditional and proposed approaches, the measured data is analysed in this step. However, in traditional DMAIC, this analysis is used to determine the root cause of the problem [60]. In contrast, this analysis is used to create a list of emissions-reduction measures in the proposed method.

4.3.2.4 *DMAIC Improve*

In traditional DMAIC, the solution to the defined problem is determined and implemented in the improvement step [60]. This is similar in the proposed approach. However, this step is more complicated since the timeline from solution to full implementation is considerably longer. The solution is the output from the modelling tool in the form of a carbon neutrality roadmap of step-by-step improvements, expressed as an emissions-based waterfall chart. The implementation process is a number of steps in which the measures are implemented according to the roadmap timeline.

4.3.2.5 *DMAIC Control*

In traditional DMAIC, the control step occurs after implementation of the improvement to monitor the process and ensure that the improvement is maintained; if this is not the case, then the Define step is revisited and the cycle continues based on the new problem [60]. In the adapted approach, this control step overlaps the improvement step to ensure that the measures are implemented timeously and that the expected reductions are achieved after each step. This interplay between improvement and control is critical since a large negative discrepancy between the theoretical and practical results of any step must be accounted for further along the roadmap to reach carbon neutrality within the timeframe. If the theoretical targets are not reached after any step, the Analysis step is revisited to determine further energy performance improvement opportunities, and the cycle continues from this point.

4.3.2.6 *Summary*

Traditional DMAIC forms the basis of the proposed detailed methodology, where each step has been adapted to pertain to the process of emissions reduction to reach carbon neutrality. However, there are numerous quality management tools that are used within traditional DMAIC, and these are explored in the next section to determine their applicability to the proposed methodology.

4.3.3 DMAIC Tools

Typical quality management tools used in each step of the traditional DMAIC process and those that are used in multiple steps are presented in Table 4.2, with a discussion on the relevance of each tool to the proposed methodology.

Table 4.2: Comparison of DMAIC tools

Phase	Tool [60]	Function [60]	Relevance
Define	SIPOC	Defines the boundaries of the project according to its suppliers, inputs, processes, outputs, and customers	Not relevant in the Define step as this relates only to the calculation of the carbon footprint
	5 Whys	Defines the problem through successively more thorough questioning of a broad problem statement	
	Stakeholder Analysis	Aligns stakeholders and project interests to determine appropriate communication styles and to manage expectations	
	In and Out of the Box	Explores project scope through brainstorming of traditional and innovative solutions	

	Is/Is Not Matrix	Defines project scope by clarifying exactly what is included	
Measure	No unique tools		
Analyse	Cause and Effect (Fishbone) Diagram	Provides a logical representation of potential problem causes	Not relevant as these tools identify the root causes of the problem, which is not the function of this step in the proposed approach
	Pareto Chart	Graphically illustrates the contributions of each parameter to the overall problem by means of a bar chart ranked according to impact	
	Root Cause Verification Matrix	Validates identified root causes	
	Box Plots	Graphically illustrates the data distribution and process variation	
	Hypothesis Testing	Determines the statistical significance of process assumptions	
	Correlation and Regression Analysis	Determines the relationship between process variables	
	Design of Experiments	Optimises a process by evaluating the impact of multiple factors on the process and exploring the interactions between factors	

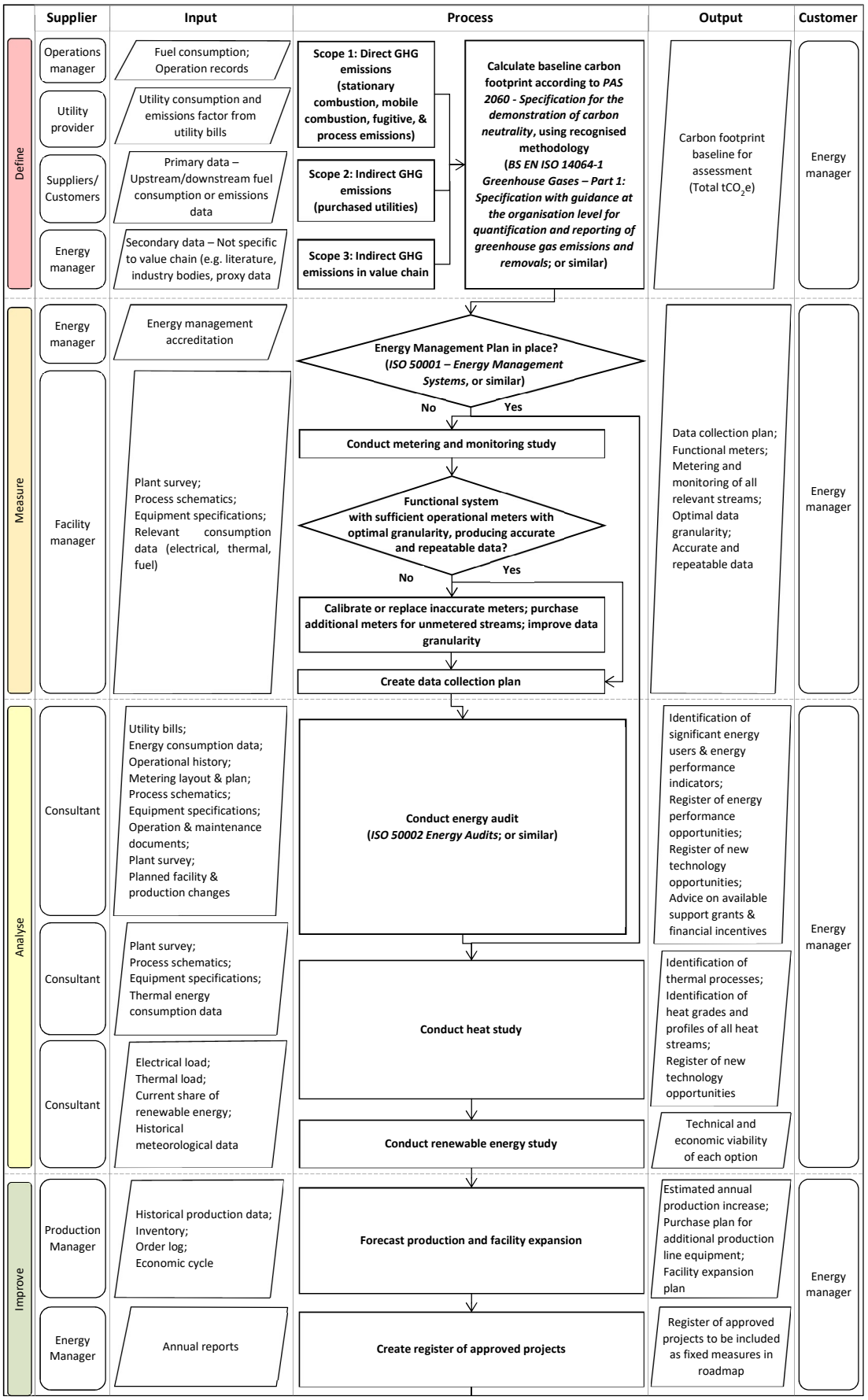
Improve	Solutions Selection Matrix	Ranks solutions for process improvement using a rating system	This is covered in more depth by the emissions and financial modelling of the proposed project-based modelling tool
	Cost Benefit Analysis	Determines the financial impact of potential solutions	
Control	Control chart	Provides statistical information in the form of a line graph which is used to monitor processes and detect variation	Not relevant as the control step checks if implemented measures achieve targeted emissions reduction, and continuous emissions monitoring is not required
Multiple phases	Tollgate Checklist	Determines readiness to move from one DMAIC step to the next.	Not relevant as criteria for progression through steps is clearly defined
	Failure Modes and Effect Analysis	Evaluates processes to highlight potential failures and their causes and effects; often used in multiple phases for comparison	Not relevant as process failure is not the focus of the proposed methodology

	Value Stream Mapping	Provides high-level visual representation of the organisation by mapping the flow of people, raw material, parts, products, equipment, information, and engineering	Could be useful as a comparison of the current initial and final states of the emissions reduction process
	Process Map	Provides visual representation of each step within individual processes to identify problems	

The majority of the tools presented deal with problem definition, process variation and failure identification, and are thus not relevant to the proposed detailed methodology. Value stream mapping and process mapping are useful tools at any DMAIC phase. However, they are not prescribed within the proposed methodology, although they could be used at the discretion of the organisation to aid any of the DMAIC phases. The SIPOC is a high-level, visual tool used to frame the process identified for improvement by mapping and defining its boundaries. Although it is not directly applicable within the Define step in which it is typically used, it is useful to clarify the requirements and organisational responsibilities of the overall emissions-reduction process. Consequently, the detailed methodology proposed in this study for industrial organisations is presented as a DMAIC/SIPOC hybrid approach, where the SIPOC steps are mapped to phases of the DMAIC framework. The benefit of the hybrid approach is that it has the advantages of each approach—DMAIC provides the high-level structure and defined outcomes, and the SIPOC details the process steps and clearly identifies the influencing factors of the process.

4.3.4 Proposed SIPOC-DMAIC methodology

The new and novel adaption of the traditional DMAIC framework developed in this research is illustrated in Figure 4.3, and discussed thereafter. The customer listed in the final column is the person within the organisation, typically the energy manager, who is responsible for managing the carbon neutrality process.


Supplier
Input
Process
Output
Customer
Define
Operations manager
Utility provider
Suppliers/ Customers
Energy manager
Fuel consumption; Operation records
Utility consumption and emissions factor from utility bills
Primary data – Upstream/downstream fuel consumption or emissions data
Secondary data – Not specific to value chain (e.g. literature, industry bodies, proxy data
Scope 1: Direct GHG emissions (stationary combustion, mobile combustion, fugitive, & process emissions)
Scope 2: Indirect GHG emissions (purchased utilities)
Scope 3: Indirect GHG emissions in value chain
Calculate baseline carbon footprint according to PAS 2060 - Specification for the demonstration of carbon neutrality, using recognised methodology (BS EN ISO 14064-1 Greenhouse Gases – Part 1: Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removals; or similar)
Carbon footprint baseline for assessment (Total tCO2e)
Energy manager
Measure
Energy manager
Facility manager
Energy management accreditation
Plant survey; Process schematics; Equipment specifications; Relevant consumption data (electrical, thermal, fuel)
Energy Management Plan in place? (ISO 50001 – Energy Management Systems, or similar)
No
Yes
Conduct metering and monitoring study
Functional system with sufficient operational meters with optimal granularity, producing accurate and repeatable data?
No
Yes
Calibrate or replace inaccurate meters; purchase additional meters for unmetered streams; improve data granularity
Create data collection plan
Data collection plan; Functional meters; Metering and monitoring of all relevant streams; Optimal data granularity; Accurate and repeatable data
Energy manager
Analyse
Consultant
Consultant
Consultant
Utility bills; Energy consumption data; Operational history; Metering layout & plan; Process schematics; Equipment specifications; Operation & maintenance documents; Plant survey; Planned facility & production changes
Plant survey; Process schematics; Equipment specifications; Thermal energy consumption data
Electrical load; Thermal load; Current share of renewable energy; Historical meteorological data
Conduct energy audit (ISO 50002 Energy Audits; or similar)
Conduct heat study
Conduct renewable energy study
Identification of significant energy users & energy performance indicators; Register of energy performance opportunities; Register of new technology opportunities; Advice on available support grants & financial incentives
Identification of thermal processes; Identification of heat grades and profiles of all heat streams; Register of new technology opportunities
Technical and economic viability of each option
Energy manager
Improve
Production Manager
Energy Manager
Historical production data; Inventory; Order log; Economic cycle
Annual reports
Forecast production and facility expansion
Create register of approved projects
Estimated annual production increase; Purchase plan for additional production line equipment; Facility expansion plan
Register of approved projects to be included as fixed measures in roadmap
Energy manager

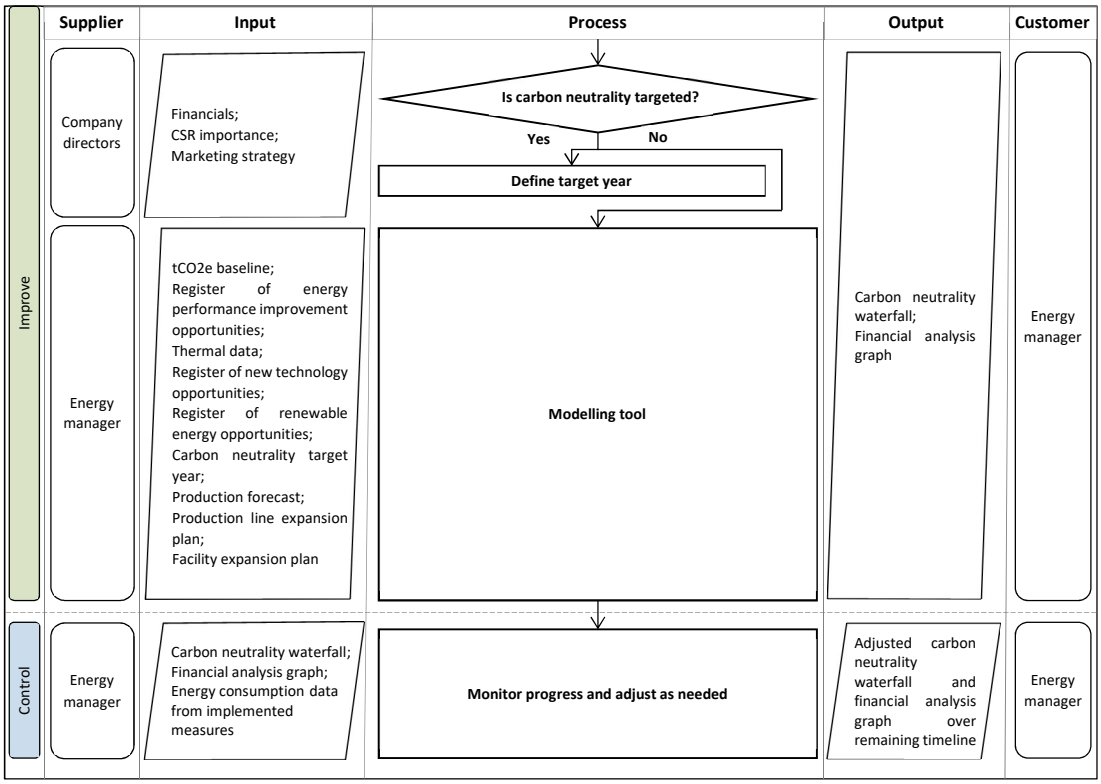


Figure 4.3: Methodology for carbon neutrality in industrial organisations

4.3.4.1 *SIPOC-DMAIC Define*

The carbon footprint baseline is calculated as the total GHG emissions applicable for carbon neutrality assessment according to the global standard PAS 2060 [52]. The total carbon footprint comprises scope 1 emissions calculated from fuel consumption and operation records; scope 2 emissions calculated using the consumption values in utility bills; and relevant scope 3 emissions using primary data measured from upstream and downstream sources, and secondary data where measurements are not possible or accurate. Note that scope 3 emissions under 1% of total emissions are currently not mandatory for carbon accounting, but are mandatory for carbon neutrality certification as per PAS 2060. The carbon footprint is calculated using a recognized methodology, such as BS EN ISO 14064-1 [52].

4.3.4.2 *SIPOC-DMAIC Measure*

The Measure step ensures that the metering and monitoring systems are sufficient to facilitate collection of the energy consumption data required for the Analyse step. All relevant processes must be metered by functional meters that record and monitor data effectively at an appropriate granularity for each process. This is achieved by

surveying the plant and equipment on site, examining the process schematics and equipment specifications to identify the processes to be metered, and analysing relevant consumption data. This information is used to formulate a data collection plan to document the process and ensure consistency in data collection with accurate, repeatable data. This step can be bypassed if there is an energy management plan in place—e.g., I.S. EN ISO 50001—as this incorporates a data collection plan which meets the requirements of this step.

4.3.4.3 *SIPOC-DMAIC Analyse*

This step comprises the following three activities to yield inputs for the modelling tool:

- Energy audit – An energy audit in accordance with a relevant standard such as ISO 50001 uses utility bills, energy consumption data, operational history, metering layouts, process schematics, equipment specifications, operation and maintenance documents, plant surveys, and planned facility and production changes to identify the significant energy users (SEUs), and energy performance indicators (EPIs). SEUs have the greatest potential for energy reduction, and EPIs normalize energy consumption for continuous monitoring to optimise efficiency. However, the primary function of the energy audit in this methodology is to generate a register of potential emissions-reduction measures based on energy performance improvement (demand reduction and efficiency) and new technology (equipment) opportunities. Additionally, it advises on available grants and financial incentives for specific measures, for use in the financial analysis of the modelling tool.
- Heat study – A heat study uses plant surveys, process schematics, equipment specifications, and thermal energy consumption data to identify the thermal processes, heat grades and profiles, and the heat recovery barriers of specific streams owing to physical limitations (plant layout) and other factors. This study can vary in its technical level, from private consultants conducting detailed heat studies to in-house calculations based on energy data, supplier quotes, and equipment specifications. The outcomes of this study are added to the register of emissions-reduction measures.

- Renewable heat study – A renewable energy study uses the electrical and thermal loads, current share of renewable energy, and historical meteorological data to generate technically and economically feasible renewable energy options for further analysis within the modelling tool.

4.3.4.4 *SIPOC-DMAIC Improve*

The Improve step focuses on the detailed modelling tool, which generates the carbon neutrality waterfall and financial analysis based on user inputs and inputs inherent to the modelling tool. The user inputs are as follows; they are the outputs from the Analyse step as well as some additional inputs.

- Production forecast and facility expansion – It is important to map the future energy requirements over the carbon neutrality timeline to ensure that the emissions-reduction measures are futureproofed against possible changes in production and facility expansion. Production can be forecast using trends in historical production data, inventory, order logs, and knowledge of the economic cycle. Planned purchases of additional production lines and facility expansion should be noted. This information is input into the model to accurately scale the organisation's energy requirements.
- Current projects - A register of current projects for increased efficiency, heat recovery, purchase of new equipment, and investment of further renewable energy is required for input into the modelling tool. These are approved or in-progress projects that are planned for implementation regardless of the outcome of the carbon neutrality roadmap. The list of projects is found in various annual management reports such as capital expenditure, energy management, sustainability, ESG, strategic investment plans, and facilities management reports.
- Future Projects – The register of potential future projects forms the foundation of the modelling tool inputs. These projects are emissions-reduction measures that could be implemented at any stage of the timeline to aid progress towards carbon neutrality. The register is created from the energy audit, heat study, and renewable energy study.

- Define carbon neutrality targets –The modelling tool incorporates scenario modelling to consider the effect of the carbon neutrality certification; the choice must be made to use the tool for this purpose or as an aid for decarbonisation planning. Regardless of the scenario, the target year must be set as the evaluation year for emissions reduction, and to account for the financial impact of offsetting remaining emissions in the case where carbon neutrality is targeted.

The model's inherent inputs include the current and future carbon tax and the minimum future renewable energy mandated by country policy. The modelling tool includes scenario modelling, where the user can to study the effect of the parameters by switching off any of the future emissions-reduction measures and changing the cost parameters (discount rate and the utility, renewable energy, and carbon offset costs and rates of increase).

4.3.4.5 *SIPOC-DMAIC Control*

The energy consumption data is used to calculate the total carbon footprint after implementation of each measure to compare the theoretical and actual progress. The total footprint must be used to consider the interaction effects of the independent emissions-reduction measures. Regression analysis such as 'Option C – Whole Facility' of the International Performance & Verification Protocol could be used for this calculation to normalize the results against the baseline to determine the efficacy of each measure [52]. However, the absolute emissions also need to be calculated to control the carbon neutrality process, where emissions-saving measures are added to the waterfall if required to compensate for shortfalls.

4.4 Conclusions

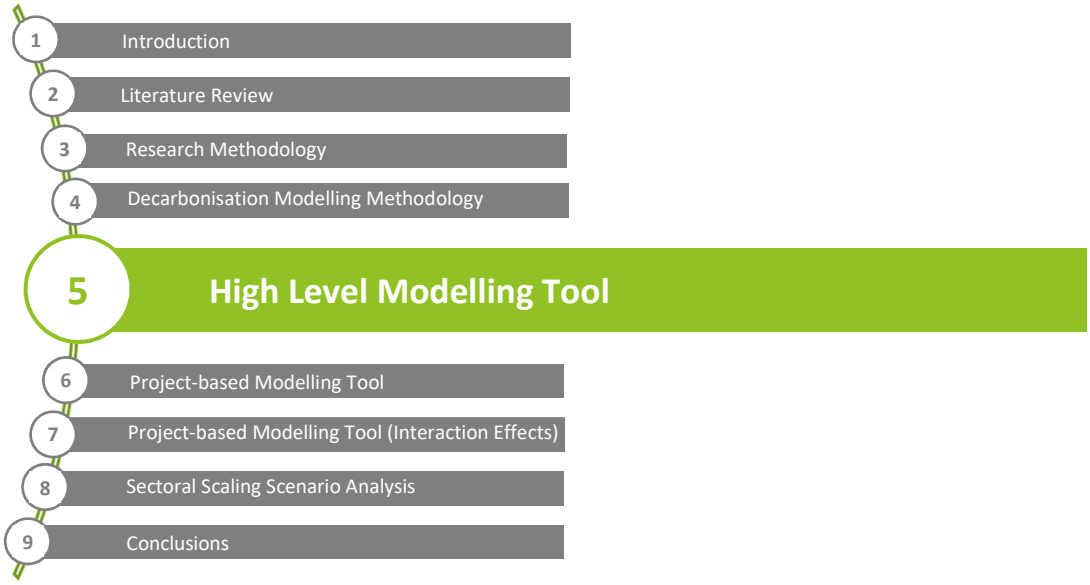
This chapter describes the development of a nested methodology and associated toolkit comprising high-level and project-based modelling tools; these are aimed at assisting organisations in planning carbon neutrality. The high-level methodology includes a high-level modelling tool for preliminary planning based on readily available data at the site level. The generated outputs are a carbon neutrality waterfall and financial analysis based on typical industry data and recommended

decarbonisation technologies. The use of this tool alleviates green stagnation by progressing the decarbonisation journey, and mitigates the financial risk of investing in costly studies which are a barrier to using more detailed modelling tools. Based on the generated output, the decision can be made to invest in energy audits, renewable energy studies, and heat studies as per the detailed hybrid DMAIC-SIPOC methodology to gather data required for more detailed and accurate carbon neutrality planning. This is achieved through the use of a detailed, project-based modelling tool, the final outputs of which are an organisation-specific carbon neutrality roadmap and financial analysis. The cross-sectoral methodology proposed in this work exhibits broad applicability across various stages of carbon neutrality planning and offers a highly detailed, stepwise approach to carbon neutrality through emissions modelling. As such, it addresses the research gap of an open-access, detailed, cross-sectoral methodology with reference to a modelling tool.

The following chapters detail the development and implementation of the two modelling tools in the toolkit—the high-level tool applicable in the early planning stages (Chapter 5), and the project-based tool applicable at more advanced stages. Owing to the complexity of the project-based modelling tool, it is split over two chapters—Chapter 6 discusses the basic project-based tool, and Chapter 7 discusses the method developed to consider the interaction effects between emissions-reduction measures within the project-based tool . The planning stage, function, and barrier of each tool is shown in Table 4.3 along with the chapter in which it is described.

Table 4.3: Modelling Toolkit Description

Tool	Planning Stage	Function	Barriers	Ch.
High Level	Initial	**Entry level tool** based on site-level energy data	Lack of entry level tools that provide a high-level plan for carbon neutrality to alleviate green stagnation	5
Project-based	Advanced	Detailed **project-based tool** based on renewable energy studies, energy audits, and heat studies	Lack of open-access tools that are aimed at the organisational level and provide detailed carbon neutrality roadmaps and financial analysis	6
		Detailed **project-based tool** that considers **interaction effects** between emissions-reduction measures	Insufficient consideration of interaction effects between emissions-reduction measures in existing open-access tools at the organisational level	7



5.1 Introduction

As discussed in Chapter 4, the methodology proposed in this work involves the development of a modelling toolkit with which to aid non-EII industrial organisations in carbon neutrality planning. This chapter presents the high-level modelling tool as highlighted in Table 5.1, and addresses the following research objective:

'RO2.1 - Development of a high-level modelling tool to aid non-EII industrial organisations in early-stage carbon neutrality planning.'

Table 5.1: Modelling toolkit summary

Tool	Function	Ch.
High Level	Entry level tool for preliminary planning	5
Project-based	Detailed project-based tool	6
Project-based (Interaction Effects)	Progression of detailed project-based tool	7

This is a high-level modelling tool that aims to assist organisations at the early stages of their decarbonisation journey, using readily available yet site-specific information. The intention is to provide a broad indication of the quantity of their emissions and the associated estimated financial impact of pursuing carbon neutrality. Based on the generated output, the decision can be made to invest in energy audits, renewable energy studies, and heat studies as per the methodology to gather data required for more detailed carbon neutrality planning. The use of this high-level modelling tool

alleviates green stagnation by progressing the decarbonisation journey, and mitigates the financial risk of investing in costly studies which are a barrier to using more detailed modelling tools.

The remainder of this chapter is as follows. Section 5.2 details the software development process and presents the modelling tool architecture and the relevant UML diagrams. Section 5.3 discusses the development of the modelling tool roadmap and presents the technical foundation for each step. Section 5.4 provides an operational overview of the high-level modelling tool and discusses its applicability. Section 5.5 details the two categories of modelling tool inputs, the organisation-specific inputs required by the user and the built-in inputs inherent to the modelling tool. Section 5.6 illustrates the modelling methodology, and sections 5.7 and 5.8 present the mathematical models used to generate the modelling tool outputs—carbon neutrality waterfall and financial analysis, respectively. Section 5.9 presents a case study that illustrates the modelling tool output. Finally, section 5.10 presents the conclusions and discusses the limitations of the high-level modelling tool.

5.2 Modelling tool software development process

The user interface is a Microsoft Excel file (Microsoft Office Professional Plus 2016) with dedicated sheets for the different user input types. The inherent inputs are in a separate Microsoft Excel file. The modelling tool was developed in Python in the Google Colaboratory environment. This is used to generate models using the imported input data, and a pdf report is generated with the results. A simple representation of the three-layer architecture of the modelling tool is shown in Figure 5.1. The design and functionality of the high level modelling tool is communicated using UML. The class, package, deployment, and activity diagrams are shown in Figure 5.2, Figure 5.3, Figure 5.4, and Figure 5.5, respectively. The use case diagram is shown in Figure 5.6 and its actors and their roles are described in Table 5.2.

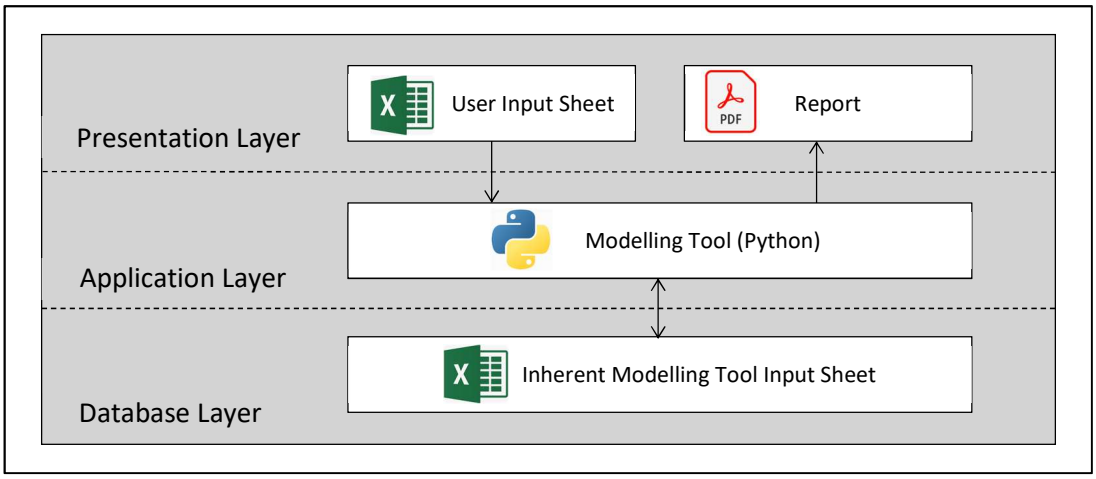


Figure 5.1: Modelling tool architecture diagram

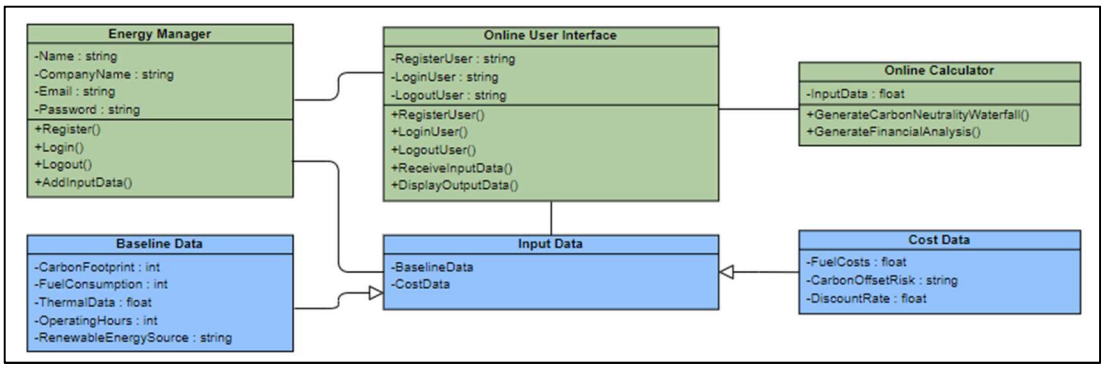


Figure 5.2: Class diagram

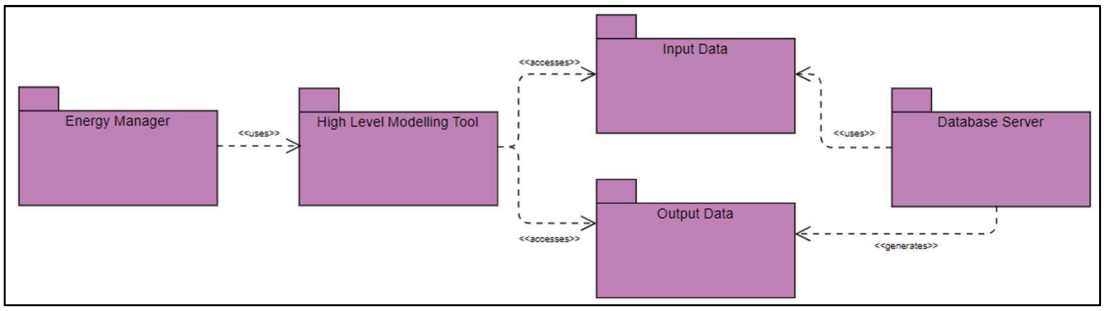


Figure 5.3: Package diagram

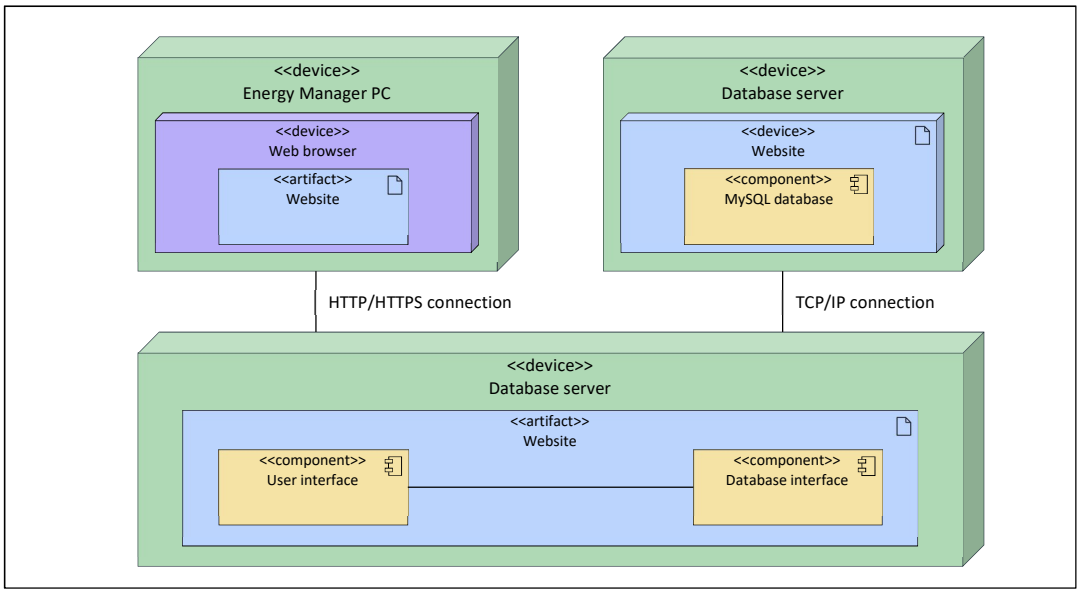


Figure 5.4: Deployment diagram

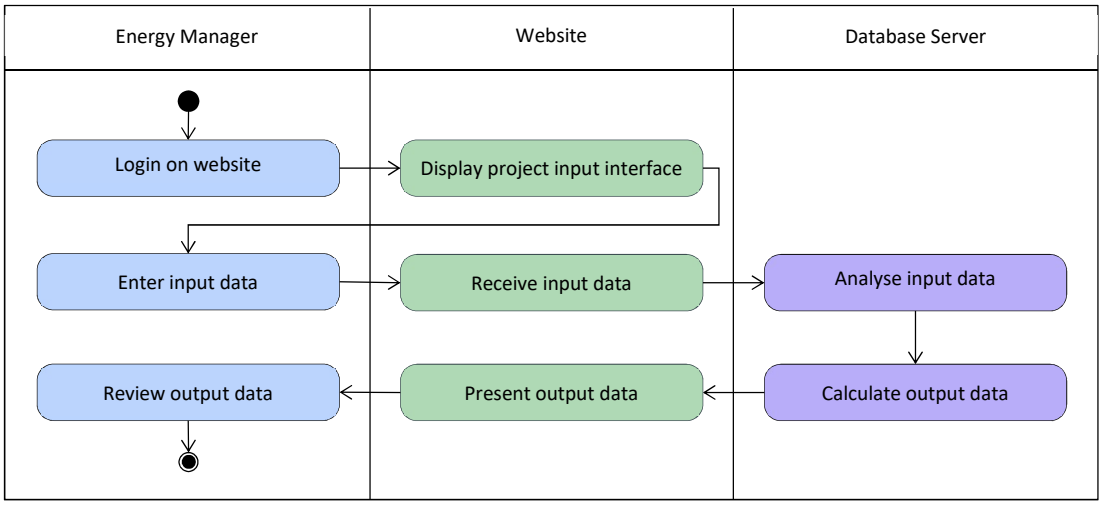


Figure 5.5: Activity diagram

Table 5.2: Actors and roles

Actor	Role
Energy Manager	User of the carbon neutrality tool
Carbon Neutrality High Level Tool Website	Online tool
Carbon Neutrality Consultant	Employee of the software development company who is available to guide the user through use of the tool and answer questions
Website Administrator	Person responsible for maintaining the website of the online tool

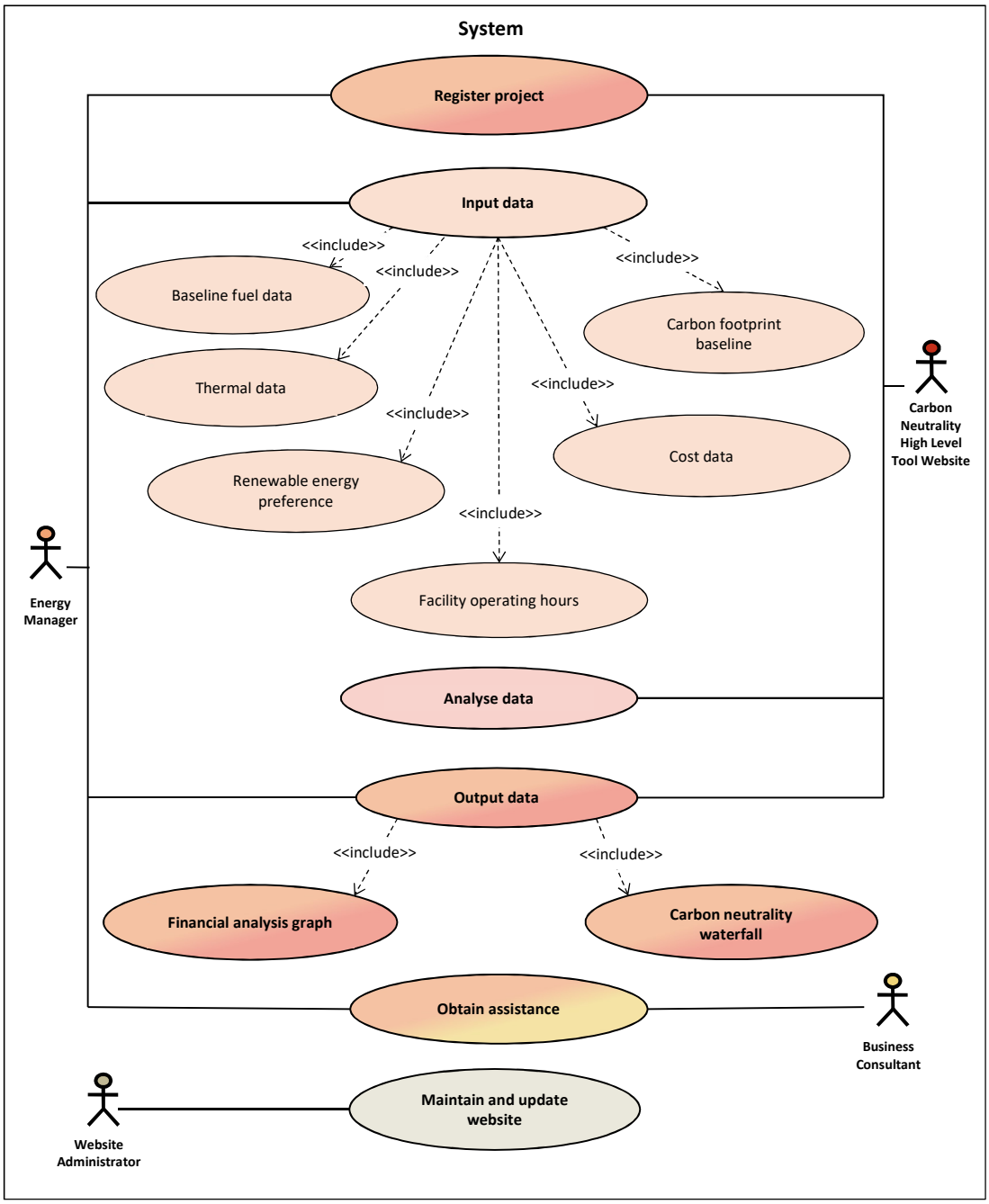


Figure 5.6: Use Case diagram

5.3 Modelling tool development

The proposed high-level approach to emissions reduction is a hybrid of two frameworks—the energy hierarchy and the five deep decarbonisation pillars (energy hierarchy is used rather than SER since the focus is environmental rather than broader sustainability). The energy hierarchy prioritises its measures into tiers according to decarbonisation impact and is aimed at the organisational level, but this is not presented as a pathway. The deep decarbonisation approach offers

interconnected, independent strategies that are not weighted according to potential impact. The proposed roadmap provides the optimal sequence and scale of relevant elements from these complementary frameworks. As discussed in section 2.3.3, the energy hierarchy tiers are 1) energy demand reduction; 2) energy efficiency; 3) utilisation of sustainable resources; 4) utilisation of other, low-GHG-emitting resources; and 5) utilisation of resources as we do now. The first three tiers are considered high priority for the purposes of this modelling tool as they represent the best approach in different categories: behaviour, equipment, and energy supply, respectively. Tier 4 involves switching fuel sources to alternative non-renewable sources with lower emissions factors. Although this provides some level of emission reduction, its contribution is not deemed to be sufficiently high to be considered a step on the roadmap. Tier 5 represents the current state which does not contribute to emissions reduction. The five pillars of deep decarbonisation are energy efficiency, clean energy, electrification, clean fuels, and carbon capture (section 2.3.4). In this context, 'energy efficiency' is an umbrella term encompassing demand reduction and as well as equipment, process, and material efficiency improvements. The first three pillars are applicable in terms of demand and efficiency, electricity supply, and technology, respectively. Clean fuels refers to the decarbonisation of liquid fuels through replacement with biofuels, synthetic fuels, and hydrogen. However, liquid fuels only comprise approximately 6% of Ireland's final industrial sector energy [143]; and this includes fuel oils used in heating which could be replaced as part of an electrification strategy. Electrification offers the benefit of having a single, scalable renewable energy strategy since renewable electricity is already required for non-thermal loads. For these reasons, the contribution of clean fuels is not deemed to be sufficiently high to be considered a step on the roadmap. Carbon capture is not considered within this modelling tool as a strategy at the organisational level owing to financial, technological, infrastructure, and geographic constraints. Thus, energy demand, energy efficiency, electrification, renewable electricity are considered in this order as the foundations of the high-level carbon neutrality roadmap based on the energy hierarchy and the deep decarbonisation pillars. The strategy employed in the high-level tool is to reduce energy consumption, electrify the thermal load,

switch from the direct use of fossil fuels to renewable electricity, and finally offset any remaining emissions.

Near-term carbon neutrality roadmaps at the organisational level typically span five to ten years in line with the SBTi [144]. Accordingly, this modelling tool generates a five-year roadmap since it is based on broad assumptions and emissions-reduction strategies, and a longer plan introduces further time-based inaccuracies. The financial analysis is generated for a period of 15 years to provide an indication of the compounded effect of the financial savings including the carbon offset savings which are only applicable after the carbon neutrality target year. For the purposes of this modelling tool, these timeframes are deemed sufficient to gain an understanding of the scale of financial investment and emissions reduction. The derivation of the detailed modelling tool methodology is illustrated in Figure 5.7 and described in the following subsections.

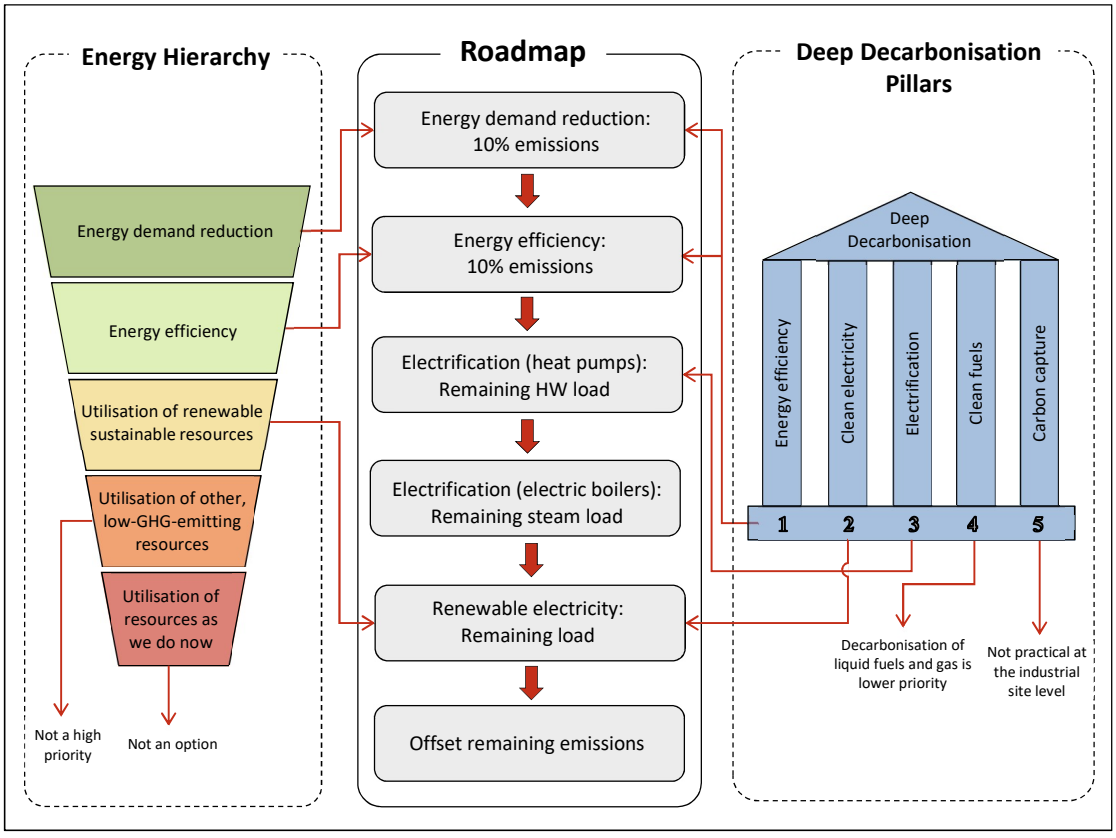


Figure 5.7: Modelling tool roadmap

5.3.1 Energy reduction

The U.S. Environmental Energy Agency (EPA) administers the Energy Star Challenge for Industry as an initiative to assist industrial organisations in improving energy performance [145]. They found an average reduction of 20% in energy use from energy efficiency measures (including demand reduction) across all members [146]. The exact reductions and proportions depend on the current situation, extent of projects implemented, and the technologies employed. However, this is a typical value that can be applied at the organisational level to provide a high-level indication of the effects of demand reduction and energy efficiency. Consequently, this value is used in this modelling tool, and is split equally based on a typical split of investment costs (discussed further in section 5.5.2.2) [147].

5.3.1.1 *Energy demand reduction*

As the highest priority in the energy hierarchy and a contribution to a pillar of deep decarbonisation, energy demand reduction is the first step on the roadmap, and an emissions reduction of 10% is applied in year 1.

5.3.1.2 *Energy efficiency*

As the second highest priority in the energy hierarchy and a pillar of deep decarbonisation, energy efficiency measures are applied in year 2 to the extent of 10% emissions reduction compared to the baseline carbon footprint.

5.3.2 Electrification

CAP 24 highlights electrification of industrial heat as an important decarbonisation strategy [21] since the industrial sector contributes significantly to Ireland's total heat demand (35% in 2022 [148]) and combustion for heat is the highest contributor to Ireland's industrial emissions [21]. Industrial heat is categorised into four temperature grades, and their contributions to the industrial sector heat demand are as follows [149]:

- Low grade heat: <100 °C; 8% of total heating demand
- Medium-low grade heat: 100-150 °C; 32% of total heating demand
- Medium grade heat: 150-500 °C; 35% of total heating demand
- High grade heat: >500 °C; 26% of total heating demand

Medium-low and medium grade heat in the form of hot water and steam generation have the highest contributions, are applicable across all sub-sectors, and are suitable for direct electrification. In 2020, Madeddu et al. conducted a study of technologies for the electrification of industry and categorised them according to temperature range, technological maturity, applications, efficiency/COP, and electrification stage (Stage 1 – entry level, Stage 2 – technologically advanced, Stage 3 – maximum potential with high technological uncertainty). [150] In this modelling tool, only stage 1 technologies are considered as this is an entry level tool aimed at organisations beginning their carbon neutrality journey; these options are listed in Table 5.3.

Table 5.3: Stage 1 electrification technology options [150]

Temperature (°C)				Technological Maturity	Applications	Efficiency /COP
<100	100–400	400–1000	>1000			
Compression heat pumps and chillers				Established (<100 °C)	Space heating; hot water; low-pressure steam; drying; cooling & refrigeration	COP 2-5
Mechanical vapour recompression				Established	Energy recovery to provide steam and process heat	COP 3-10
Electric boilers				Established	Space heating; hot water; thermal oil; steam	0.95-0.99
Infrared heaters				Established	Drying; paint curing; plastic treatments; food processing	0.60-0.90
Microwave & radio frequency heaters				Established	Drying; ceramics firing & sintering; cement treatment; food processing	0.50-0.85

As shown, mechanical vapour recompression is the most efficient established technology for both hot water and steam; however, it relies on energy recovery and as such is not suitable for all applications. Compression heat pumps are the next most efficient technology, with high technologically maturity for applications <100 °C,

making them ideal for hot water generation. They are suitable for low-pressure steam rather than high-pressure steam which is typically required in industrial applications. It should be noted that this table was developed in 2020 and heat pump technology is continually evolving. However, the International Energy Agency produced a report on heat pump technologies in 2023 to assess the technology readiness level (TRL) of heat pumps from different suppliers. High-temperature heat pumps (those operating at a supply temperatures above 100 °C) were rated between 'TRL 4 – Technology validated in lab' and 'TRL 9 – Actual system proven in operational environment' depending on the heat pump design, application, and size based on information provided by suppliers. [151]. Although high-temperature heat pumps are commercially available, this variation in TRL supports Madeddu et al.'s finding that high-temperature heat pumps are not established for temperatures above 100 °C. As shown in Table 5.3, electric boilers, comprising electric resistance and electrode boilers, are an established technology for industrial steam generation. The remaining technologies (infrared, microwave, and radio frequency heaters) are less efficient and include specific applications within EIIs, e.g. firing and sintering in the ceramics and refractory industry and cement treatment within the cement industry [150], which are not considered in this work. Consequently, heat pumps and electric boilers are deemed the most appropriate electrification options and are used in the modelling tool as the sources of hot water and steam generation, respectively. The modelling tool assumes that the energy source of the baseline thermal load is non-electrical, and that the hot water is generated by boilers rather than through heat exchange with the steam system.

5.3.3 Renewable energy

It is assumed that no user-sourced renewable energy is consumed on site in the baseline year since the modelling tool is designed for early-stage carbon neutrality planning. In addition, the proposed utility renewable energy share increase over the carbon neutrality timeline is not considered as it presents a level of risk, and the intention of this modelling tool is to assist organisations in taking action to reduce their emissions. Emissions reductions achieved through proposed utility renewable

energy shares are considered an extra benefit; the more detailed project-based modelling tool includes this as a scenario.

5.3.3.1 *Renewable electricity*

Renewable electricity can be sourced through offsite generation facilitated by financial instruments. Onsite generation is by means of wind farms or solar photovoltaic (PV) plants. Financial instruments comprise direct and virtual corporate power purchase agreements (CPPA). Direct CPPAs are a contract between the organisation and the renewable energy supplier, in which the electricity is supplied by a specific renewable energy project and is physically transferred through the grid. In virtual CPPAs, organisations offset their emissions according to purchased renewable energy fed into the electricity grid by renewable energy providers. This exchange is based on the Guarantee of Origin certificate and there is no physical transfer of energy. Renewable electricity can also be sourced through onsite generation by means of wind farms or solar photovoltaic (PV) plants; this is considered additional renewable electricity as direct action is taken to reduce emissions. Within the carbon offsets market, additionality is an increasingly important concept whereby action is taken to ensure that emissions are reduced relative to the baseline scenario [152]. This modelling tool considers investment in onsite generation technology as the source of renewable electricity. This guarantees high additionality through a direct increase in renewable electricity to meet the full electrical load, and facilitates straightforward and transparent validation of renewable energy to support carbon neutrality claims.

In the carbon neutrality roadmap, the utility electricity is replaced with renewable electricity in year 5 to address the full electrical load. Although the electrical load increases in years 3 and 4 owing to electrification through heat pumps and electric boilers, the investment in renewable electricity only occurs in year 5, i.e. after electrification. This allows for more accurate equipment sizing, as well the submission of a single planning application based on the revised load as it is technically and financially challenging to do this incrementally. This means that the emissions increase in years 3 and 4 since utility electricity has a higher emissions factor than utility gas. However, electrification is contingent on renewable electricity

and the roadmap should be viewed a single project with the ultimate goal of carbon neutrality.

5.3.3.2 *Other renewable energy*

Renewable sources of liquid fuels and gas can be generated onsite through anaerobic digestion and biodiesel plants. However, these strategies are not included in the modelling tool as they require investment in additional infrastructure and equipment. Moreover, the contribution to emissions reduction is unlikely to be significant given that the focus of this roadmap is on electrification (as per CAP 24) owing to the high thermal loads typical of non-EII industrial organisations.

Geothermal energy is a reliable and continuous renewable energy source [153]. Geothermal applications include electricity generation and heat generation, where the latter comprises direct heating and indirect heating by means of ground source heat pumps [153]. The available geothermal energy is highly dependent on the site location and the installation costs for geothermal systems are high [153] Thus, geothermal energy is not considered as a standalone renewable energy strategy within the modelling tool.

5.3.4 Offset remaining emissions

The final step in the roadmap is to address the emissions balance through carbon offsetting by means of purchasing carbon credits on the voluntary carbon market. The market facilitates investment in technology- or nature-based projects that remove or reduce GHGs in the atmosphere. The carbon credits have a broad cost range dependent on numerous factors including the type of project, the standard to which it is certified, the inclusion of sustainability co-benefits, and the validation of affected SDGs. An additional factor that has emerged in recent years is the vintage of the carbon credit. More recently verified carbon credits are more likely to comply with the current standards and have some level of sustainability co-benefits or SDG inclusion. They are better perceived in the market and are more robust against regulatory changes. Consequently, newer vintage carbon credits are favoured, and there is an associated cost premium for their lower risk level [154]. The average

carbon credit costs for two vintage bands and the risk premium are shown in Table 5.4 for the 2023 year.

Table 5.4: Carbon credit vintage and cost [154]

Vintage	2023 Values
Older than five years	€ 5.18 /tCO_2e
More recent than five years	€ 7.77 /tCO_2e
Premium	50%

5.4 Modelling tool overview and applicability

The modelling toolkit was developed for use in Ireland since various built-in model inputs are based on Irish legislation or proposals. However, it has been designed such that it could be easily adapted for use in other geographical locations by amending the input parameters to match local market conditions. Figure 5.8 shows a flowchart overview of the high-level modelling tool, indicating the data sources, inputs, and model outputs. The data sources for the modelling tool inputs are categorised as user (organisation specific) and inherent (general inputs applicable to all organisations, which are built into the model). For each user model input, the specific location (sheet) in the user input document is indicated. The modelling tool outputs are a carbon neutrality waterfall and a financial analysis graph that indicates the cumulative costs and savings and the breakeven points.

5.5 Modelling tool inputs

The modelling tool inputs defined by the user and those inherent to the modelling tool are discussed in subsections 5.5.1 and 5.5.2, respectively

5.5.1 User inputs

User inputs are those defined by the user for their organisation, and there are two tabs for completion on the user input sheet, Baselines and Costs, which are discussed in the following sub-sections. Default values are provided for all inputs to facilitate the use of the modelling tool at the early stages of carbon neutrality planning.

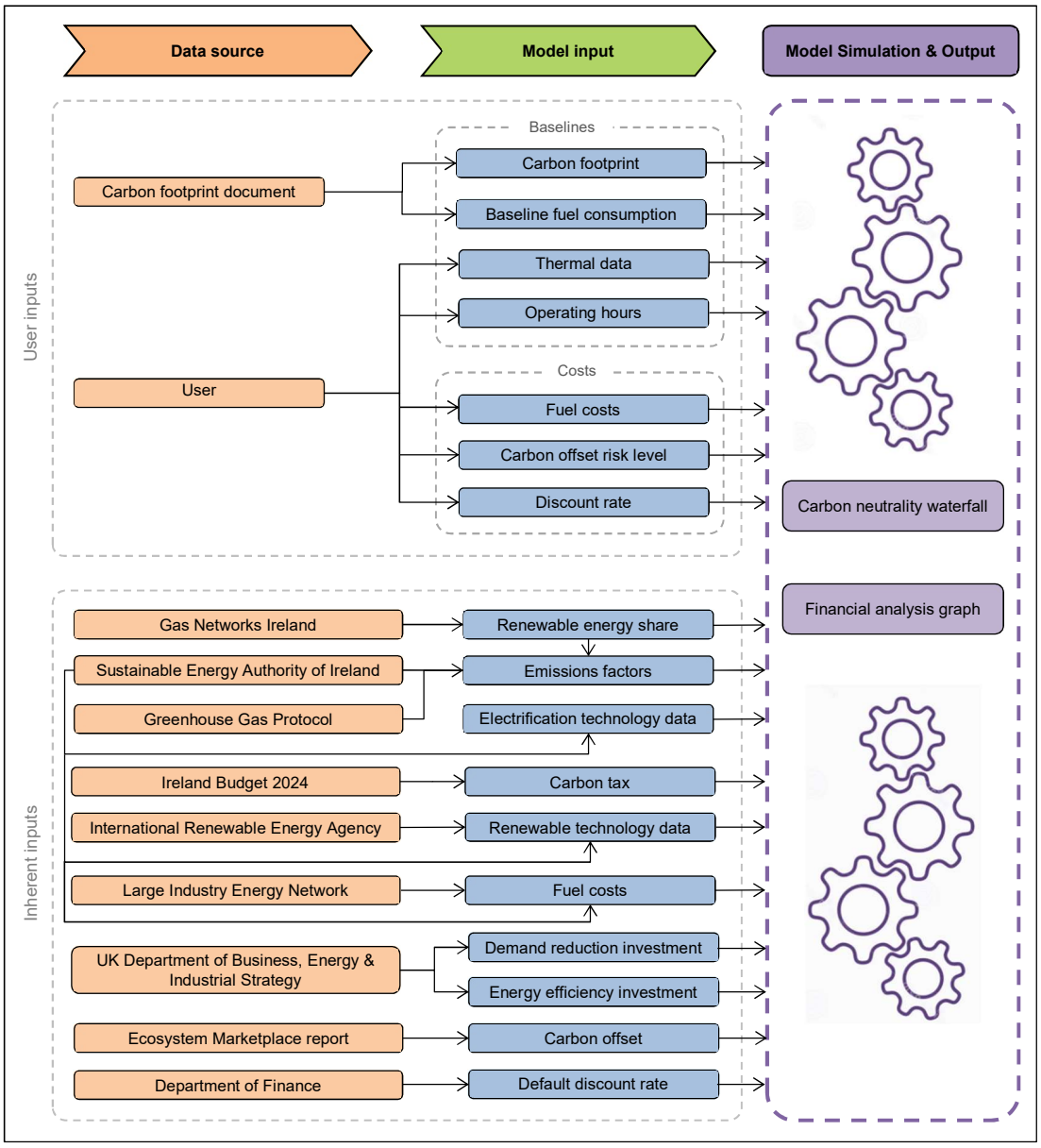


Figure 5.8: Model description – High Level Modelling Tool

5.5.1.1 *Baselines*

The baseline inputs, the default values, and their functions within the modelling tool are shown in Table 5.5 and discussed in the following subsections. The baseline input data required can be sourced from utility bills and high-level site data, without the requirement for advanced metering strategies.

Table 5.5: Inputs for Baselines

Input		Default	Function
General	Facility annual operating hours	n/a	Sizes electrification equipment
	Annual energy spend (€)	n/a	Determines cost of energy efficiency and demand reduction
	Carbon footprint	n/a	Emissions baseline for roadmap
	Baseline electricity consumption (MWh)	n/a	Calculates emissions & financial savings
	Baseline gas consumption (MWh)	n/a	
	Baseline gasoil consumption (kl)	n/a	
	Renewable energy source: wind or solar PV?	Solar PV	Determines investment costs
Thermal	Total thermal output (MWh)	n/a	Determines level of electrification
	Steam proportion of thermal load (%)	50	Sizes electric boiler for steam
	Steam generated by gas or oil boiler?	n/a	Fuel cost for financial analysis
	Boiler efficiency – steam (%)	86	Relates steam load to energy input
	HW proportion of thermal load (%)	50	Sizes heat pump for hot water
	Hot water generated by gas or oil boiler?	n/a	Fuel cost for financial analysis
	Boiler efficiency – hot water (%)	86	Relates hot water load to energy input

5.5.1.1.1 General

The annual operating hours of the facility is required to accurately size electrification equipment to calculate the investment costs used in the financial analysis. There is

no default value since this is known to the organisation. The annual energy spend is used to gauge the potential investment required to implement efficiency and demand reduction measures; this is discussed further in section 5.5.2.2. The carbon footprint is required as the baseline for the carbon neutrality roadmap. Figure 5.9 shows a breakdown of final energy according to energy type in industry for 2022 [148]. The most common fuel categories are natural gas, electricity, and oil products, and these collectively comprise approximately 85% of the final energy. The two highest contributing oil products are petroleum coke (38%) and gasoil/diesel/DERV (32%) [155]. Petroleum coke is limited to the manufacture of non-metallic mineral products, which are EIIs such as the cement, brick, glass, and ceramic industries [155]. Consequently, petroleum coke is not considered a standard fuel owing to its limited applicability. Gasoil/diesel/DERV is more widely spread across all industries [155] and is used as fuel for heating and onsite electricity generation. The renewables category in the graph excludes renewable electricity, and its relatively high proportion is attributed to the use of biomass in the wood-processing industry and renewable waste in the cement industry. This is not indicative of a typical industrial organisation and the quantities of renewable energies are not required in the modelling tool since they do not contribute to emissions and are unlikely to have a significant effect on the financial analysis. Consequently, the modelling tool requires the baseline fuel consumption of the common industrial fuels, namely electricity, natural gas, and gasoil (hereafter referred to as oil); these are used to calculate the emissions reductions and costs associated with electrification and increased renewable energy share. The baseline values for additional fuels used on site, such as petrol, are not required as the effect of demand reduction and efficiency measures is included in the site-wide emissions reduction. From a financial perspective, the percentage reduction in emissions is directly translated to the fuel consumption since it is assumed that there are no changes in emissions factors since the baseline year. The costs associated with the emissions reduction are calculated using the three common fuels only since these are the highest contributors to final energy; the contributions from additional fuels are assumed to be negligible. The consumption levels for the three common fuels should be available as they are delivered or metered into the site, and serve as the input data for the carbon footprint calculation. The preferred

source of onsite renewable energy is required to determine the cost of electrification; the default source is solar PV based on the ease of installation.

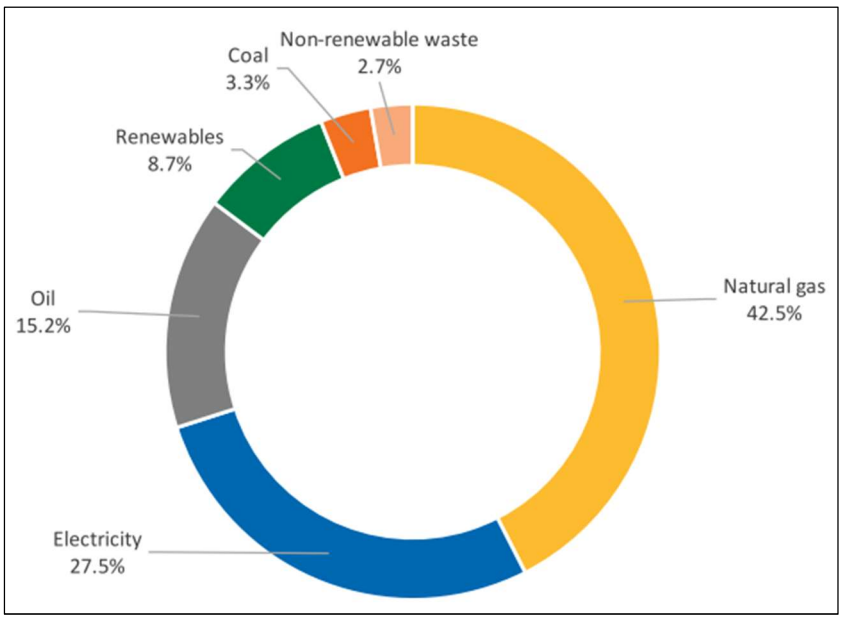


Figure 5.9: Energy type breakdown in industry final energy (2022) [148]

5.5.1.1.2 Thermal

The total thermal output and the proportions of hot water and steam are required to assign the load to heat pumps and electric boilers, respectively, and to determine the relevant cost bands for utility electricity and gas (the oil cost is independent of consumption). The proportions vary according to the industry sector, with steam dominating in sectors characterised by high-temperature processes, such as the pharmaceutical sector. A default ratio of 50/50 for steam/HW is used in the modelling tool; this is an approximation of the industrial heat grade contributions with hot water as the source for low and medium-low grade heat, and steam as the source of medium grade heat. The condensing boiler fuel type determines the cost savings attributed to electrification through the elimination of gas or oil for heat and steam generation.

The boiler efficiencies are required to relate the demand side to the supply side by the conversion of the thermal loads to the fuel input to calculate the emissions savings. Although condensing boilers can achieve efficiencies greater than 90%, this is not always achieved in practice. A default efficiency of 86% is provided in

accordance with the average SEAI National Heat Study values for oil and gas boilers [143].

5.5.1.2 *Financial*

The initial cost inputs, the default values, and their function within the modelling tool are shown in Table 5.6. The discount rate is the rate of return used in the financial analysis to adjust future cash flows to their present values; this is specific to the organisation as it is dependent on the investment risk level. A default discount rate of 4% is provided, based on the Department of Finance 2024 rate for public service projects [156].

The fuel cost inputs required are the current costs for utility electricity, gas, and oil. Electricity and gas costs vary with consumption, and the default values are calculated using typical industry data to identify the typical utility cost bands. The Large Industry Energy Network (LIEN) of Ireland is an energy efficiency network comprising 197 organisations committed to emissions reduction. The network's total primary energy requirement in 2022 was 30,327 GWh. Based on the industry fuel breakdown for 2022 shown in Figure 5.9, this relates to electricity and gas loads of 43 and 66 GWh, respectively. Thus, the default electricity cost is 22 c/kWh, which is the 2024 value listed by the Sustainable Energy Authority Ireland for band IE (20-70 GWh/annum) [157]. Similarly, the default gas cost is 5.9 c/kWh, which is the value for band I4 (28-278 GWh/annum) [157]. The oil cost is independent of the consumption level, and a default value of is 127 c/l is used [157]. The annual growth rates of utility fuel costs are difficult to predict given the unstable prices over the last five years as a result of the COVID-19 pandemic and the Russian war on Ukraine. The roadmap strategy is to fully electrify the thermal load in years 3 and 4 which removes the requirement for gas and oil, and to decarbonise the electricity supply in year 5 by removing it from the grid. Consequently, utility fuel is only used for a short time period, and the baseline costs are deemed to be relevant with no scaling required.

For the carbon offset, two options are provided based on risk level: 'Low Risk' represents the newer vintage carbon credit at a cost of € 7.77/tCO_2e; 'High Risk' represents the older vintage carbon credit at a cost of € 5.18/tCO_2e. These values are

treated as set values for the duration of the carbon neutrality timeline. The default option is low risk to consider the worst-case scenario.

Table 5.6: Cost Inputs

Input	Default	Function
Discount rate	4%	Rate of return in financial analysis
Electricity cost - Utility (€/MWh)	220	Fuel costs used in financial analysis
Gas cost (€/MWh)	59	
Oil cost (€/kl)	1270	
Carbon offset	Low Risk	Determines cost used in financial analysis

5.5.2 Inherent inputs

The three inherent model inputs—technology, financial, and emissions factors—are discussed in this section.

5.5.2.1 *Technology inputs*

The technical parameters of the electrification technologies and the onsite renewable electricity generation technologies used in the modelling tool are shown in Table 5.7 along with their function within the modelling tool.

Table 5.7: Technical parameters of new technologies

Technology	Parameter	Value	Function
Heat pump	COP	4	Relates output to fuel input
Electric boiler	Efficiency	0.99	
Wind power plant	Capacity factor	29%	Sizes renewable technology
	Coefficient of power	50%	
	Annual energy output (kWh/kW_R)	1270	
Solar PV system	Capacity factor	17%	
	Efficiency	23%	
	Annual energy output (kWh/kW_R)	343	

The heat pump COP and electric boiler efficiency are 4 and 0.99, respectively, in accordance with Table 5.3 and the SEAI National Heat Study [143]. The energy output from renewable energy is affected by the capacity factor and the efficiency of the renewable technology. The renewable energy capacity factor relates the average annual energy output to the rated power over the available hours in a year (8760). The modelling tool uses the 2022 capacity factors of 29% for wind energy in Ireland [148], and 17% for solar PV based on the global average [158]. The solar PV efficiency of converting sunlight into useable electricity is taken as 23% [159]; the wind energy efficiency of converting kinetic energy in useable electricity known as the coefficient of power and is assumed as 50% [160]. The resulting energy outputs for wind energy and solar PV are 1270 and 343 kWh/kW_R, respectively.

5.5.2.2 *Financial inputs*

The inherent financial inputs and their functions within the modelling tool are shown in Table 5.8 and discussed thereafter.

Table 5.8: Inherent Cost Inputs

Input	Value	Function
Demand reduction investment cost (% Energy spend)	24	Investment costs in years 1 to 4
Energy efficiency investment cost (% Energy spend)	24	
Heat pump investment cost (€/kW)	250	
Electric boiler investment cost (€/kW)	250	
Carbon tax (€/tCO_2)	56 (+7.50 annually)	Contribution to annual cost
Wind farm investment cost (€/kW_R)	2400	Investment cost in year 5
Wind farm O&M cost (€/kW_R/year)	28	Contribution to annual cost from year 5
Solar PV investment cost (€/kW_R)	1060	Investment cost in year 5
Solar PV O&M cost (€/kW_R/year)	13	Contribution to annual cost from year 5

The UK Department of Business, Energy, and Industrial Strategy commissioned a survey in 2022 of 1144 manufacturing organisations—ranging from SMEs to large businesses—to better understand the energy management and energy efficiency practices of the manufacturing sector [147]. The survey participants were tasked with reviewing a list of potential energy efficiency measures, indicating which measures would benefit their facilities, and then proposing an investment cost to implement the chosen measures. The potential energy efficiency measures relevant to this study are: improvements to industrial processes, heat-related improvements, building improvements, implementation or improvement of an energy management system, implementation or improvement of control and monitoring systems for energy consumption, and behavioural and cultural changes within the organisation. The average total investment cost of applying these improvements to the relevant organisations is approximately €35 million. Using the total annual energy spend of all organisations surveyed (€74 million) yields an investment cost of 48% of the annual energy spend. Although this value is not directly related to the assumed load reductions in section 5.3.1, it is deemed indicative of the scale of investment required to implement these measures. This value split equally between demand reduction and energy efficiency improvements, yielding an investment cost of 24% of the annual energy spend for each category. This is divided equally between the demand reduction and energy efficiency steps.

The investment cost per kW thermal output for the electrification technologies decreases with increasing thermal output. Heat comprises approximately two-thirds of the industrial sector's final energy demand [161]. Based on the average energy demand of LIEN members and a 24h manufacturing schedule, the required thermal output of a typical Irish organisation can be assumed as 12 MW, divided equally between hot water and steam. Consequently, the cost used within this modelling tool is € 250/kW for each technology (heat pumps and electric boilers) based on the SEAI National Heat Study value for a thermal output of 6 MW [143]. Maintenance costs are not considered as the new technology is replacing existing, older equipment which are likely to have greater maintenance costs.

Ireland's carbon tax is set at the national level and is independent of the user's organisation. It is only applicable to fuels outside of the European Union's Emissions Trading Scheme (EU ETS), and thus is not applicable to electricity. Natural gas and oil are subject to carbon tax, which is applied as a separate item on the gas bill and is thus included as a separate financial input in the model. Although the carbon tax is applied to carbon dioxide emissions and does not include equivalent emissions from the remaining greenhouse gases, the contribution of other greenhouse gases is minimal (see Table 5.9). The natural gas carbon tax for 2024 is 56 €/tonne CO_2 and its proposed annual growth rate is 7.50 €/tonne CO_2 until 2030 when 100 €/tonne CO_2 is reached [162]; these proposed values are used in the model, where the values for the years beyond 2030 remain at the 2030 level since no further increase has yet been proposed.

To avoid unnecessarily complex modelling, it is assumed that all renewable electricity generated is used on site, i.e. the modelling tool does not consider the financial impact of excess energy that can be sold to the grid. Installation costs of renewable technologies vary depending on numerous factors. The installation cost of a wind farm in Ireland can be assumed to be an average of €2400/kW [163]. However, there are ongoing costs for additional maintenance and operations, monitoring and control systems, asset management, land lease agreements, and insurance; the 2021 cost for Ireland for O&M encompassing all of these activities was €28/kW/year, which is used in the modelling tool [158]. For solar PV, a typical installation cost of €1060/kW is used, based on average 2022 European values, with an O&M cost of €13/kW/year based on the 2022 global value [158]. The modelling tool does not consider escalation in the annual costs over the carbon neutrality timeline as the future value of money is offset by the downward trend in O&M costs attributed to advancements in technology, and increased service provider experience and competition, and increasing use of advanced monitoring systems and data analytics [158].

5.5.2.3 *Emissions factors*

The emissions factors used in the modelling tool must be expressed in tCO_2e to account for all greenhouse gas emissions in accordance with 'PAS 2060:2014 Specification for the Demonstration of Carbon Neutrality' [38]. In GHG accounting,

the equivalent CO_2 values for all greenhouse gases other than carbon dioxide are calculated using the global warming potential and mass of each greenhouse gas [164]. The following three sources were used to calculate the emissions factors used in the modelling tool:

1. Sustainable Energy Authority of Ireland (SEAI) [165]: The emissions factors provided are specific to Ireland and are net calorific values that represent the quantity of useable energy (these values are used in Ireland's National Energy Balance). However, the SEAI emissions factors consider only carbon dioxide emissions rather than those of all greenhouse gases, and a breakdown of the other GHGs associated with energy generation is not provided.
2. The Greenhouse Gas Protocol [166]: The emissions factors provided consider all greenhouse gases with a breakdown of the contributions of each gas. However, the emissions factors provided are global and thus not specific to Ireland, which may lead to inaccuracies specifically in the case of electricity where the generation fuel mix may differ considerably.
3. Ireland's National Biomethane Strategy [167]: The national gas supply provided by Gas Network Ireland includes renewable energy in the form of Biomethane in accordance with Ireland's national Biomethane strategy; the current contribution is 0.001%.

For the purposes of this work, an adjustment factor is defined for each fuel as the ratio of the CO_2 equivalent emissions factor to the CO_2 emissions factor defined in the GHG Protocol; this is used to scale the SEAI CO_2 emissions factors to include all GHG emissions. The electricity emissions factors with and without other GHGs for the UK are used to determine the adjustment factor. For natural gas and oil, the proportions of emissions contributed by greenhouse gases other than carbon dioxide are assumed to be the same for Ireland as globally since this should not be dependent on geographical location. Consequently, the adjustment factor is deemed an acceptable method of converting CO_2 emissions to CO_2 equivalent emissions, especially considering the scale of the equivalent emissions (~1%). Another factor to be considered in the determination of the emissions factors is the renewable energy share of each fuel. The SEAI emissions factor for electricity includes the renewable

energy share of 40.7% for 2023 [168], and no further adjustment is required. The SEAI emissions factor for gas relates to pure natural gas rather than the national gas supply. Although the current utility gas supply includes Biomethane, its contribution is deemed negligible in terms of the effect on the gas emissions factor. No renewable energy share is considered for oil. The derivation of all emissions factors is as per Eq. 2. The inputs and calculated values are shown in Table 5.9 for the year 2023, which is used as the minimum user baseline year in the model. These emissions factors are applied throughout the carbon neutrality timeline with no adjustment for increasing RES in the utility supply.

$$\underbrace{EF_{model}}_{\text{Emissions Factor in } CO_2e} = \underbrace{\left(\frac{EF_{CO2e}}{EF_{CO2}}\right)}_{\text{GHG Adjustment Factor}} \times \underbrace{EF_{SEAI}}_{\text{Emissions Factor in } CO_2} \qquad \textit{Eq. 2}$$

Table 5.9: 2023 emissions factors

Fuel	Adjustment Values (tCO_2/unit) [166]		GHG Adjustment factor	EF_{SEAI} (tCO_2/unit) [165]	EF_{model} (tCO_2e/unit)
	EF_{CO2}	EF_{CO2e}			
Electricity (MWh)	0.2050	0.2071	1.01	0.2548	0.2574
Natural Gas (MWh)	0.217	0.218	1.002	0.204	0.205
Oil (kl)	3.005	3.021	1.005	2.951	2.967

5.6 Modelling Methodology

The modelling tool methodology is described by the flowchart in Figure 5.10. The input data is manipulated to generate the carbon neutrality waterfall and financial analysis, and the relevant mathematical models are presented in sections 5.7 and 5.8, respectively.

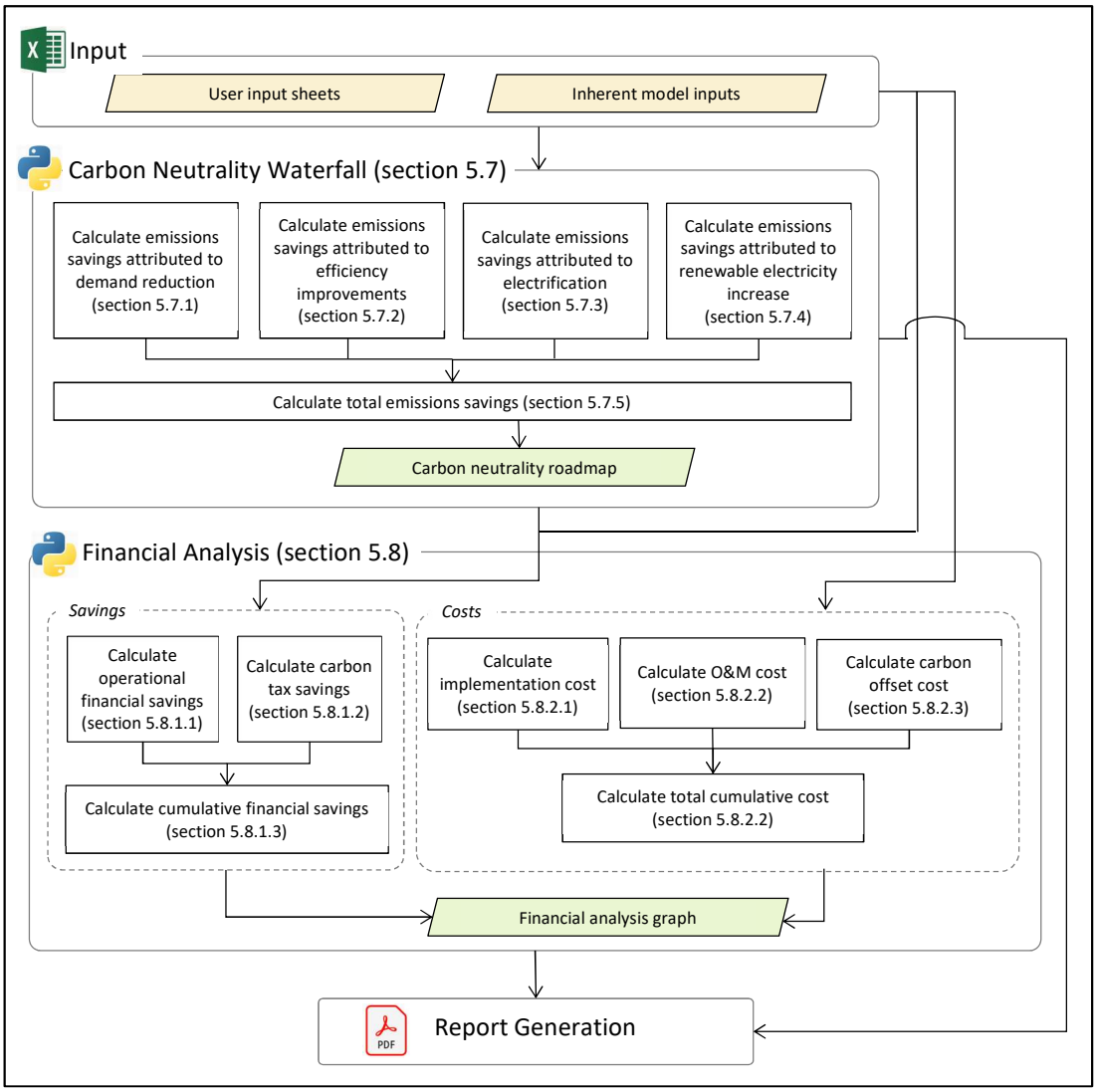


Figure 5.10: Flowchart of modelling methodology – High Level modelling tool

5.7 Model Simulation and Outputs – Carbon Emissions Waterfall

The carbon neutrality waterfall shows the reduction in emissions from the baseline year to the carbon neutrality target year. The baseline year is considered as year zero of the carbon neutrality roadmap. Each waterfall step is divided into four sections where relevant to attribute the emissions savings to the fuel; these are the three standard fuels (electricity, gas, oil) and 'other' to indicate the scale of alternative fuels used. The mathematical model used to generate the carbon neutrality waterfall is discussed in this section and is shown graphically in Figure 5.11.

5.7.1 Emissions savings attributed to demand reduction (year 1)

The emissions savings attributed to demand reduction in year 1 is described by Eq. 3 as a percentage of the baseline carbon footprint.

$$(ES_{dr})_{y_1} = 0.1 \times CF \qquad \text{Eq. 3}$$

Emissions savings from demand reduction = Scale of demand reduction × Baseline carbon footprint

5.7.2 Emissions savings attributed to efficiency improvements (year 2)

The emissions savings attributed to efficiency improvements in year 2 is described by Eq. 4 as a percentage of the baseline carbon footprint.

$$(ES_{eff})_{y_2} = 0.1 \times CF \qquad \text{Eq. 4}$$

Emissions savings from efficiency improvements = Scale of efficiency improvements × Baseline carbon footprint

5.7.3 Emissions savings attributed to electrification (years 3 & 4)

Heat pumps and electrode boilers serve as the new technology for the electrification of the hot water and steam loads, respectively. The savings from these new technologies are based on the remaining thermal load (80% of baseline) after the reductions in demand and efficiency applied in years 1 and 2 of the carbon neutrality roadmap. The efficiencies of the current and new technologies are used to relate the revised thermal output to the consumption of each fuel, and the emissions factor of each fuel is then applied to calculate the total emissions savings. The emissions savings attributed to electrification of the hot water system by heat pumps is shown in Eq. 5. Similarly, the emissions savings attributed to the electrification of the steam system by electric boilers is shown in Eq. 6. Note that both of these emissions savings are likely to be negative in accordance with the electrification strategy in which renewable energy is only sourced in year 5 to address the full load.

$$(ES_{HW})_{y_3} = 0.8 \times TO \times TO_{\%HW} \times \left(\frac{EF_{oil/gas}}{\eta_{oil/gas\ boiler}} - \frac{EF_{elec}}{\eta_{hp}}\right) \qquad \text{Eq. 5}$$

Emissions savings: heat pumps = Remaining thermal output × HW share of thermal output × Emissions & efficiency adjustment for gas/oil boiler − Emissions & efficiency adjustment for heat pump

$$(ES_{steam})_{y_4} = 0.8 \times TO \times TO_{\%steam} \times \left(\frac{EF_{oil/gas}}{\eta_{oil/gas\ boiler}} - \frac{EF_{elec}}{\eta_{elec\ boiler}}\right) \qquad \text{Eq. 6}$$

Emissions savings: electric boilers = Remaining thermal output × Steam share of thermal output × Emissions & efficiency adjustment for gas/oil boiler − Emissions & efficiency adjustment for electric boiler

5.7.4 Emissions from renewable electricity (year 5)

The total electrical load comprises the baseline electricity load and the full thermal load, both of which are adjusted for the demand and efficiency reductions. The additional electrical load from electrification of the steam and hot water thermal loads are calculated using the adjusted thermal loads and the efficiencies of the new technologies; the equations are shown in Eq. 7 and Eq. 8, respectively. The total emissions savings attributed to the increase in renewable electricity in year 5 is as per Eq. 10.

$$Load_{heat\ pump} = \frac{0.8 \times TO \times TO_{\%HW}}{\eta_{hp}} \qquad \textit{Eq. 7}$$

$$Load_{elec\ boiler} = \frac{0.8 \times TO \times TO_{\%steam}}{\eta_{elec\ boiler}} \qquad \textit{Eq. 8}$$

$$\underbrace{(ES_{re})_{y_5}}_{\text{Emissions savings from renewable electricity}} = \underbrace{\left((0.8 \times FC_{elec}) + Load_{heat\ pump} + Load_{elec\ boiler}\right)}_{\text{Adjusted baseline electricity consumption}} \times \underbrace{EF_{elec}}_{\text{Electricity emissions factor}} \qquad \textit{Eq. 9}$$

Electrical heat pump load; Electrical boiler load

5.7.5 Emissions balance

The total emissions savings represent the steps in the carbon neutrality waterfall from the carbon footprint baseline. The emissions balance is the remaining emissions to be offset to achieve carbon neutrality (Eq. 10). This balance comprises gas used for industrial processes (i.e. not heating), as well as alternative fuels.

$$\underbrace{EB_{ycn}}_{\text{Emissions balance}} = \underbrace{CF}_{\text{Carbon footprint}} - \left(\underbrace{ES_{dr}}_{\text{Demand reduction}} + \underbrace{ES_{eff}}_{\text{Efficiency improvements}} + \underbrace{ES_{HW}}_{\text{Electrification of hot water}} + \underbrace{ES_{steam}}_{\text{Electrification of steam}} + \underbrace{ES_{re}}_{\text{Renewable electricity}}\right) \qquad \textit{Eq. 10}$$

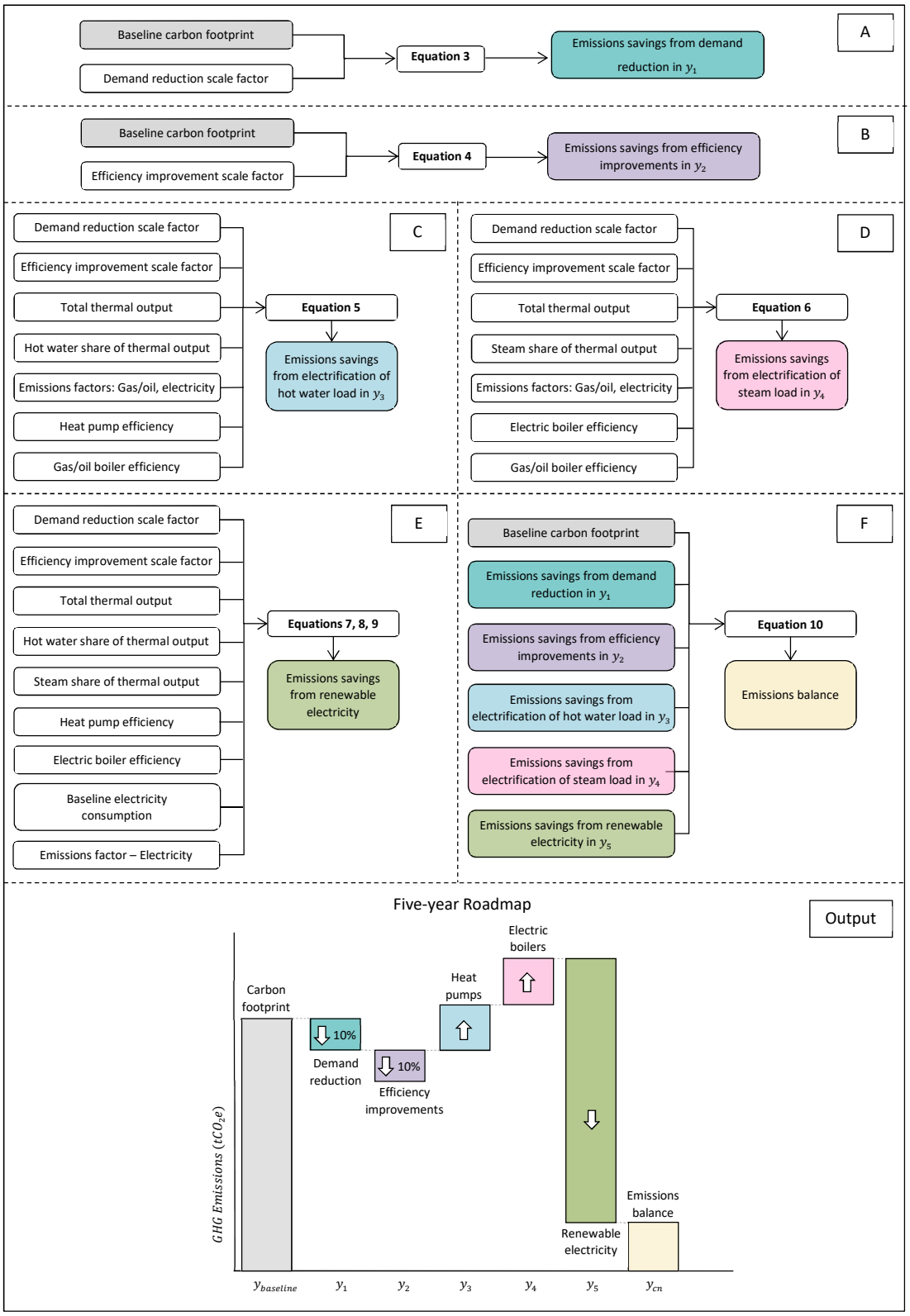


Figure 5.11: Graphical representation of carbon neutrality waterfall equations

5.8 Model Simulation and Outputs – Financial Analysis

The financial analysis is in the form of a graph that compares the cumulative costs and savings. The graph spans 15 years regardless of whether the breakeven point is

reached as this timeframe is deemed sufficient to indicate the financial effects of emissions reduction.

5.8.1 Financial savings

The equations used to determine the cumulative financial savings are discussed in the following sub-sections.

5.8.1.1 *Operational financial savings*

The operational financial savings are calculated using the fuel consumption savings and fuels costs, and are shown graphically in Figure 5.12.

5.8.1.1.1 Year 1 – Demand reduction

The fuel consumption savings attributed to demand reduction for each of the three common fuels is calculated as shown in Eq. 11, where the emissions reduction percentage is applied to all fuels equally. Although additional fuels are likely to be consumed on site, these common fuels make up the majority of energy used on typical industrial sites and this method is considered sufficiently accurate to portray the high-level financial analysis. The operational financial savings are the sum of the financial savings of each fuel (Eq. 12).

$$\underbrace{(FCS_{dr})_i}_{\text{Fuel consumption savings}} = \underbrace{(0.1}_{\text{Scale factor}} \times \underbrace{FC_{baseline})_i}_{\text{Baseline fuel consumption}} \qquad \textit{Eq. 11}$$

$$\underbrace{OFS_{y_1}}_{\text{Operational financial savings in year 1}} = \sum_{i=1}^{i=n} \Big(\underbrace{FCS_{dr}}_{\text{Fuel consumption savings}} \times \underbrace{Cost_{y_1}}_{\text{Cost in year 1}} \Big)_i \qquad \textit{Eq. 12}$$

Summed for all fuels

5.8.1.1.2 Year 2 – Efficiency improvements

The fuel consumption savings attributed to efficiency improvements are calculated as shown in Eq. 13 using the same rationale as for the demand reduction savings. The operational financial savings for year 2 are as per Eq. 14, using the baseline fuel consumption.

$$\left(FCS_{eff}\right)_i = 0.1 \times (FC_{baseline})_i \qquad \text{Eq. 13}$$

Fuel consumption savings = Scale factor × Baseline fuel consumption

$$OFS_{y_2} = \sum_{i=1}^{i=n} \left((FCS_{dr} + FCS_{eff}) \times Cost_{y_2} \right)_i \qquad \text{Eq. 14}$$

Operational financial savings in year 2 = [Fuel consumption savings in years 1 & 2 × Cost in year 2] Summed for all fuels

5.8.1.1.3 Year 3 – Electrification of hot water

Electrification of the hot water load is by means of gas or oil boiler replacement with heat pumps. The energy consumed in the generation of hot water is scaled to account for previous demand reduction and efficiency projects. The gas/oil consumption savings attributed to electrification are shown in Eq. 15 Eq. 15, using the boiler efficiency to relate the adjusted thermal load to the fuel consumption. The operational financial savings from electrification in year 3, and the total operational financial savings based on the fuel consumption savings to date are as shown in Eq. 17 and Eq. 18, respectively.

$$\left(FCS_{ga\ /oil_{hp}}\right)_{y_3} = 0.8 \times TO \times TO_{\%HW} \times \left(\frac{1}{\eta_{gas/oil\ HW}}\right) \qquad \text{Eq. 15}$$

Gas/oil savings from HW heat pumps = Remaining thermal output × HW share of thermal output × Adjustment for boiler efficiency

$$\left(FCS_{elec_{hp}}\right)_{y_3} = -\left(0.8 \times TO \times TO_{\%HW} \times \frac{1}{\eta_{hp\ HW}}\right) \qquad \text{Eq. 16}$$

Electricity savings from heat pumps = − Remaining thermal output × HW share of thermal output × Adjustment for heat pump efficiency

$$\left(OFS_{elec_{hp}}\right)_{y_3} = \left(FCS_{elec_{hp}} \times Cost_{elec}\right)_{y_3} + \left(FCS_{gas/oil_{hp}} \times Cost_{gas/oil}\right)_{y_3} \qquad \text{Eq. 17}$$

Operational financial savings from heat pumps = Financial savings from utility electricity + Financial savings from gas/oil replacement

$$OFS_{y_3} = \left(OFS_{elec_{hp}}\right)_{y_3} + \sum_{i=1}^{i=n}\left(\left(FCS_{dr} + FCS_{eff}\right) \times Cost_{y_3}\right)_i \quad \text{Eq. 18}$$

Operational financial savings in year 3 = *Savings from heat pumps* + *Operational financial savings from fuel savings in years 1&2*

5.8.1.1.4 Year 4 – Electrification of steam

Electrification of the steam load is by means of gas or oil boiler replacement with electric boilers. The same process is followed as for the electrification of hot water by heat pumps, and the relevant savings for year 4 are shown in Eq. 19, Eq. 20, Eq. 21, and Eq. 22, respectively.

$$\left(FCS_{gas/oil_{boiler}}\right)_{y_4} = 0.8 \times TO \times TO_{\%steam} \times \left(\frac{1}{\eta_{gas/oil\ steam}}\right) \quad \text{Eq. 19}$$

Gas/oil savings from electric boiler = *Remaining thermal output* × *Steam share of thermal output* × *Adjustment for boiler efficiency*

$$\left(FCS_{elec_{boiler}}\right)_{y_4} = -\left(0.8 \times TO \times TO_{\%steam} \times \frac{1}{\eta_{elec\ steam}}\right) \quad \text{Eq. 20}$$

Electricity savings from electric boiler = − *Remaining thermal output* *Steam share of thermal output* × *Adjustment for electric boiler efficiency*

$$\left(OFS_{elec_{boiler}}\right)_{y_4} = \left(FCS_{elec_{boiler}} \times Cost_{elec}\right)_{y_4} + \left(FCS_{gas/oil_{boiler}} \times Cost_{gas}\right)_{y_4} \quad \text{Eq. 21}$$

Operational financial savings from electric boilers = *Financial savings from utility electricity* + *Financial savings from gas/oil replacement*

$$OFS_{y_4} = \left(OFS_{elec_{boiler}}\right)_{y_4} + \left(FCS_{elec_{hp}} \times (Cost_{elec})_{y_4}\right) + \left(FCS_{gas/oil\ hp} \times \left(Cost_{gas/oil}\right)_{y_4}\right) + \sum_{i=1}^{i=n}\left(\left(FCS_{dr} + FCS_{eff}\right) \times Cost_{y_4}\right)_i \quad \text{Eq. 22}$$

Operational financial savings in year 4 = *Operational financial savings from electric boilers* + *Adjusted operational financial savings from fuel savings in year 3* + *Adjusted operational financial savings from fuel savings in years 1&2*

5.8.1.1.5 Year 5 – Renewable electricity

Renewable electricity is provided to address the full electrical load which encompasses the baseline load adjusted for demand reduction and efficiency improvements, plus the additional loads from electrification of the hot water and steam systems by heat pumps and electric boilers, respectively. The electrification savings are negative to transform them from electrical savings in Eq. 16 and Eq. 20 to electrical load. The operational financial savings attributed to the provision of renewable electricity for the full electrical load relates to the utility electricity saved,

and is calculated as shown in Eq. 23. (The financial aspects of the renewable electricity are discussed in section 5.8.2.) The total operational financial savings based on the fuel consumption savings of all fuels to date are as shown in Eq. 24.

$$\underbrace{(OFS_{re})_{y_5}}_{\text{Operational financial savings from renewable electricity}} = \underbrace{\left((0.8 \times FC_{elec}) + \left(-FCS_{elec_{hp}}\right)_{y_3} + \left(-FCS_{elec_{boiler}}\right)_{y_4}\right)}_{\text{Baseline electricity adjusted for demand reduction \& efficiency improvements}} \times \underbrace{\left(Cost_{util_{elec}}\right)_{y_5}}_{\text{Electricity cost}} \qquad \textit{Eq. 23}$$

$$\underbrace{OFS_{y_5}}_{\text{Operational financial savings in year 5}} = \underbrace{(OFS_{re})_{y_5}}_{\text{Operational financial savings from renewable electricity}} + \underbrace{\left((FCS_{dr} + FCS_{eff} + FCS_{hp} + FCS_{elec_{boiler}}) \times Cost_{y_5}\right)_{gas}}_{\text{Gas savings to date} \times \text{Gas cost in year 5}} + \underbrace{\left((FCS_{dr} + FCS_{eff} + FCS_{hp} + FCS_{elec_{boiler}}) \times Cost_{y_5}\right)_{oil}}_{\text{Oil savings to date} \times \text{Oil cost in year 5}} \qquad \textit{Eq. 24}$$

5.8.1.1.6 Years 6-15

The active years of the carbon neutrality timeline are years 1 – 5 where measures are taken to reduce emissions. However, the remaining years accrue financial savings compared to the baseline as a result of these earlier savings; these saving are equal to those in year 5 which comprise the savings from all active measures (Eq. 25).

$$For\ years\ 6\ to\ 15: \underbrace{OFS_{y_x}}_{\text{Operational financial savings}} = \underbrace{OFS_{y_5}}_{\text{Operational financial savings in year 5}} \qquad \textit{Eq. 25}$$

5.8.1.1.7 Cumulative operational financial savings

The cumulative operational savings for each year of the carbon neutrality financial timeline (years 1-15) are as shown in Eq. 26. The savings comprises the operational financial savings from the year of consideration, and all savings from previous years. There is no adjustment for present value costs since no escalation of fuel costs is considered in the modelling tool.

$$\underbrace{COFS_{y_x}}_{\text{Cumulative operational financial savings}} = \underbrace{\sum_{j=1}^{j=x} OFS_{y_j}}_{\text{Operational financial savings in year of consideration}} \qquad \textit{Eq. 26}$$

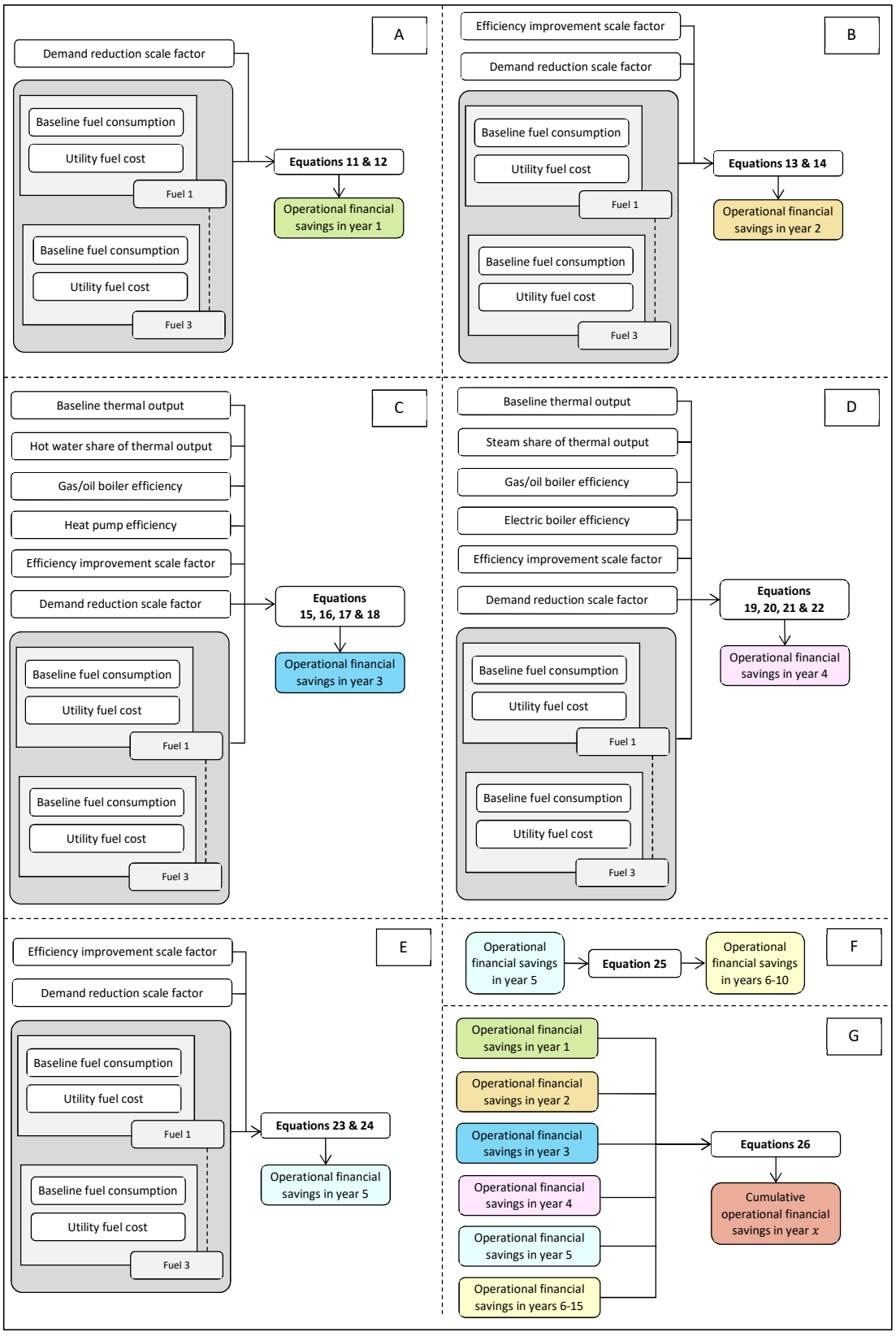


Figure 5.12: Graphical representation of operational financial savings equations

5.8.1.2 *Carbon tax savings*

Carbon tax is affected by the reduced fossil fuel (gas and oil) consumption attributed to demand reduction, efficiency improvements, and electrification. The total fossil fuel emissions savings in years 1, 2, 3, and 4 are shown in Eq. 27, Eq. 28, Eq. 29, and Eq. 30, respectively. There are no new sources of fossil fuel emissions savings in year 5 since the savings are confined to electricity which is not subject to carbon tax. The total fossil fuel emissions savings in the remaining years of the carbon neutrality financial analysis (years 5-15) is equal to that in year 4 (Eq. 31). The set carbon tax values for future years are adjusted to present value costs using the organisation's discount rate in the compound annual growth rate equation (Eq. 32). The resulting carbon tax savings per year attributed to the emissions savings to date is as shown in Eq. 33, and the cumulative savings is shown in Eq. 34.

$$(TES_{ff})_{y_1} = 0.1 \times \left((FC \times EF)_{gas} + (FC \times EF)_{oil}\right) \quad \text{Eq. 27}$$

Total fossil fuel emissions savings in year 1 = *Scale of demand reduction* × *(Gas emissions* + *Oil emissions)*

$$(TES_{ff})_{y_2} = 0.1 \times \left((FC \times EF)_{gas} + (FC \times EF)_{oil}\right) + (TES_{ff})_{y_1} \quad \text{Eq. 28}$$

Total fossil fuel emissions savings in year 2 = *Scale of efficiency improvements* × *(Gas emissions* + *Oil emissions)* + *Total fossil fuel emissions savings in year 1*

$$(TES_{ff})_{y_3} = \left(0.8 \times TO \times TO_{\%HW} \times \frac{EF_{oil/gas}}{\eta_{oil/gas\ boiler}}\right) + (TES_{ff})_{y_2} \quad \text{Eq. 29}$$

Total fossil fuel emissions savings in year 3 = *Oil/gas emissions savings from heat pumps* + *Total fossil fuel emissions savings in year 2*

$$(TES_{ff})_{y_4} = \left(0.8 \times TO \times TO_{\%steam} \times \frac{EF_{oil/gas}}{\eta_{oil/gas\ boiler}}\right) + (TES_{ff})_{y_3} \quad \text{Eq. 30}$$

Total fossil fuel emissions savings in year 4 = *Oil/gas emissions savings from electric boilers* + *Total fossil fuel emissions savings in year 3*

$$For\ x = 5\ to\ 15: (TES_{ff})_{y_x} = (TES_{ff})_{y_4} \quad \text{Eq. 31}$$

$$\left(Carbon\ tax_{y_x}\right)_{PV} = \frac{\left(Carbon\ tax_{y_x}\right)_{FV}}{(DR+1)^n} \quad \text{Eq. 32}$$

Carbon tax savings in year of consideration = *Future value of carbon tax adjusted using discount rate*

$$\underbrace{CTS_{y_x}}_{\text{Carbon tax savings in year of consideration}} = \underbrace{Carbon\ tax_{y_x}}_{\text{Carbon tax in year of consideration}} \times \underbrace{(TES_{ff})_{y_x}}_{\text{Total fossil fuel emissions savings in year of consideration}} \quad \text{Eq. 33}$$

$$\underbrace{CCTS_{y_x}}_{\text{Cumulative carbon tax savings in year of consideration}} = \underbrace{\sum_{j=1}^{j=x} CTS_{y_j}}_{\text{Sum of carbon tax savings to date}} \quad \text{Eq. 34}$$

5.8.1.3 *Cumulative financial savings*

The cumulative financial savings at the present value is the sum of the cumulative operational financial savings and the carbon tax savings, as shown in Eq. 35. A graphical representation of the financial savings is shown in Figure 5.13.

$$\underbrace{CFS_{y_x}}_{\text{Cumulative financial savings}} = \underbrace{COFS_{y_x} + CCTS_{y_x}}_{\text{Cumulative operational and carbon tax savings}} \quad \text{Eq. 35}$$

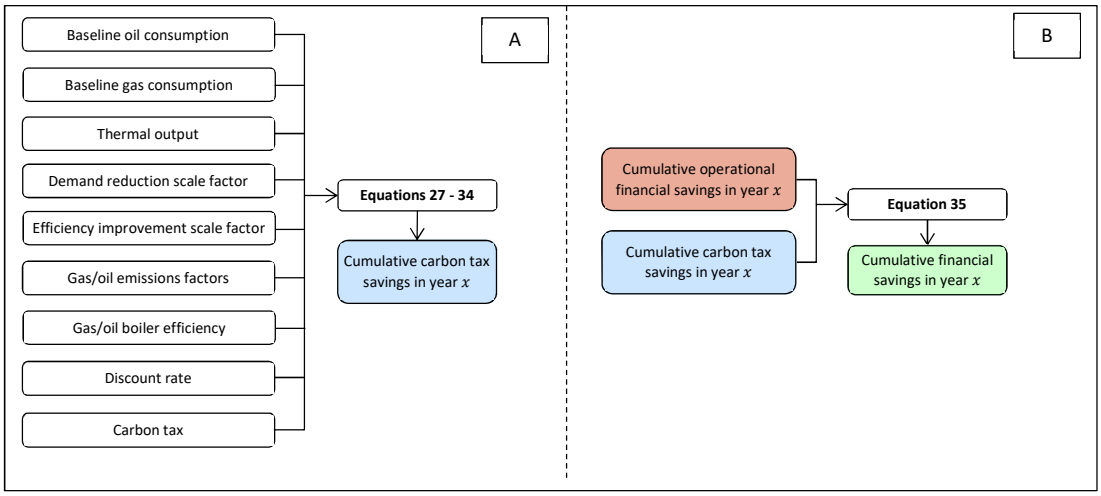


Figure 5.13: Graphical representation of cumulative financial savings equations

5.8.2 Financial Costs

The mathematical model used to determine the cumulative financial costs are discussed in this section, and are shown graphically in Figure 5.14. Note that all costs are depicted in present value.

5.8.2.1 *Total implementation cost*

Implementation costs are incurred in year 1 to 5 of the carbon neutrality roadmap. For years 1 and 2, the costs are a function of the annual energy spend; these are shown in Eq. 36 and Eq. 37 for demand reduction and energy efficiency improvements, respectively. For years 3 and 4 (Eq. 38 and Eq. 39, respectively), the costs are calculated based on typical heat pump and electric boiler investment costs (per kW) as well as the heat demand and operating hours of the facility. In year 5, the implementation cost is dependent on the renewable energy technology; the rated power for each technology is calculated as per Eq. 40 and the associated cost is as per Eq. 41. All costs are present values.

$$IMP_{y_1} = 0.24 \times annual\ spend \qquad \textit{Eq. 36}$$

$$IMP_{y_2} = 0.24 \times annual\ spend \qquad \textit{Eq. 37}$$

$$\underbrace{IMP_{y_3}}_{\text{Implementation costs: heat pumps}} = \underbrace{250}_{\text{Cost /kW}} \times \underbrace{\frac{(1000 \times Load_{heat\ pump})}{operating\ hours}}_{\text{Heat pump size}} \qquad \textit{Eq. 38}$$

$$\underbrace{IMP_{y_4}}_{\text{Implementation costs: heat pumps}} = \underbrace{250}_{\text{Cost /kW}} \times \underbrace{\frac{(1000 \times Load_{elec\ boiler})}{operating\ hours}}_{\text{Electric boiler size}} \qquad \textit{Eq. 39}$$

$$\underbrace{P_R}_{\text{Rated power}} = \underbrace{\begin{cases} \dfrac{1000 \times \left((0.8 \times FC_{elec}) + Load_{heat\ pump} + Load_{elec\ boiler}\right)}{1270} & Wind\ energy \\ \dfrac{1000 \times \left((0.8 \times FC_{elec}) + Load_{heat\ pump} + Load_{elec\ boiler}\right)}{343} & Solar\ PV \end{cases}}_{\text{Electrical load / annual energy output}} \qquad \textit{Eq. 40}$$

$$\underbrace{IMP_{y_5}}_{\text{Implementation cost: renewable energy}} = \underbrace{\begin{cases} P_R \times 2400 \\ P_R \times 1060 \end{cases}}_{\text{Rated power}} \times \underbrace{\begin{matrix} Wind\ energy \\ Solar\ PV \end{matrix}}_{\text{Cost per kW}} \qquad \textit{Eq. 41}$$

5.8.2.2 *O&M cost*

There are annual O&M costs associated with the implementation of renewable energy in year 5, which are applicable from years 5-15 of the carbon neutrality timeline, as shown in Eq. 42.

$$\text{For x} = 5 - 15: \quad O\&M_{y_x} = \begin{cases} 28 \times P_R & Wind\ energy \\ 13 \times P_R & Solar\ PV \end{cases} \qquad \textit{Eq. 42}$$

5.8.2.3 *Carbon offset cost*

The carbon offset is only considered in the years following the carbon neutrality target year (years 6 – 15). The carbon offset cost for the year of consideration is calculated as per Eq. 43 based on the user-defined carbon offset risk level.

$$For\ years\ 6\ to\ 15: \underbrace{COC_{y_x}}_{\substack{\text{Carbon offset cost in} \\ \text{year of consideration}}} = \underbrace{Carbon\ offset_{y_x}}_{\substack{\text{Carbon offset in year} \\ \text{of consideration}}} \times \underbrace{\left(CF - \sum_{j=6}^{j=x} TES_{y_j} \right)}_{\substack{\text{Total emissions savings} \\ \text{in year of consideration}}} \qquad \textit{Eq. 43}$$

5.8.2.4 *Total cumulative cost*

The total cumulative financial cost in y_x is the sum of the implementation, O&M, and carbon offset costs of all years (Eq. 44). All costs are present values.

$$\underbrace{CFC_{y_x}}_{\substack{\text{Total cumulative} \\ \text{cost in time period}}} = \underbrace{\sum_{j=1}^{j=x} (IMP + O\&M + COC)_{y_j}}_{\substack{\text{Sum of all implementation, O\&M,} \\ \text{and carbon offset costs to date}}} \qquad \textit{Eq. 44}$$

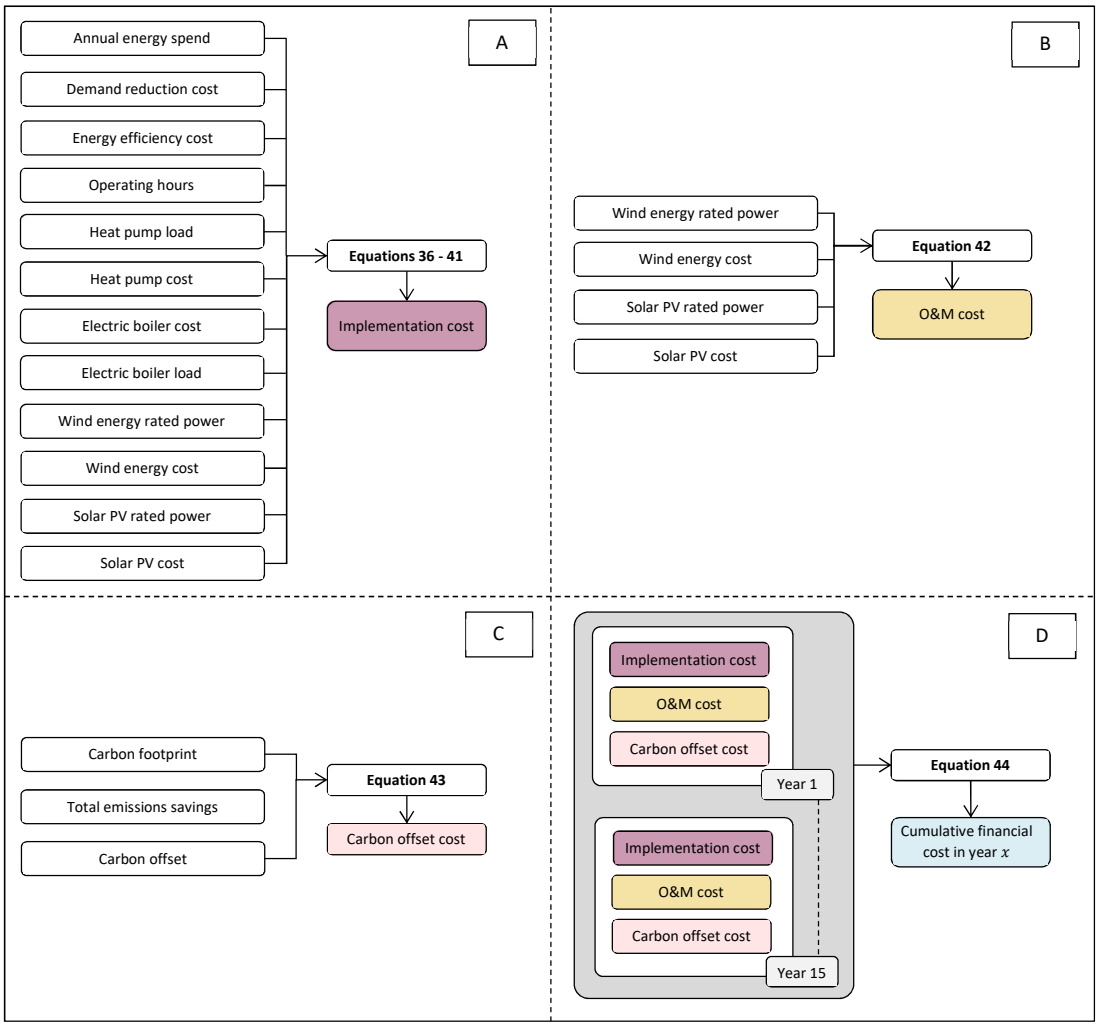


Figure 5.14: Graphical representation of financial cost equations

5.9 Case Study

A case study is presented to illustrate the operation of the modelling tool. It is based on an organisation with a carbon footprint of 10 000 tCO_2e arising from electrical and natural gas loads of 16.3 and 27.6 GWh, respectively. The thermal load of 25 GWh is addressed entirely by natural gas. The facility has a 24h operating schedule resulting in 8760 annual operating hours, and solar PV is the selected renewable technology.

Default values are used throughout the analysis. The user input sheets and the generated report are shown in Appendix A1 and A2, respectively. The generated outputs in the form of the carbon neutrality roadmap and the financial analysis are shown in Figure 5.15 and Figure 5.16, respectively. The waterfall steps are divided to indicate the electricity and gas savings in yellow and blue, respectively. The first two years show a decrease in both fuels, attributed to demand reduction and efficiency

savings. Years 3 and 4 indicate the overlap (in green) of the gas savings and the increase in electricity from electrification. Year 5 shows the electricity savings as a result of transferring the electrical load to solar PV. Finally, year 6 is the emissions balance to be offset through the purchase of carbon credits; these are emissions related to non-thermal, non-electrical loads, e.g. the use of natural gas directly for industrial processes. The financial analysis shows that the initial cumulative savings are greater than the cumulative costs of the investment in demand reduction, efficiency improvements, and electrification. The substantial investment in renewable energy outweighs the savings until year 13 where the breakeven point is reached. The steep savings curve in the later years highlights the compound effect of the emissions-reduction measures implemented in the initial years of the timeline.

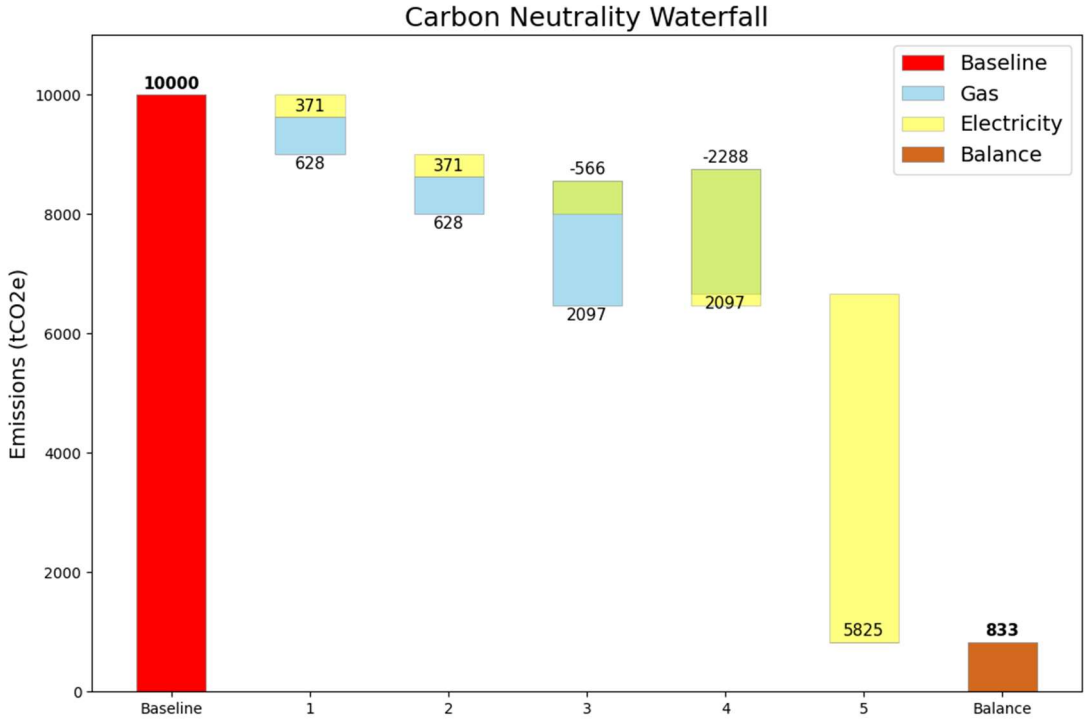


Figure 5.15: Case study: Carbon neutrality waterfall

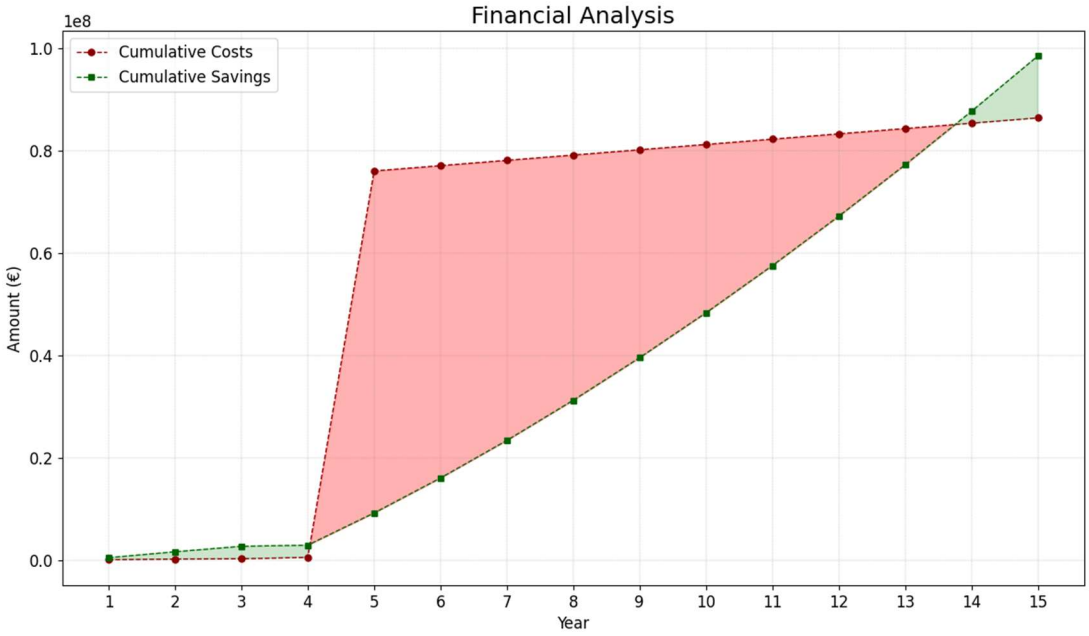


Figure 5.16: Case study: Financial analysis

5.10 Validation

The overarching requirement for the selection of a validation case study is that the organisation is a non-EII organisation. Further selection criteria are as follows: five-year plan to achieve carbon neutrality, planned implementation of specific demand reduction and/or efficiency measures, electrification strategy, planned investment in onsite renewable energy to address the full electrical load, and scoped investment costs for all measures and equipment. The selected case study was first modelled using the modelling tool with the baseline information as the user input. Then, the case study was modelled based on the actual planned projects and costs as a comparison for validation. The results showed that the total investment cost was overestimated by the model by 25%, which is predominantly attributed to the installation cost of the renewable energy system. Given that the intention of the high level modelling tool is to provide an indication of the scale of investment required to reach carbon neutrality to inform decision-making, the generated models can be considered feasibility studies to inform decision-making for investment in more detailed carbon neutrality planning. The +25% error in the validation case study falls within the expected error range for asset costing in feasibility projects as defined by the Association for the Advancement of Cost Engineering (AACE); these ranges are -

15% to +50% for process industries [169] and -20% to +30% for construction and building industries [170]. Using these industries as a guide, the case study error can be considered acceptable. In addition, this is a single case study and inputs are likely to vary between different applicable organisations. The inherent inputs used to calculate the investment costs of renewable energy are based on values from the literature, and to override these values would require a large number of validation case studies with similar results. Thus, no changes were made to the modelling tool as a result of the validation process using the single applicable case study.

5.11 Limitations and Uncertainty

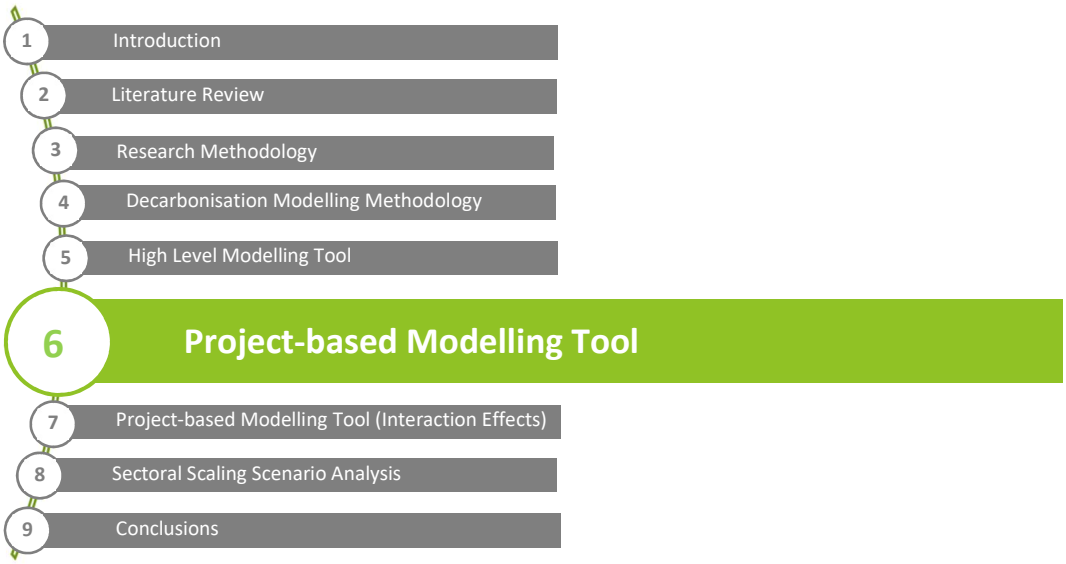
The modelling tool outputs a carbon neutrality pathway and financial analysis based on the following steps: demand reduction, energy efficiency improvements, electrification of high thermal load, and the use of installed onsite renewable electricity. As such, its applicability is limited to non-EII organisations that have high thermal loads suitable for electrification and that have sites suitable for the installation of renewable energy systems. The use of the modelling tool in other cases may yield inaccurate results, where the level of inaccuracy is difficult to quantify.

However, within the defined application, there are a number of assumptions that may lead to inaccuracy in the results—scenario inaccuracy resulting from the modelling tool design, and parameter inaccuracy resulting from assumed inherent inputs. In terms of scenario accuracy, the modelling tool assumes an emissions reduction of 20% from demand reduction and efficiency improvements combined in years 1 and 2. However, this can vary considerably; the study on which this average value is based exhibited a range of 0-57% based on 702 organisations. This equates to an uncertainty range of -21% to +12% for the total investment cost, based on default model inputs. In terms of parameter inaccuracy, the inherent inputs with the greatest effect on the generated models are the likely the wind energy and solar PV investments costs, however this uncertainty is difficult to quantify.

5.12 Conclusions

A high-level modelling tool for carbon neutrality in non-EII industrial manufacturing is presented, and the required user inputs, model inputs, and model equations on

which it is based are discussed. The generated outputs are intended to provide an indication of the scale of emissions reduction that can be achieved by implementing the recommended measures, and the financial impact thereof. There is likely a high level of inaccuracy since this model is applicable only where the assumptions are reasonable for the organisation. A validation case study leveraged for the project-based modelling tool and applied to this tool as a comparison indicates that the level of inaccuracy is in the region of 25% in terms of the investment cost to reach carbon neutrality. This is deemed acceptable since the aim of the high-level tool is to alleviate green stagnation by motivating organisations to further explore the carbon neutrality process by following the methodology detailed in Chapter 4. As such, it can be considered a feasibility study, which lowers the risk of investing in energy audits, heat studies, and renewable energy studies that form the basis for the more in-depth modelling tool presented in the following chapters.



6.1 Introduction

This chapter presents the project-based modelling tool of the modelling toolkit as highlighted in Table 6.1, and addresses the following research objective:

'RO2.2 - Development of a detailed, project-based modelling tool to aid non-EII industrial organisations in achieving carbon neutrality.'

Table 6.1: Modelling toolkit summary

Tool	Function	Ch.
High Level	Entry level tool for preliminary planning	5
Project-based	Detailed project-based tool	6
Project-based (Interaction Effects)	Progression of detailed project-based tool	7

This chapter focusses on the DMAIC Improve Step of the methodology, and involves the development of a detailed, projects-based modelling tool that requires significant user input derived from studies conducted as part of the methodology detailed in Chapter 4. The intention is to bridge the research and development gap between modelling tools aimed at the country or regional level, and commercial proprietary carbon-management software that are aimed at industrial organisations but do not appear to offer detailed and structured roadmaps to carbon neutrality.

The remainder of this chapter is as follows: section 6.2 provides an overview of the modelling tool in the form of a broad description and an operational overview.

Section 6.3 details the two categories of modelling tool inputs—the organisation-specific inputs required by the user and the built-in inputs inherent to the modelling tool. Section 6.4 presents the modelling tool methodology in the form of a flowchart. Section 6.5 describes the rationale behind the data preparation required as the first step in the modelling tool, and presents the relevant mathematical models. Sections 6.6 and 6.7 present the mathematical models used to generate the modelling tool outputs—carbon neutrality waterfall and financial analysis, respectively. Section 6.8 discusses the verification and validation approaches of the modelling tool, and details the verification process based on representative industrial data, and modelling tool validation by means of a case study. Section 6.9 presents the conclusions and discusses the limitations of this version of the modelling tool.

6.2 Modelling tool overview

The following sub-sections communicate the design and functionality of the project-based modelling tool, and provide a description and operational overview.

6.2.1 Modelling tool design and functionality

The package, class, activity, and use case diagrams of the project-based modelling tool are presented in Figure 6.1, Figure 6.2, Figure 6.3, and Figure 6.4, respectively. The deployment diagram is the same as that for the high level modelling tool (Figure 5.4).

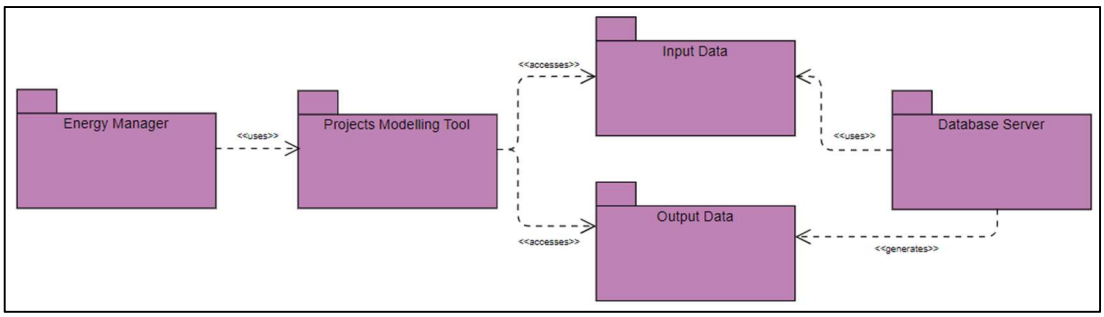


Figure 6.1: Package diagram

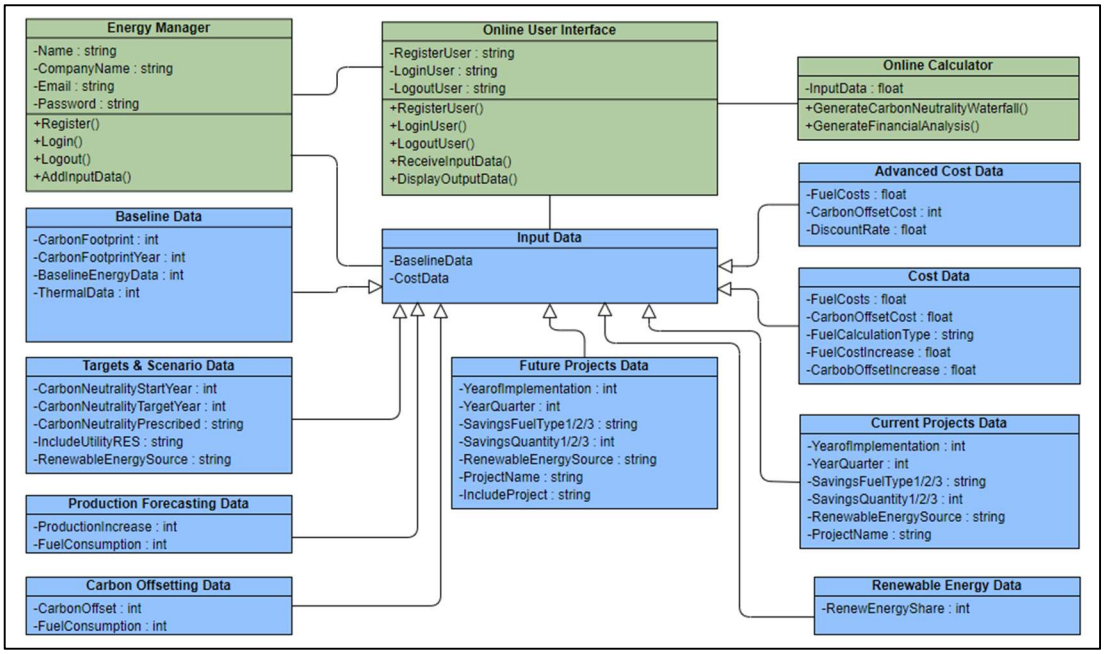


Figure 6.2: Class diagram

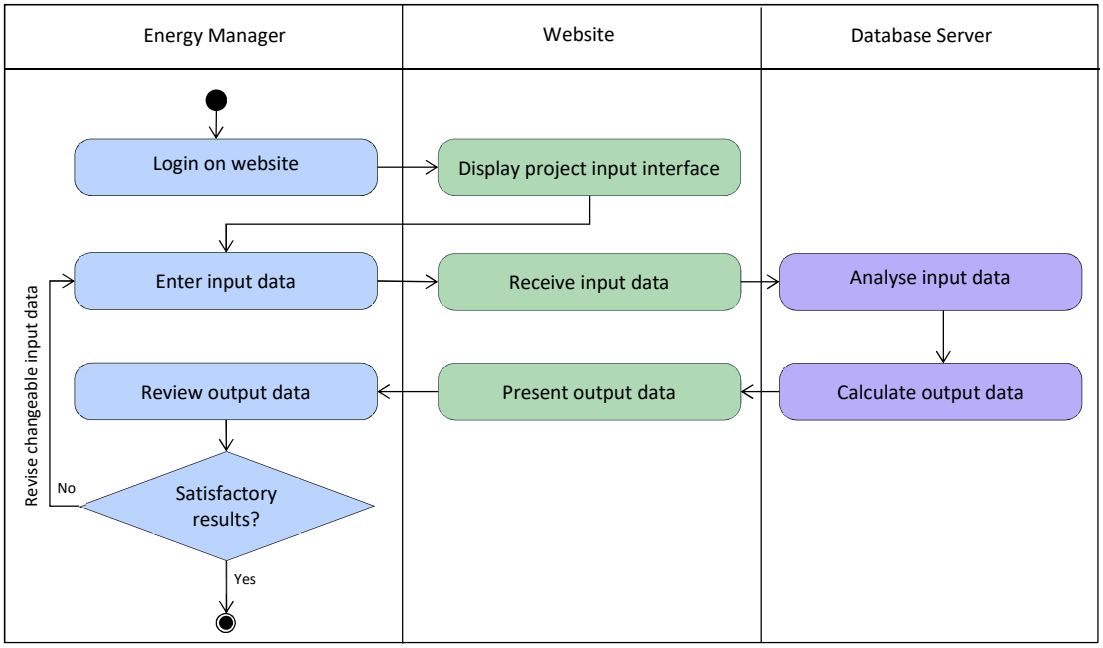


Figure 6.3: Activity diagram

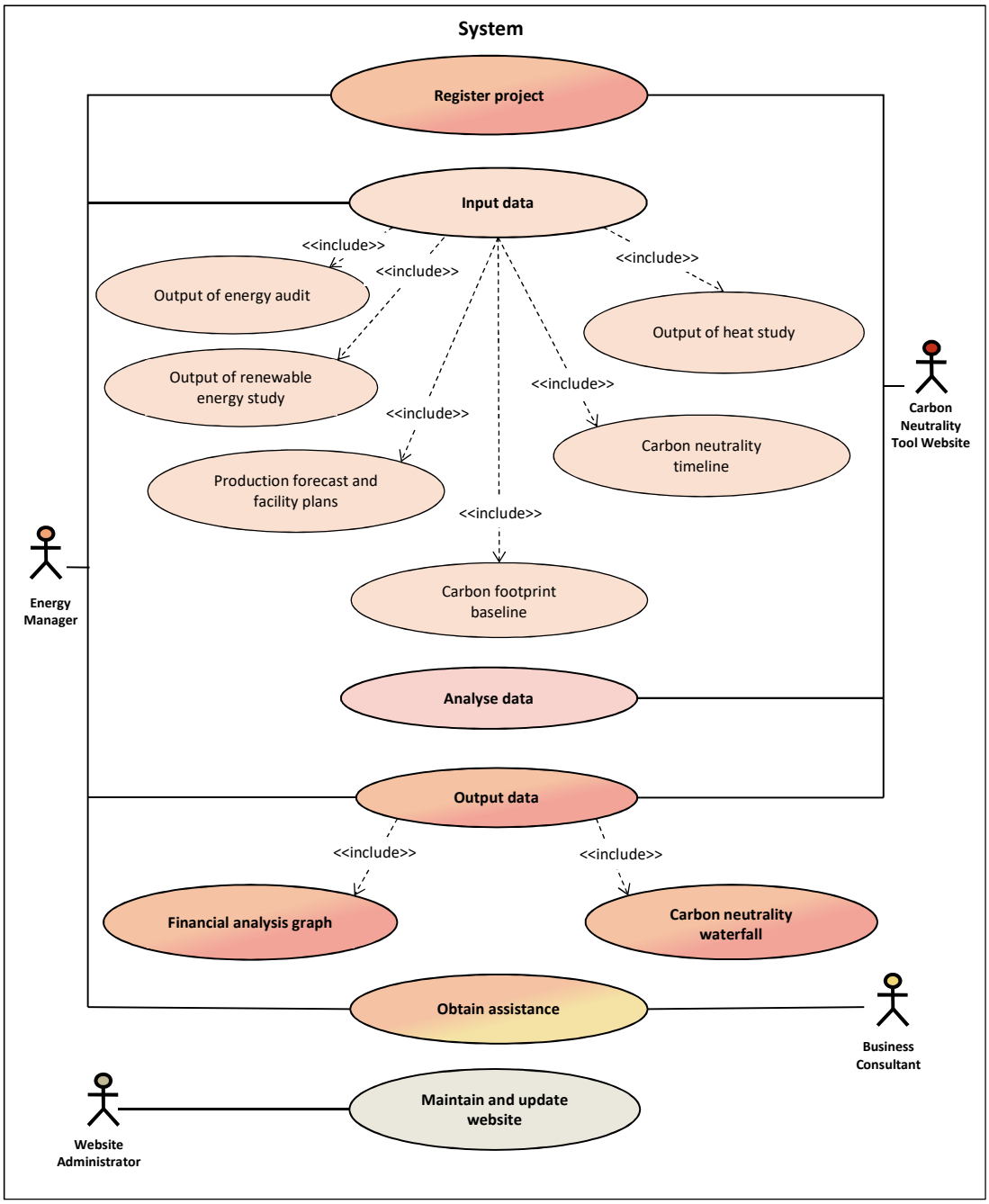


Figure 6.4: Use Case diagram

6.2.2 Modelling tool description

This modelling tool forms the basis of the Improve step of the DMAIC-SIPOC-based methodology for carbon neutrality in industrial manufacturing described in Chapter 4. It can be used in two ways—as a tool to explore the best options for achieving carbon neutrality, and as a decision-support system (DSS) to determine the impact of implementing emissions-reduction measures without the goal of carbon neutrality certification.

6.2.3 Modelling tool operational overview

Figure 6.6 shows a flowchart overview of the modelling tool, indicating the data sources, inputs, model outputs, and validation processes. There are two types of data source and associated model input—user and inherent, which are indicated by the large, grey, dashed blocks in the figure. The user input is organisation specific and comprises an Excel spreadsheet with nine sheets dedicated to different categories of model input; the input sheets are indicated by small, grey, blocks containing the model inputs (blue blocks). The data sources for the required information are various energy and emission reports as well as the organisation's energy manager (orange bocks). The inherent input comprises general inputs applicable to all organisations; these are based on national policies and protocols and are built into the modelling tool. The modelling tool outputs are a carbon neutrality waterfall and a financial analysis graph that indicates relevant financial metrics. These outputs were validated for accuracy through manual calculations, and for applicability through a case study of a medical device manufacturer using provided data; the validation results are shown to feed back into the model as they were used to correct or improve the model.

The modelling tool outputs generated in Python are a carbon neutrality waterfall and a financial analysis graph that indicates relevant financial metrics. These outputs were verified for accuracy through manual calculations, and validated for applicability through a case study of a medical device manufacturer using provided data; the validation results are shown to feed back into the model as they were used to correct or improve the model. The modelling tool inputs are discussed further in section 6.3, and the mathematical models used to generate the carbon neutrality waterfall and financial analysis outputs are presented in sections 6.6 and 6.7, respectively.

6.3 Model input

The two categories of modelling tool inputs (user and inherent) are discussed in detail in the following sub-sections.

6.3.1 User inputs

The majority of inputs are user inputs, which are those defined by the user for their organisation. They are based on the outputs of carbon footprinting, energy audits, heat studies, renewable energy studies, and supply chain data in accordance with the carbon neutrality methodology proposed in this work. The year and fiscal quarter of each user input is required. This time period was chosen to align with quarterly reporting to aid financial tracking, and because it is deemed sufficiently short given that near-term carbon neutrality roadmaps at the organisational level typically span five to ten years in line with the SBTi [144]. Note that where time-specific inputs are required, the input period runs for 15 years from the carbon footprinting baseline year; this is typically beyond the end of the carbon neutrality target year, but this allows further inputs to be taken into account in the financial analysis where the breakeven point may be outside of the carbon neutrality timeline.

There are ten tabs for completion on the user input sheet, two of which are dedicated to emissions-reduction measures—Current Projects and Future Projects. Current projects comprise implemented and approved projects, where the former are projects that have been completed since the year of the carbon footprint baseline, and the latter are projects that have been approved and planned for completion prior to the start of the carbon neutrality timeline. Future projects are optional emissions-saving measures that are under consideration for implementation within the carbon neutrality timeline. The differentiation of these projects is shown in Figure 6.5.

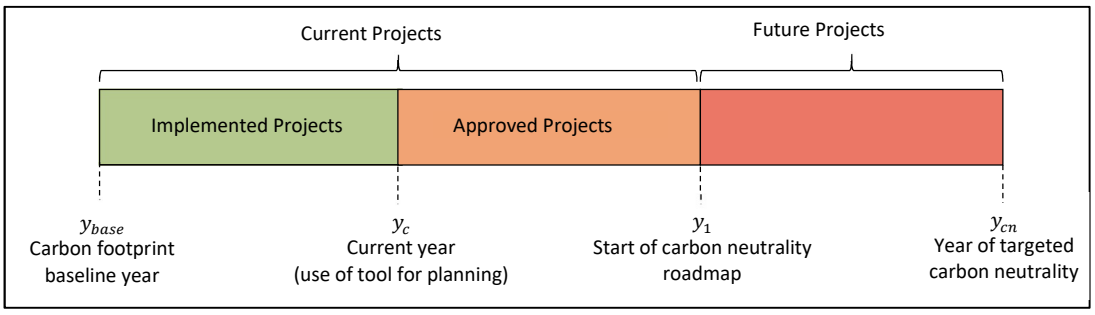


Figure 6.5: Project definition

The remaining eight tabs on the user input sheet are Baselines, Targets & Scenarios, Costs, Advanced Costs, Production Forecasting, Carbon Offsetting, Scope 3 Emissions

Reduction, and Renewable Share. The modelling tool user inputs for all tabs are discussed in the following sub-sections.

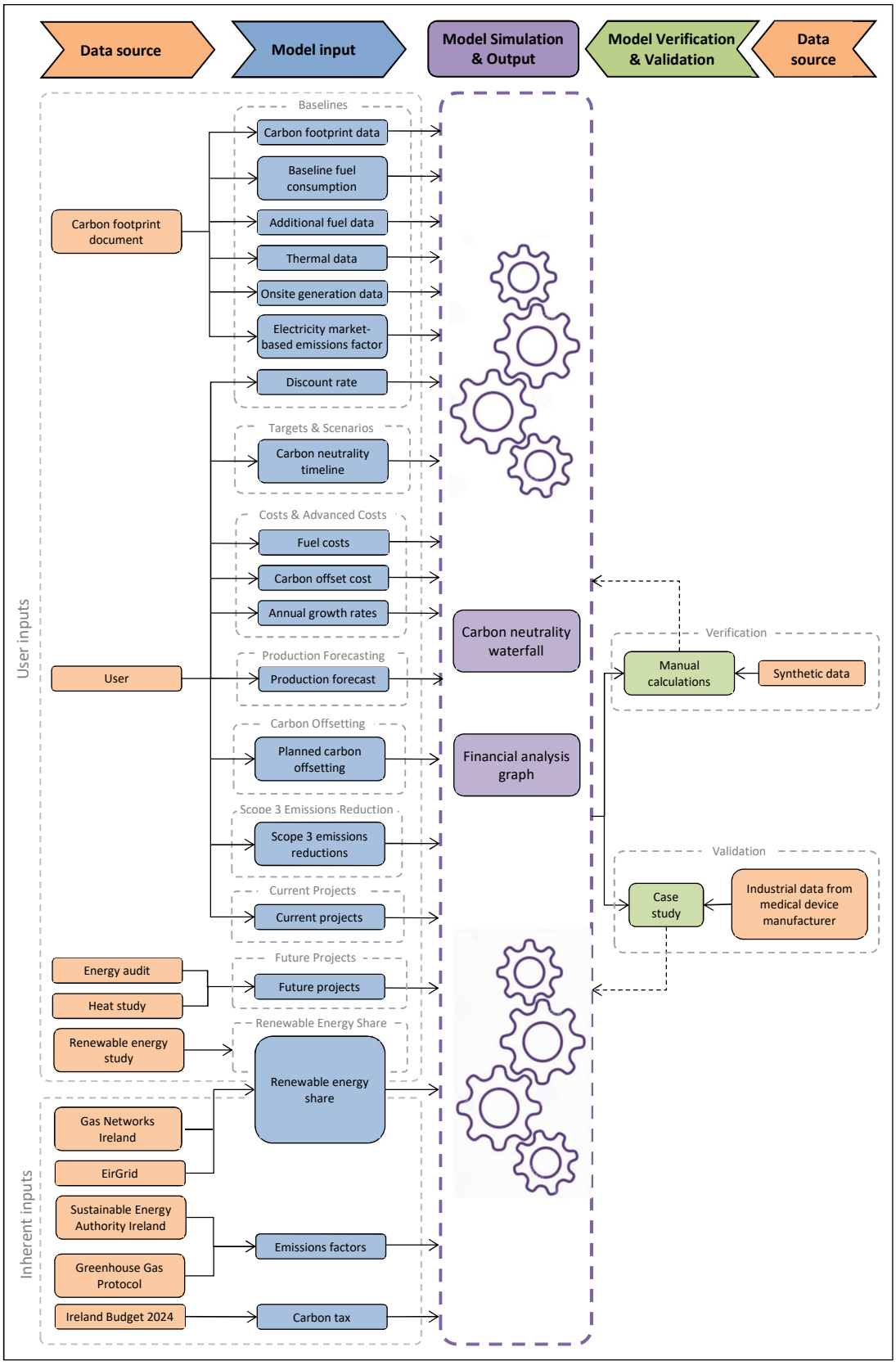
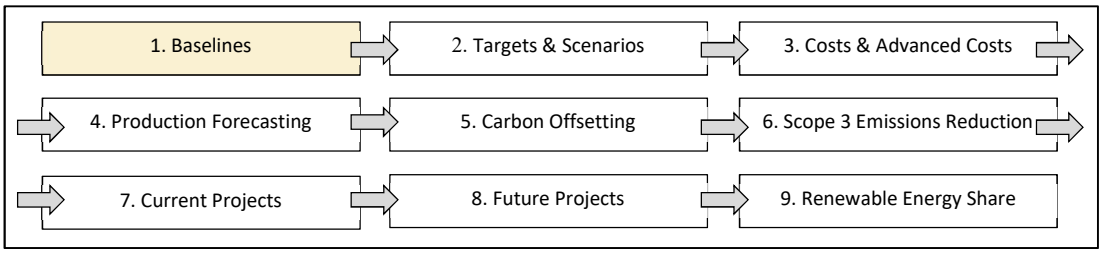


Figure 6.6: Model description – Project-based Modelling Tool

6.3.1.1 *Baselines*



The baseline inputs and their functions within the modelling tool are shown in Table 6.2, and the inputs relating to the energy sources and onsite generation are discussed in more detail in the subsequent sections. The baseline input data required can be sourced from the carbon footprinting exercise required in the Define Step of the methodology. Alternatively, for relevant organisations in Ireland, this data may be readily available from the LIEN questionnaire used to gather energy performance data.

Table 6.2: Inputs for Baselines

Input		Function
General	Year of most recent carbon footprint	Determines effect of increased renewable share and the projects implemented between footprint and start of carbon neutrality plan
	Carbon footprint	Forms emissions baseline for waterfall
	Discount rate	Rate of return in financial analysis
Energy sources	Baseline fuel consumption (standard fuels)	Calculates savings from increased renewable energy share
	Number of additional fuels considered?	Provides option for additional fuels to be added

	Baseline fuel consumption (additional fuel)	Calculates the savings from increased renewable energy share
	Baseline fuel emissions factor (additional fuel)	Used in emissions reduction calculations
	Electricity market-based emissions factor	Used in emissions calculations to relate electricity emissions savings to baseline emissions
	Steam output – gas/oil boilers (MWh)	Relates thermal load to energy input
	Steam output – electric boilers (MWh)	
	Steam boiler efficiency (gas/oil)	
	Steam boiler efficiency (electrode)	
	HW output – gas/oil boilers (MWh)	
	HW output – electric boilers (MWh)	
	HW output – heat pumps (MWh)	
	HW output – steam heat exchange (MWh)	
	HW boiler efficiency (gas/oil)	
	HW boiler efficiency (electrode)	
	HW heat pump efficiency	
	Steam-HW heat exchange efficiency	
Onsite generation	Onsite electrical generation – gas (MWh)	Used in emissions reduction calculations
	Efficiency of gas- or oil-fuelled generators	
	Onsite electrical generation – oil (MWh)	
	Efficiency of diesel-fuelled generators	

6.3.1.1.1 General

The carbon footprint and the year it represents are required as baseline data for the carbon neutrality roadmap. The discount rate is the rate of return used in the

financial analysis to adjust future cash flows to their present values; this is specific to the organisation as it is dependent on the investment risk level.

6.3.1.1.2 Energy sources

The standard fuels are electricity, gas, and oil as per the high level modelling tool. Combustion for heat is the highest contributor to Ireland's industrial emissions [21], and there is a focus on reducing the associated emissions to achieve carbon neutrality. Steam and hot water are outputs from combustion for heat on site and are mediums for transferring thermal energy. Since they are reliant on standard fuels, they cannot be classified as fuels themselves. As such, they straddle the supply and demand sides by functioning as both a user and a source of energy, as shown in Figure 6.7. Since industrial processes can be powered by standard fuels or these thermal mediums, the term 'Energy Source' is used as the user input. The user input sheet provides the following energy source options, for which the baseline fuel consumption must be defined: Electricity (MWh), Gas (MWh), Oil (kl), Thermal: Steam (MWh), Thermal: HW (MWh), and Additional Fuel (Unit). The additional fuel option allows for the inclusion of any less common fuels, such as petrol, coal, wood chip, and milled peat. The emissions from the additional fuel is accounted for in the baseline carbon footprint, and thus it need only be added if it is affected by emissions-reduction measures or its renewable share is set to increase, in which case the emissions factor needs to be defined.

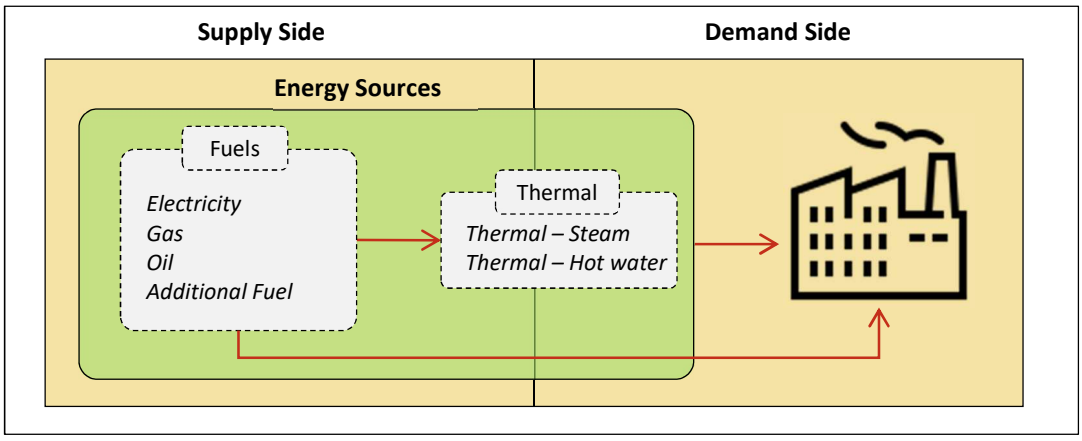


Figure 6.7: Definition of energy sources

The market-based emissions factor for electricity used to calculate the carbon footprint may be entered to ensure consistency between the baseline emissions and

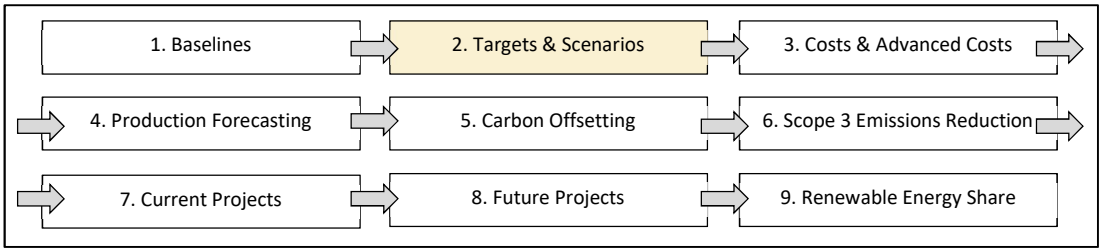
emissions savings. Alternatively, a location-based emissions factor can be calculated within the modelling tool, and this is discussed further in section 6.3.2.2.

Further detail in the form of the origin and the thermal efficiency is required to process the thermal energy sources. The origin options for steam are gas, oil, and electrode boilers; the origin options for hot water are gas, oil, and electrode boilers; heat pumps; and heat exchange with the steam line. The thermal efficiencies are required to relate the demand side to the supply side by the conversion of the thermal loads to the fuel input to calculate the emissions savings.

6.3.1.1.3 Onsite electrical generation

A portion of the electricity consumed on site may be generated onsite by non-renewable sources such as gas-or oil-powered equipment, e.g. combined heat and power generators. The energy savings attributed to emissions-reduction measures of electrical equipment are based on the electricity used and not the fuel powering the source of this electricity. Thus, the efficiencies of the gas- and oil-fuelled generation plants and their contributions to the total electricity consumed on site are required to calculate the baseline electricity emissions factor and the total electricity available.

6.3.1.2 *Targets & Scenarios*



Scenario analysis allows the comparison and evaluation of roadmaps and financial analysis based on different input data. The user input sheet need only be filled in once, and different scenarios can be turned on and off to vary the model outputs. This scenario modelling provides an overview of possible future outcomes and financial impacts and it is intended as a decision-support tool to highlight the optimal scenario based on user-defined constraints. The first scenario modelling option in this section is the commitment to carbon neutrality. If carbon neutrality is prescribed, then it must be achieved and the remaining emissions in the target year must be

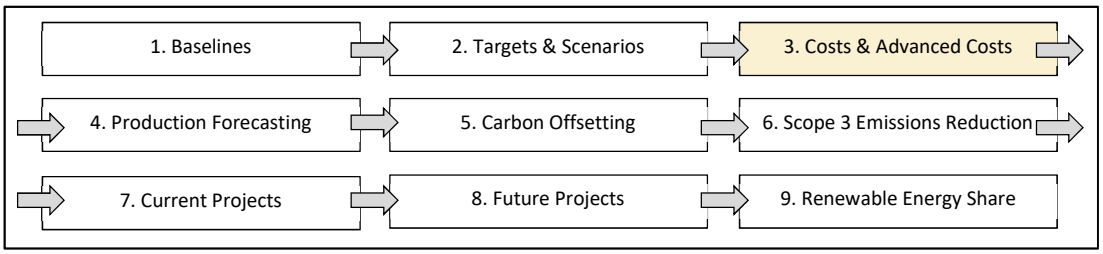
balanced by carbon offsetting. If it is not prescribed, the financial model can be used as a decision-support tool to visualise the financial effect of implementing the emissions-reduction measures.

The second scenario modelling option in this section is the inclusion of the renewable energy shares of the utilities; these are model inputs based on the projected shares by Ireland's utility providers. This is provided as a scenario rather than being inherent to the model as there is more risk related to relying on measures outside the control of the organisation. Although the resulting figures should be viewed with caution, this scenario indicates the effect of utility participation. Note that the utility renewable energy shares are included from the baseline year to the current year regardless of the scenario since these values are reliable. In the scenario where the renewable energy share is excluded over the carbon neutrality timeline, the utility emissions factors remain as those of the current year. The required user inputs and their functions for these scenarios and the carbon neutrality targets are shown in Table 6.3.

Table 6.3: Inputs for Targets & Scenarios

Input	Function
Carbon neutrality start year	Determines first year of carbon neutrality waterfall
Carbon neutrality target year	Determines final year of carbon neutrality waterfall, after which balance of emissions is shown
Is carbon neutrality prescribed?	Determines if carbon offset cost is included in financial analysis
Should the proposed future renewable share from the utility provider be included?	Inclusion of the utility renewable share decreases emissions and therefore carbon tax and carbon offset costs

6.3.1.3 *Costs & Advanced Costs*



There are two input options for the user-defined costs for the renewable and utility source of each fuel, as well as the current carbon offset. The simple option requires the current cost (€) and estimated annual growth rate (%); the advanced input option requires manual input for each year as far as is known. This functionality is more likely to be used in the carbon offset case where companies have entered agreements, resulting in fixed costs for a set period. However, the functionality is provided for all cost inputs. The initial cost inputs are shown in Table 6.4 for a single parameter; and the advanced options are shown in Table 6.5. For both the simple and advanced costs, the parameters are utility and renewable contributions of electricity, gas, and oil, as well as the carbon offset. The renewable energy costs are input in this manner as a unit cost; this is in contrast to the high level modelling tool in which the approach used is investment in onsite renewable energy generation. However, this approach can be used in this tool by adding the renewable energy project as an emissions-reduction measure with an associated cost. In this way, this modelling tool allows for different options of including renewable energy.

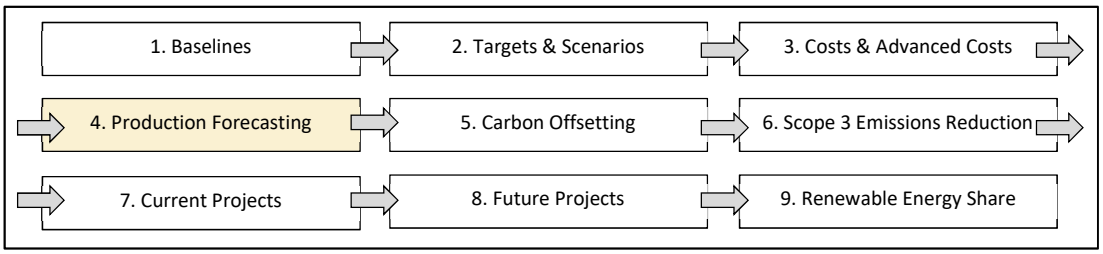
Table 6.4: Inputs for Simple Costs

Input	Function
Input option	Dropdown menu to choose Simple or Advanced option
Cost (€/unit)	Current cost to use as baseline in Simple option only
Annual increase (%)	Annual cost increase to calculate the future value

Table 6.5: Inputs for Advanced Costs

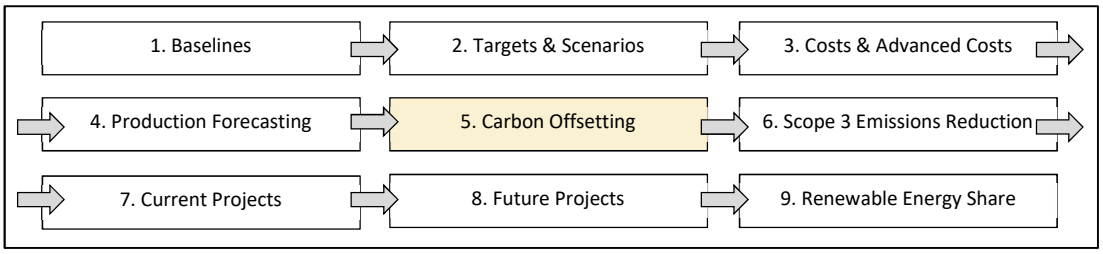
Input	Function
Cost per year (€/unit/yr)	Used directly in the calculations as future values

6.3.1.4 *Production forecasting*



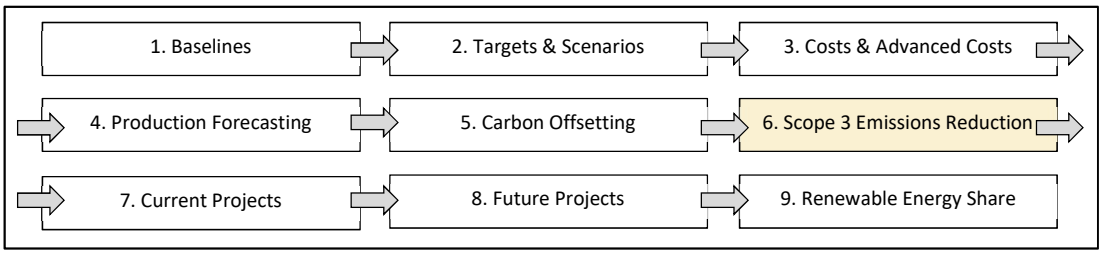
The production forecasting input captures major energy consumption increases in the period between the carbon footprint baseline year and the start of carbon neutrality timeline to ensure that the most accurate values are used at the beginning of the roadmap. This input applies to substantial changes in consumption related to the installation of new production lines, rather than to expected annual fluctuations in energy consumption. Future energy increases can be input into the carbon neutrality timeline at the point at which they are expected to come online. The inputs start from the time period following the baseline year, and are input as percentage increases from the baseline year. Alternative increases in energy consumption that are not directly related to production, such as those associated with facility expansion, can be input directly into the current or optional projects input sheets as negative savings.

6.3.1.5 *Carbon offsetting*



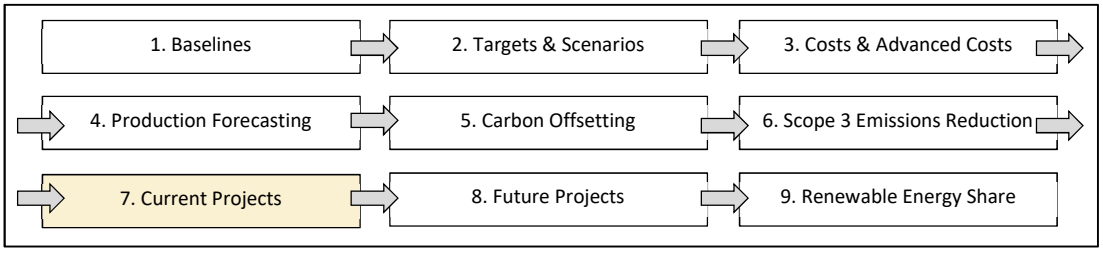
Some organisations may undertake carbon offsetting projects prior to achieving a carbon neutral status. This input captures any emissions that have been offset between the baseline year and the current year, as well as any planned future offsetting. However, this applies only to offsets that are intended as recurring quarterly amounts. The cost of this is not included in the financial analysis since it is already captured in the budget as a planned item.

6.3.1.6 *Scope 3 emissions reduction*



Since scope 3 emissions sources contributing greater than 1% of the total GHG emissions total are required in carbon neutrality accounting, there may be planned measures to reduce these emissions. Scope 3 emissions cover a broad range of sources that are calculated either from primary data obtained from suppliers, or from secondary data obtained from databases. These calculations can be complex, and may include scaled modelling based on representative data. In addition, the emissions factors built into this modelling tool are specific to the organisation as they consider the renewable energy share; these are not appropriate for emissions sources outside of the organisation. Thus, any emissions savings attributed to changes in the value chain are first calculated and then entered directly into this input sheet. Note that only scope 3 reductions from sources considered in the carbon footprint can be input into the modelling tool to avoid overestimation of emissions savings.

6.3.1.7 *Current projects*



The energy and emissions savings of all current projects (implemented and approved) must be accounted for in the model to adjust the carbon footprint calculated in the baseline year to yield the emissions balance at the start of the carbon neutrality roadmap. The year and fiscal quarter of the planned completion of each emissions-reduction measure is required as the time period. The energy savings and associated emissions reductions are considered in the time period following completion to

ensure that the savings are realised over the full time period. This is a conservative approach as there may be unaccounted emissions savings within the implementation time period depending on the date of completion.

The input sheet has entries for up to three energy sources per measure. This captures the full effect of the emissions reduction since some measures affect more than one energy source (e.g., an electrode boiler decreases gas consumption and increases electricity consumption; a CHP system decreases thermal and electrical consumption, and increases gas or oil consumption).

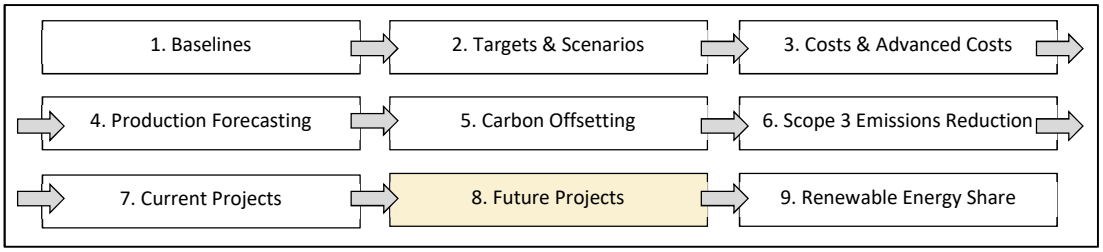
The financial data is in the form of the capital cost to implement the measure and any additional grant support for which the project is eligible. Financing options available to industrial organisations implementing emissions-reduction measures involving capital equipment include loans, operating leases, capital leases, and energy performance contracts. However, these cost models are complex and are deemed beyond the scope of this modelling tool. Consequently, only cash purchase is considered, where payment (less any grants) is due on completion of the project. Only the financial data of approved projects are considered because implemented projects are assumed to be settled financially prior to the current planning time period in which the tool is used. Maintenance costs for all measures are not considered; this is a conservative approach since new technologies are likely to have lower maintenance costs than the older equipment they are replacing, and maintenance costs are expected to be negligible for efficiency projects.

The required user inputs and their function within the modelling tool for the current projects are shown in Table 6.6.

Table 6.6: Inputs for Current Projects

Input	Function
Project name	Description of the emissions-saving measure
Year of implementation	Year of planned project completion
Fiscal quarter	Quarter within the implementation year (1, 2, 3, or 4)
Number of energy sources affected	*n* = 1, 2, or 3
Savings energy source 1, 2, or 3	Select option for energy source affected (Electricity in MWh, Gas in MWh, Thermal: Steam in MWh, Thermal: HW in MWh, Oil in kl, Additional Fuel in units defined, or Not Applicable if only one energy source is affected). This is entered separately for each energy source.
Savings quantity 1, 2, or 3	Estimated energy source quantity saved in units shown. This is entered separately for each energy source.
Implementation cost (€)	Capital cost to implement emissions-saving measure
Business grant (€)	Business grants received to implement project

6.3.1.8 *Future projects*

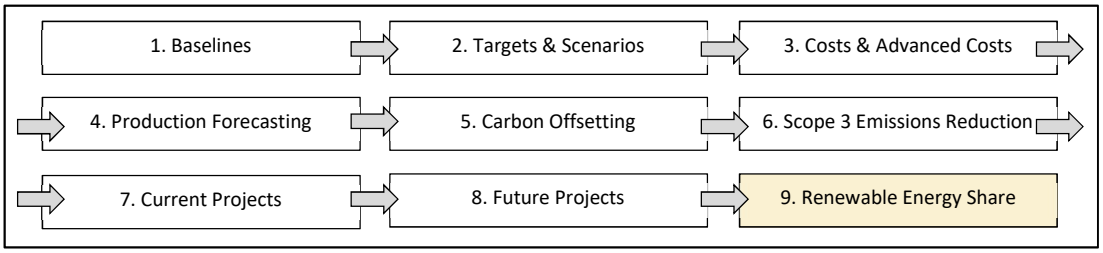


The inputs for future projects are the same as those for current projects, with the addition of a selection box for inclusion in the model. This selection box allows the project data to be entered into the model once to make it available for inclusion or exclusion when exploring output options. The required user inputs and their function within the modelling tool for the optional projects are shown in Table 6.7.

Table 6.7: Inputs for Future Projects

Input	Function
Project name	Description of the emissions-saving measure
Year of implementation	Year of planned project completion
Fiscal quarter	Quarter within the implementation year (1, 2, 3, or 4)
Savings energy source 1, 2, or 3	Select option for energy source affected (Electricity in MWh, Gas in MWh, Thermal: Steam in MWh, Thermal: HW in MWh, Oil in kl, Additional Fuel in units defined, or Not Applicable if only one energy source is affected). This is entered separately for each energy source.
Savings quantity 1, 2, or 3	Estimated energy source quantity saved in units shown. This is entered separately for each energy source.
Implementation cost (€)	Capital cost to implement emissions-saving measure
Business grant (€)	Business grants received to implement project

6.3.1.9 *Renewable energy share*



The inputs for renewables are the renewable energy share for each fuel type for the carbon neutrality timeline and beyond as far as is known or estimated; the inputs start with the year of the carbon footprinting in order to determine the baseline renewable energy shares. Where the percentage of renewable energy has not been specified, the last given value is used. These values should only include standalone renewable energy sources fed directly into the organisation, and should not take into account the forecasted renewable energy share of utility providers. The renewable energy share entered here is used in the waterfall calculations to determine the emissions savings contribution to the emissions-reduction measures implemented within the specified timeline, as well as the ongoing emissions savings of the total

site load past the carbon neutrality target year. The renewable energy costs are entered on the costing input sheet (section 6.3.1.3) to account for the cost of the additional renewable energy. Investments in the provision of the additional renewable energy to site must be input as emissions-reduction measures to account for the capital and installation costs.

6.3.2 Inherent inputs

The three inherent model inputs—financial inputs, emissions factors, and the renewable energy shares of the utilities—are discussed in this section.

6.3.2.1 *Financial inputs*

Carbon Tax is the only inherent financial input as it is set at the national level and is independent of the user's organisation. The carbon tax values presented in section 5.5.2.2 apply to this modelling tool.

6.3.2.2 *Emissions factors*

The inherent emissions factors used in the modelling tool are as per Table 5.9 in section 5.5.2.3. For electricity, this value represents the location-based emissions factor, which considers the actual fuel mix and methods of electricity generation in the geographical region in which it is consumed, and reflects the average emissions intensity of the local electricity grid [171]. However, the electricity emissions factor can also be calculated using a market-based approach. The market-based approach represents the energy intensity of the energy mix by considering the emissions related to all purchased electricity, including those from contract instruments such as power purchase agreements. The overall emissions factor for the organisation is calculated based on emissions factors provided by suppliers and the relative contributions of their energy mix to the total electricity consumed [171]. Market-based emissions factor are specific to the organisation and can be entered in the Baseline user input sheet, as discussed in section 6.3.1.1.2.

Note that these emissions factors are subject to further adjustment based on user-specific scenarios, as detailed in section 6.5.3.3. These emissions factors are applied throughout the carbon neutrality timeline, with changes made only to account for

increases in renewable energy share (both user and utility where applicable). In reality, the electricity emissions factor is also dependent on the non-renewable energy mix which is likely to change slightly over time since approximately 15% of the 2023 mix comprises coal, peat, oil, imports, and other non-renewables, and imports; these are expected to be reduced or phased out in the coming years.

6.3.2.3 *Utility renewable energy share*

The scenario where the renewable energy shares of the utility providers are considered uses the following proposed levels to calculate the overall emissions factors used in the model.

- Electricity – The renewable energy share for electricity is as per Ireland's electricity grid operator EirGrid's 'Shaping Our Electricity Future Roadmap' [172], where the emissions reduction is mainly attributed to wind energy (predominantly onshore). For the years beyond 2030, the renewable share remains at the 2030 level since no further reduction has been proposed.
- Natural Gas – The renewable energy share for natural gas is as per Gas Networks Ireland's Vision 2050 [173], where the emissions reduction is mainly attributed to abated natural gas with carbon capture and storage, with additional reductions from increasing shares of the renewable gases Biomethane and hydrogen.
- Oil – No utility RES is considered.

6.4 Modelling Methodology

The modelling methodology is described in the flowchart in Figure 6.8. The input data is analysed to calculate the fuel consumption savings and the emissions factors (section 6.5) in preparation for the carbon neutrality waterfall calculations and the financial analysis detailed in sections 6.6 and 6.7, respectively.

6.5 Data Preparation

First, the energy savings associated with the emissions-reduction measures are converted to fuel consumption savings. Then, the fuel consumption for each time period is calculated using these savings along with the forecasted changes in

production level. This fuel consumption is made up of different energy sources, and the contributions of each are quantified. The RES of the utilities is calculated based on the chosen inclusion scenario. Finally, the emissions factors are adjusted to consider the RES of the utilities. This process is discussed in further detail in the following sub-sections.

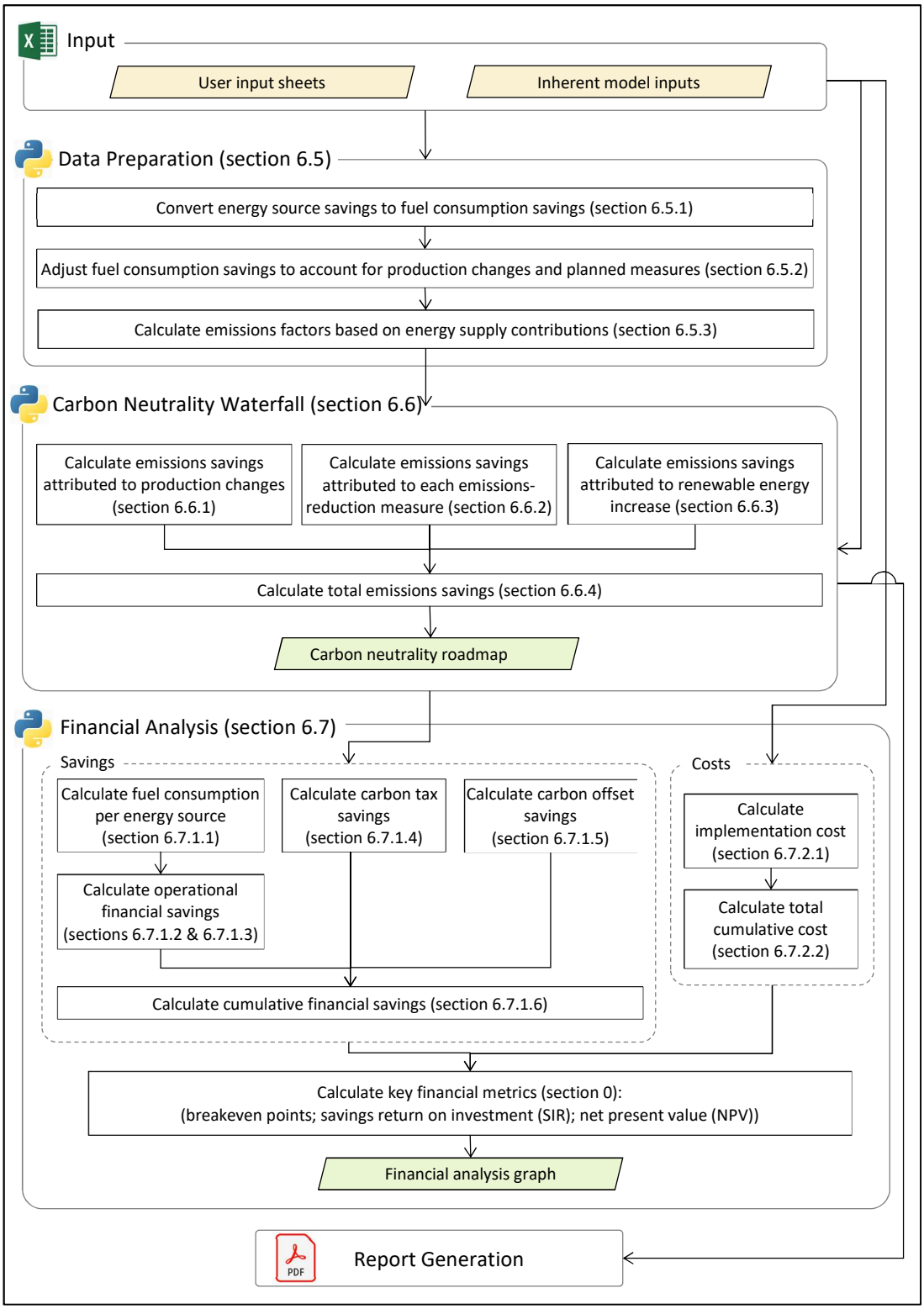


Figure 6.8: Flowchart of modelling methodology – Project-based modelling tool

6.5.1 Energy Source Savings Conversion to Fuel Consumption Savings

The energy source savings entered into the input sheet represent annual savings attributed to each measure, whereas this modelling tool uses quarter-years as the

calculation time period. These annual savings are converted to quarterly savings as shown in Eq. 45.

$$ESS_{quarterly} = \frac{ESS_{annual}}{4} \quad \text{Eq. 45}$$

The emissions factors and emissions savings calculations require the energy savings attributed to the emissions-reduction measures to be input as fuel savings. The electricity, gas, and oil savings can be input directly. However, the thermal energy savings (steam and hot water) must be converted to fuel savings using the baseline input to consider the relative contributions of each fuel and to account for boiler and heat pump efficiencies. This process is shown graphically in Figure 6.9 and described by the following equations.

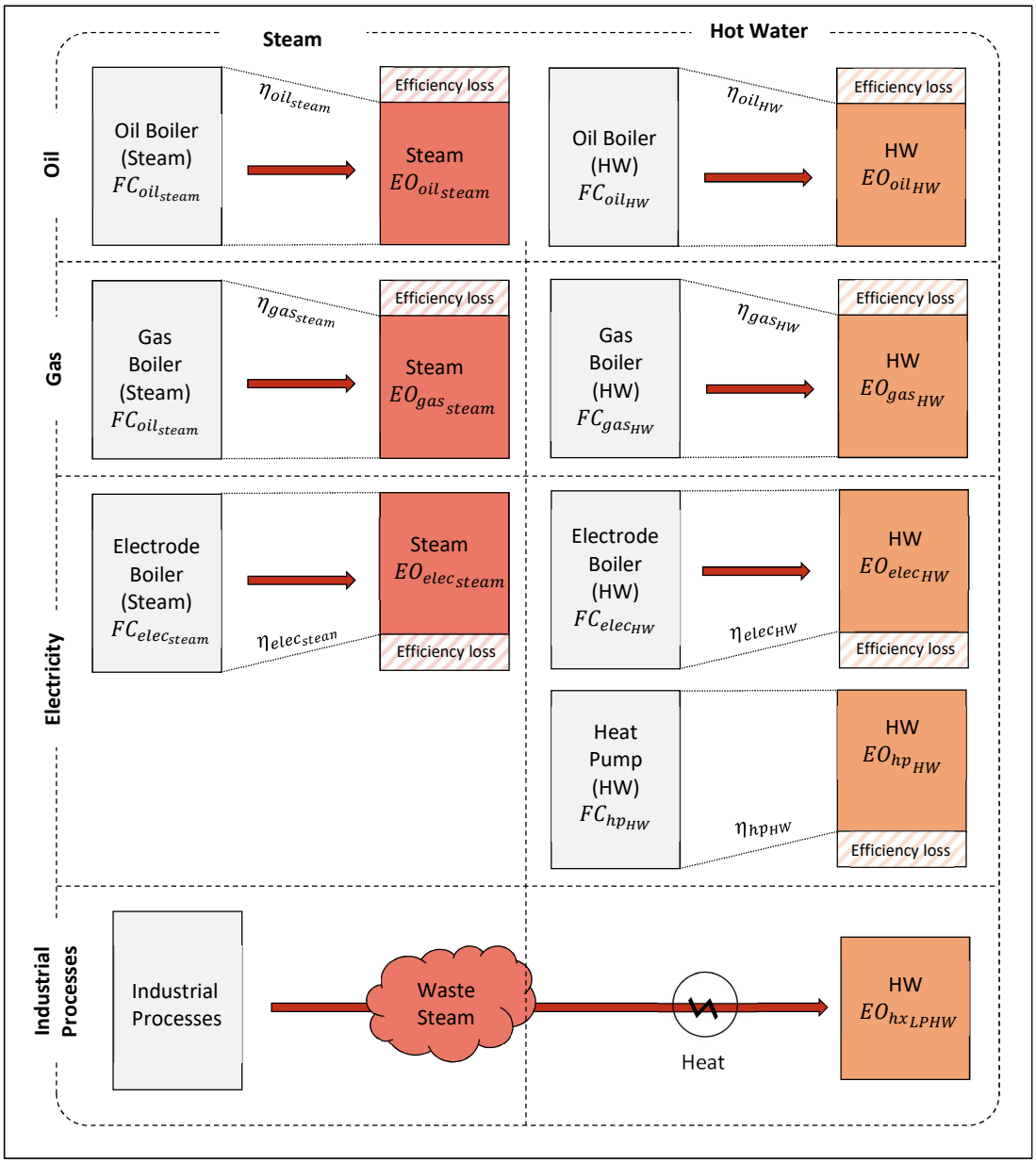


Figure 6.9: Conversion of thermal energy sources to fuels

Steam is generated by means of gas, oil, and electrode boilers. The gas, oil, and electrical consumption savings attributed to steam savings are calculated for each measure as per Eq. 46, Eq. 47, and Eq. 48, respectively, using the energy source savings, boiler output and efficiency, and the portion of total steam attributed to each fuel.

$$\underbrace{FCS_{gas_{steam}}}_{\text{Gas savings from steam savings}} = \underbrace{ESS_{steam}}_{\text{Steam savings}} \times \underbrace{\frac{1}{\eta_{gas_{steam}}}}_{\text{Boiler efficiency}} \times \underbrace{\left(\frac{EO_{gas}}{EO_{gas} + EO_{oil} + EO_{elec}}\right)_{steam}}_{\text{Portion of total steam provided by gas boilers}} \quad \text{Eq. 46}$$

$$\underbrace{FCS_{oil\,steam}}_{\text{Oil savings from steam savings}} = \underbrace{ESS_{steam}}_{\text{Steam savings}} \times \underbrace{\frac{1}{\eta_{oil\,steam}}}_{\text{Boiler efficiency}} \times \underbrace{\left(\frac{EO_{oil}}{EO_{gas} + EO_{oil} + EO_{elec}}\right)_{steam}}_{\text{Portion of total steam provided by oil boilers}} \quad \text{Eq. 47}$$

$$\underbrace{FCS_{elec\,steam}}_{\text{Electricity savings from steam savings}} = \underbrace{ESS_{steam}}_{\text{Steam savings}} \times \underbrace{\frac{1}{\eta_{elec\,steam}}}_{\text{Boiler efficiency}} \times \underbrace{\left(\frac{EO_{elec}}{EO_{gas} + EO_{oil} + EO_{elec}}\right)_{steam}}_{\text{Portion of total steam provided by electrode boilers}} \quad \text{Eq. 48}$$

The total hot water calculation includes two additional terms. The first accounts for hot water generated by heat exchange with waste steam liberated from industrial processes. Waste steam is generated regardless of its use in heat exchange, and thus the efficiency of this heat exchange is irrelevant and there are no fuel savings associated with this portion. The second term accounts for hot water generated by heat pumps. The total gas and oil consumption savings attributed to hot water savings are calculated as per Eq. 49 and Eq. 50, respectively, for each measure.

$$\underbrace{FCS_{gas\,HW}}_{\text{Gas savings from HW savings}} = \underbrace{ESS_{HW}}_{\text{HW savings}} \times \underbrace{\frac{1}{\eta_{gas\,HW}}}_{\text{Boiler efficiency}} \times \underbrace{\left(\frac{EO_{gas}}{EO_{gas} + EO_{oil} + EO_{elec} + EO_{hp} + EO_{hx}}\right)_{HW}}_{\text{Portion of total HW provided by gas boilers}} \quad \text{Eq. 49}$$

$$\underbrace{FCS_{oil\,HW}}_{\text{Gas savings from HW savings}} = \underbrace{ESS_{HW}}_{\text{HW savings}} \times \underbrace{\frac{1}{\eta_{oil\,HW}}}_{\text{Boiler efficiency}} \times \underbrace{\left(\frac{EO_{oil}}{EO_{gas} + EO_{oil} + EO_{elec} + EO_{hp} + EO_{hx}}\right)_{HW}}_{\text{Portion of total HW provided by gas boilers}} \quad \text{Eq. 50}$$

The hot water electrical consumption savings require more complex calculation to account for hot water generated by both electrode boilers and heat pumps, and their respective energy source savings are described by Eq. 51 and Eq. 52. The total electrical consumption savings for each measure is as per Eq. 53.

$$\underbrace{\left(FCS_{elec\,HW}\right)_{boiler}}_{\text{Electricity savings from electrode HW boilers}} = \underbrace{\left(ESS_{HW} \times \frac{1}{\eta_{gas\,HW}} \times \left(\frac{EO_{elec}}{EO_{gas} + EO_{oil} + EO_{elec} + EO_{hp} + EO_{hx}}\right)_{HW}\right)}_{\text{HW savings} \times \text{Boiler efficiency} \times \text{Portion of total HW provided by electrode boilers}} \quad \text{Eq. 51}$$

$$\underbrace{\left(FCS_{elec\,HW}\right)_{hp}}_{\text{Electricity savings from electric heat pumps}} = \underbrace{\left(ESS_{HW} \times \frac{1}{\eta_{hp}} \times \left(\frac{EO_{hp}}{EO_{gas} + EO_{oil} + EO_{elec} + EO_{hp} + EO_{hx}}\right)_{HW}\right)}_{\text{HW savings} \times \text{Heat pump efficiency} \times \text{Portion of total HW provided by electric heat pumps}} \quad \text{Eq. 52}$$

$$\underbrace{\left(FCS_{elec_{HW}}\right)_{total}}_{\text{Total electricity savings from HW}} = \underbrace{\left(FCS_{elec_{HW}}\right)_{boiler}}_{\text{Electricity savings from electrode boilers}} + \underbrace{\left(FCS_{elec_{HW}}\right)_{hp}}_{\text{Electricity savings from electric heat pumps}} \quad \text{Eq. 53}$$

6.5.2 Adjusted Fuel Consumption

The total fuel consumption per time period is affected by two metrics—the fuel consumptions savings of all emissions-reduction measures planned for implementation in the previous time period, and the change in production level since the previous time period. (Renewable energy is not considered at this stage since it concerns the fuel source rather than the quantity.) Production changes affect the total site energy consumption, but only a percentage of the total energy is associated with production. This percentage is dependent on the product type and the manufacturing processes, leading to a broad range of values, with energy-intensive industries having a higher percentage. In addition, the breakdown of the fuels related to production differs between facilities. To allow some measure of including production-related energy changes, the modelling tool assumes that 70% of energy is associated with production. This is calculated from the UK 2023 industrial end-use breakdown comprising end-use data of all industrial sectors for 2022 [174]. It is assumed that the end uses related to production are high-temperature processes, low-temperature processes, drying/separation, and compressed air; and the end uses related to the facility are lighting, space heating, motors, refrigeration, and other. The modelling tool further assumes that the fuel breakdown is consistent with the calculated fuel consumption values of the previous time period.

In the user input sheet, the production increase is defined as the total percentage increase in the baseline fuel consumption. In the modelling tool, the total potential fuel consumption savings related to production increase is determined by finding the incremental increase since the previous time period and applying this to the previous years' fuel consumption (Eq. 54). This is then scaled using the proportion of savings considered in the modelling tool, as shown in Eq. 55. The cumulative fuel consumption savings from all measures planned for implementation prior to the time period of consideration is shown in Eq. 56. The adjusted fuel consumption considering the savings related to production changes and to emissions-reduction

measures is calculated as in Eq. 57. These calculations are shown graphically in Figure 6.10 using an example of time period 1 and 2 of a roadmap.

$$\left(FCS_{p_total}\right)_{tp_x} = -\left(PI_{tp_x} - PI_{tp_{x-1}}\right) \times FC_{tp_{x-1}} \quad \text{Eq. 54}$$

Potential fuel consumption savings from production increase = – Incremental production increase × Fuel consumption in previous time

$$\left(FCS_{p}\right)_{tp_x} = 0.7 \times \left(FCS_{p_total}\right)_{tp_x} \quad \text{Eq. 55}$$

Fuel consumption savings from production increase = Production scale factor × Potential fuel consumption savings from production increase

$$\left(FCS_{m_total}\right)_{tp_x} = \left(\sum_{m=1}^{m=k} \left(FCS_m\right)\right)_{tp_x} \quad \text{Eq. 56}$$

Fuel consumption savings from all measures in time period of consideration = Sum of all measures in time period of consideration

$$FC_{tp_x} = \left(FC_{tp_{x-1}}\right) - \left(FCS_p + FCS_{m_total}\right)_{tp_x} \quad \text{Eq. 57}$$

Fuel consumption in time period of consideration = Fuel consumption in previous time period – Fuel consumption savings from production increase and all measures in time period of consideration

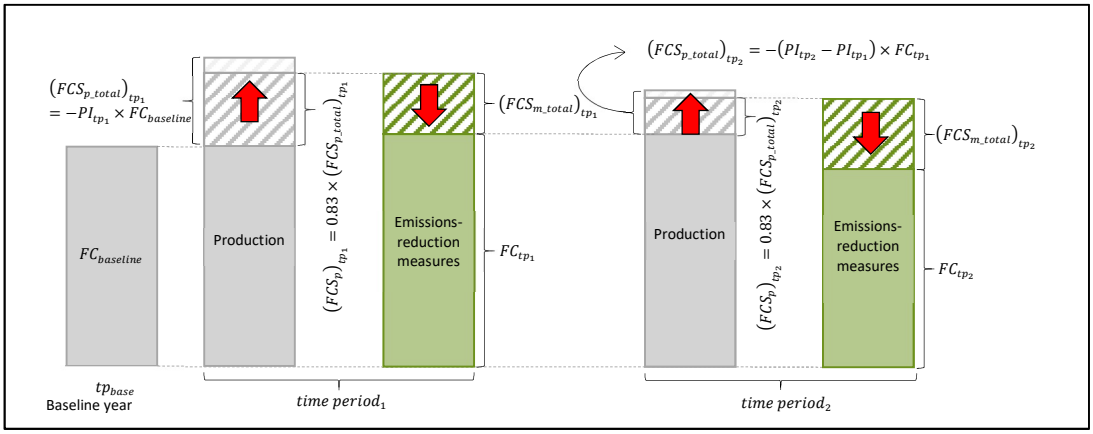


Figure 6.10: Adjusted fuel consumption

6.5.3 Energy Supply

The site fuel consumption comprises renewable energy sourced by the organisation, utility energy, and energy from non-renewable onsite generation. Onsite generation refers to the generation of an energy source through the conversion of another. Electricity, gas, and oil can be generated onsite. However, for gas and liquid fuel, this is the generation of renewable alternatives in the form of Biomethane and biofuel through onsite anaerobic digestion. Since this process is fuelled by waste, it has no

follow-on effect on other energy sources and is considered directly in the user renewable energy share. Consequently, onsite energy conversion in the context of this modelling tool refers only to onsite electricity generation from gas- or oil-fuelled equipment such as generators; combined heating and power (CHP) plants; combined cooling and power (CCP) plants; and combined cooling, heating, and power (CCHP) plants.

The following sub-sections discuss the manner in which changing energy supply contributions and utility renewable energy share affect the emissions factors along the carbon neutrality timeline and how this is incorporated into the modelling tool to consider this dynamic effect.

6.5.3.1 *Energy supply contributions*

The contributions of the three energy sources (utility, renewable, and onsite generation) to the total fuel consumption vary along the carbon neutrality timeline in response to changes in total fuel consumption (from emissions-reduction measures and changing production levels) and the energy supply configuration. There are two further parameters affecting the energy supply contributions—the renewable energy share and a change in the type or level of non-renewable onsite generation. The potential renewable energy quantity sourced by the organisation is calculated as in Eq. 58 for each time period, where it is calculated using the baseline fuel consumption rather than the variable quarterly fuel consumption since the quantity of renewable energy available may be independent of the demand. For onsite generation, the baseline level is assumed to be maintained along the carbon neutrality timeline; changes to this configuration are treated as emissions-reduction measures to account for the associated implementation cost, and are input accordingly. However, the renewable energy and onsite generation energy levels may be subject to further adjustment when the cumulative energy savings are beyond the baseline utility level.

$$\underbrace{(RE_{user})_{tp_x}}_{\text{Potential renewable energy quantity}} = \underbrace{(RES_{user})_{tp_x}}_{\text{Renewable energy share}} \times \underbrace{FC_{baseline}}_{\text{Baseline fuel consumption}} \qquad \text{Eq. 58}$$

For gas and oil, only renewable and utility energy are applicable. The initial energy savings are assumed to be from the utility source since the renewable energy quantity is not affected by the change in demand (case A1). Further load reductions beyond the utility supply level reduce the renewable energy sourced by the organisation since this is the only remaining energy source (case A2). However, there may be measures that increase the gas or oil consumption; these increases are added in reverse order, i.e. up to the potential renewable energy threshold where appropriate, and thereafter to the utility energy. This principle is shown graphically in Figure 6.11, where the known values are highlighted in yellow. The adjusted renewable energy and utility energy contributions for the time period of consideration are described by Eq. 59 and Eq. 60, respectively, for the following cases.

- Case A1 – the fuel consumption is greater than the potential renewable energy quantity, indicating that some of the load must be met by the utility.
- Case A2 – the fuel consumption is less than the potential renewable energy quantity, indicating that the full load can be met by renewable energy.

$$Case\ A1\text{: } FC_{tp_x} \geq (RE_{user})_{tp_x}$$

$$Case\ A2\text{: } FC_{tp_x} < (RE_{user})_{tp_x}$$

$$\left(RE_{user_adj}\right)_{tp_x} = \begin{cases} (RE_{user})_{tp_x} & Case\ A1 \\ FC_{tp_x} & Case\ A2 \end{cases} \quad \text{Eq. 59}$$

$$UE_{tp_x} = \begin{cases} FC_{tp_x} - \left(RE_{user_{adj}}\right)_{tp_x} & Case\ A1 \\ 0 & Case\ A2 \end{cases} \quad \text{Eq. 60}$$

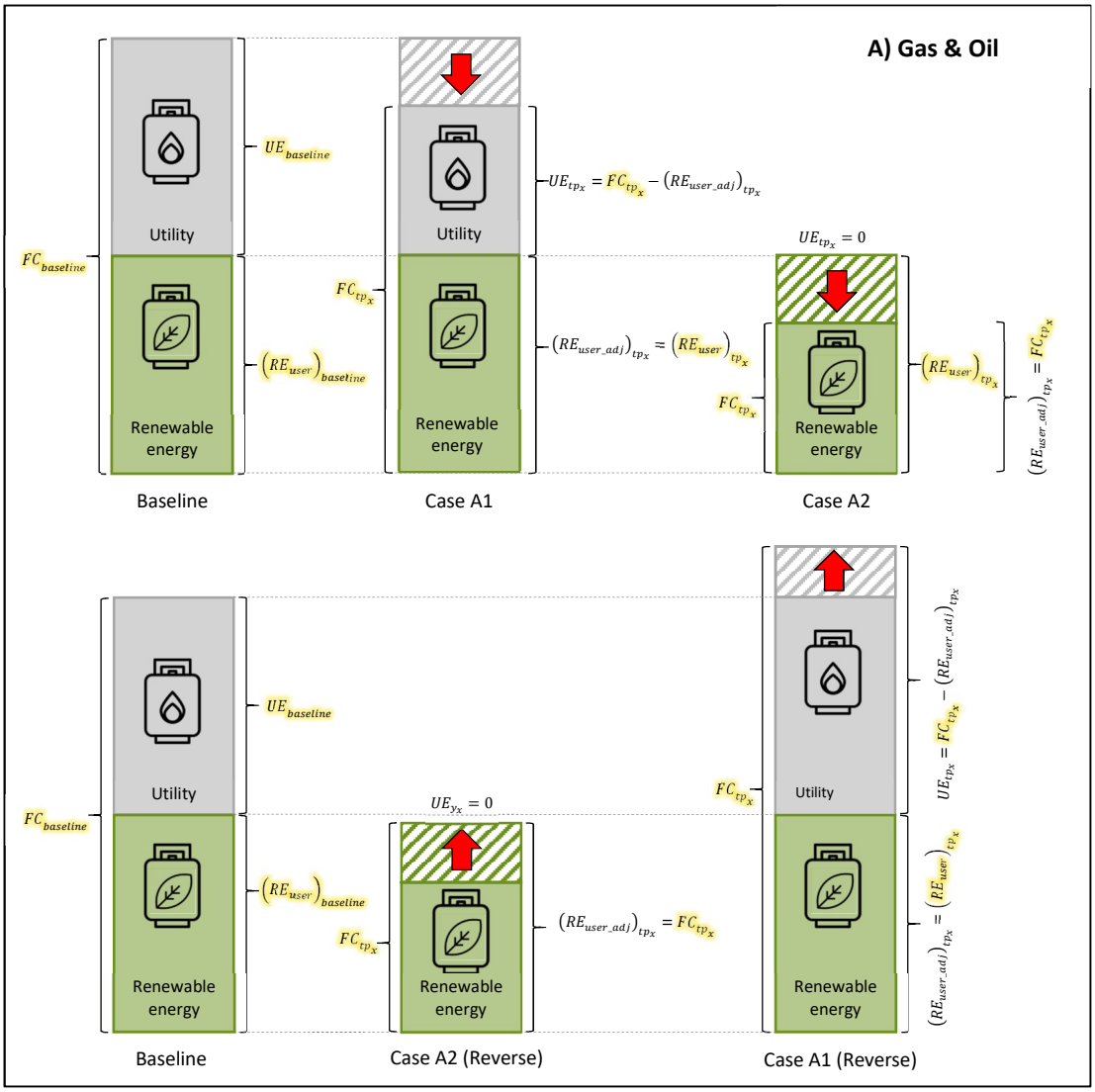


Figure 6.11: Energy supply contributions with savings: Fuel A - Gas and oil

For electricity, the load reduction is first assumed as a reduction in grid electricity (case B1). Load reductions in excess of the grid supply are allocated to onsite generation (case B2). Further load reductions beyond the onsite generation capacity are considered to be reductions in renewable electricity (case B3). For the reverse case in which the electrical load increases from a point at which onsite generation and/or grid electricity is consumed, the process is reversed (case B1 reverse & case B2 reverse). However, for the reverse case in which the electrical load increases after 100% renewable electricity has been achieved, it is assumed that this forms part of an electrification strategy and that additional renewable electricity will be sourced at the current cost to meet the additional demand (case B1-RE & case B2-RE). This principle is shown graphically in Figure 6.12, where the known values are highlighted

in yellow. The adjusted renewable energy, onsite generation, and utility energy contributions for the time period of consideration are described by Eq. 61, Eq. 62, and Eq. 63, respectively, for the following cases:

- Case B1 – the fuel consumption is greater than the sum of the potential renewable electricity quantity and the onsite electrical generation, indicating the zone of grid electricity based on baseline values. For the previous year, the fuel consumption is greater than the renewable electricity quantity, confirming that of portion of electricity is sourced from onsite generation and/or the grid.
- Case B2 – the fuel consumption is greater than the potential renewable electricity quantity and less than the sum of potential renewable electricity quantity and the onsite electrical generation, indicating the zone of onsite electrical generation based on baseline values. For the previous year, the fuel consumption is greater than the renewable electricity quantity, confirming that a portion of electricity is sourced from onsite generation.
- Case B3 – the fuel consumption is less than the potential renewable electricity quantity, indicating that all electricity is renewable.
- Case B1 RE – the fuel consumption is greater than the sum of the potential renewable electricity quantity and the onsite electrical generation, indicating the zone of grid electricity based on baseline values. However, the fuel consumption in the previous year equals the renewable electricity quantity, indicating that all electricity is sourced renewably. It is assumed that the increased electrical load will be sourced in the same manner.
- Case B2 Reverse – the fuel consumption is within the zone of onsite generation. However, the fuel consumption in the previous year equals the renewable electricity quantity, indicating that all electricity is sourced renewably. It is assumed that the increased electrical load will be sourced in the same manner.

$$Case\ B1\text{: } FC_{tp_x} \geq \left((RE_{user})_{tp_x} + OG_{baseline}\right), where\ FC_{tp_{x-1}} > \left(RE_{user_{adj}}\right)_{tp_{x-1}}$$

$$Case\ B2\text{: } (RE_{user})_{tp_x} < FC_{tp_x} < \left((RE_{user})_{tp_x} + OG_{baseline}\right), where\ FC_{tp_{x-1}} > \left(RE_{user_{adj}}\right)_{tp_{x-1}}$$

$Case\ B3: FC_{tp_x} \leq (RE_{user})_{tp_x}$

$Case\ B1 - RE: FC_{tp_x} \geq \left((RE_{user})_{tp_x} + OG_{baseline}\right), where\ FC_{tp_{x-1}} = \left(RE_{user_{adj}}\right)_{tp_{x-1}}$

$Case\ B2 - RE: (RE_{user})_{tp_x} < FC_{tp_x} < \left((RE_{user})_{tp_x} + OG_{baseline}\right), where\ FC_{tp_{x-1}} = \left(RE_{user_{adj}}\right)_{tp_{x-1}}$

$$\left(RE_{user_adj}\right)_{tp_x} = \begin{cases} (RE_{user})_{tp_x} & Case\ B1 \\ (RE_{user})_{tp_x} & Case\ B2 \\ FC_{tp_x} & Case\ B3 \\ FC_{tp_x} & Case\ B1\ RE \\ FC_{tp_x} & Case\ B2\ RE \end{cases} \quad \text{Eq. 61}$$

$$OG_{tp_x} = \begin{cases} OG_{baseline} & Case\ B1 \\ FC_{tp_x} - \left(RE_{user_{adj}}\right)_{tp_x} & Case\ B2 \\ 0 & Case\ B3 \\ 0 & Case\ B1\ RE \\ 0 & Case\ B2\ RE \end{cases} \quad \text{Eq. 62}$$

$$UE_{tp_x} = \begin{cases} FC_{tp_x} - \left(\left(RE_{user_adj}\right)_{tp_x} + OG_{tp_x}\right) & Case\ B1 \\ 0 & Case\ B2 \\ 0 & Case\ B3 \\ 0 & Case\ B1\ RE \\ 0 & Case\ B2\ RE \end{cases} \quad \text{Eq. 63}$$

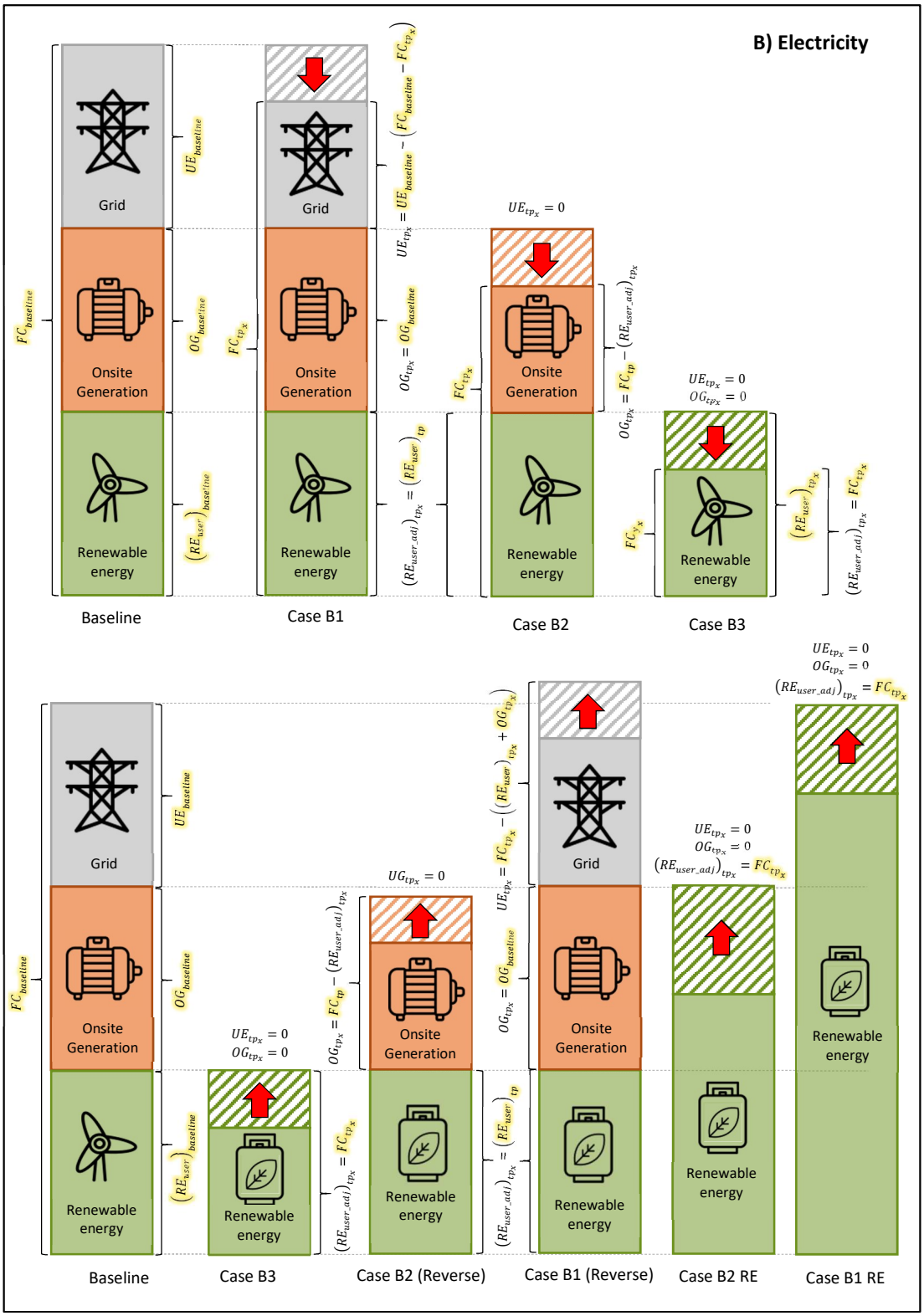


Figure 6.12: Energy supply contributions with savings: Fuel B - Electricity

6.5.3.2 *Renewable energy share - Utility*

In addition to the renewable energy sourced directly by the organisation, there is a component of renewable energy included in the utility supply. The RES included in

the utility supply is independent of the emissions-reduction measures. There are two scenarios in the modelling tool for renewable energy. The first scenario does not take into account the RES proposed by the utility providers for the carbon neutrality timeline. Only the RES from the baseline year to the current time period is used in the calculation as this has been implemented; this applies to the period between the baseline year for which the carbon footprint was calculated and the current time period in which the modelling tool is used. The second scenario considers the proposed utility RES for all time periods of the timeline. The adjusted utility RES values for each fuel for each time period of the roadmap are described by Eq. 64 and Eq. 65 for Scenario 1 and 2, respectively (Table 5.9).

$$Scenario\ 1\text{: } \underbrace{\left(RES_{utility_adj}\right)_{tp_x}}_{\text{Renewable energy share of utility}} = \begin{cases} \left(RES_{utility}\right)_{tp_x} & tp_x \leq tp_c \\ \left(RES_{utility}\right)_{tp_c} & tp_x > tp_c \end{cases} \quad \text{Eq. 64}$$

$$=\ \begin{cases} \text{Renewable energy share currently included in utility} \\ \text{Proposed renewable energy share in utility} \end{cases}$$

$$Scenario\ 2\text{: } \underbrace{\left(RES_{utility_adj}\right)_{tp_x}}_{\text{Renewable energy share of utility}} = \left(RES_{utility}\right)_{tp_x} \quad \text{Eq. 65}$$

$$=\ \text{Proposed renewable energy share in utility}$$

6.5.3.3 *Adjusted emissions factors*

The emissions factors for all energy sources are calculated for each time period, and then retrieved for the relevant time period. The contributions to the emissions factors of each energy source are illustrated in Figure 6.13. Gas and oil are sourced through utility and renewable sources only since onsite generation is not applicable. The emissions factor for oil is calculated as in Eq. 66, where the baseline utility value is scaled using the utility share of the total fuel consumption (the remaining fuel consumption is user-sourced renewable energy which does not contribute to the emissions factor). The emissions factor for gas is calculated as in Eq. 67 by first scaling the baseline utility emissions factor, which includes the baseline renewable energy, to account for increases in utility renewable energy. This is then further scaled to the utility share of the total fuel consumption.

$$\underbrace{(EF_{oil})_{tp_x}}_{\text{Emissions factor in time period of consideration}} = \underbrace{\left(EF_{baseline} \times \underbrace{\left(\frac{UE}{FC}\right)_{tp_x}}_{\text{Utility share of total energy}}\right)_{oil}}_{\text{Emissions factor inherent to model}} \quad \textit{Eq. 66}$$

$$\underbrace{(EF_{gas})_{tp_x}}_{\text{Emissions factor in time period of consideration}} = \underbrace{\left(EF_{baseline} \times \underbrace{\left(\frac{1-(RES_{utility_adj})_{tp_x}}{1-(RES_{utility})_{baseline}}\right)}_{\text{Scaling of non-renewable energy share}} \times \underbrace{\left(\frac{UE}{FC}\right)_{tp_x}}_{\text{Utility share of total energy}}\right)_{gas}}_{\text{Emissions factor inherent to model}} \quad \textit{Eq. 67}$$

The emissions factor for electricity is more complex as it includes electricity generated onsite using gas and oil. The emissions factor contribution from the electrical grid is calculated as shown in Eq. 68. The emissions factor contribution from onsite generation using gas and oil is calculated as in Eq. 69, where the efficiency of onsite generation is taken into account to relate the supply to the demand. This is because the majority of electrical measures act on the demand side and not all sites have onsite generation. Consequently, all measures are treated as demand reductions since insufficient information is provided to distinguish between supply side and demand side measures. The total emissions factor applicable to electricity is shown in Eq. 70.

$$\underbrace{(EF_{elec_utility})_{tp_x}}_{\text{Utility emissions factor in time period of consideration}} = \underbrace{\left(EF_{baseline} \times \underbrace{\left(\frac{1-(RES_{utility_adj})_{tp_x}}{1-(RES_{utility})_{baseline}}\right)}_{\text{Scaling of non-renewable energy share}} \times \underbrace{\left(\frac{UE}{FC}\right)_{tp_x}}_{\text{Utility share of total energy}}\right)_{elec}}_{\text{Emissions factor inherent to model}} \quad \textit{Eq. 68}$$

$$\underbrace{(EF_{elec_onsite})_{tp_x}}_{\text{Onsite generation emissions factor in time period of consideration}} = \underbrace{\left(\left(EF_{gas} \times \underbrace{\left(\frac{OG_{gas}}{OG}\right)}_{\text{Share of onsite generation from gas}} \underbrace{\left(\frac{1}{\eta_{gas}}\right)}_{\text{Efficiency adjustment}}\right) + \left(EF_{oil} \times \underbrace{\left(\frac{OG_{oil}}{OG}\right)}_{\text{Share of onsite generation from oil}} \underbrace{\left(\frac{1}{\eta_{oil}}\right)}_{\text{Efficiency adjustment}}\right)\right)_{tp_x}}_{\text{Gas emissions factor}} \times \underbrace{\left(\frac{OG}{FC}\right)_{tp_x}}_{\text{Onsite generation share of total energy}} \quad \textit{Eq. 69}$$

$$\underbrace{(EF_{elec})_{tp_x}}_{\text{Overall emissions factor in time period of consideration}} = \underbrace{(EF_{elec_utility}}_{\text{Utility contribution}} + \underbrace{EF_{elec_onsite})_{tp_x}}_{\text{Onsite generation contribution}} \quad \textit{Eq. 70}$$

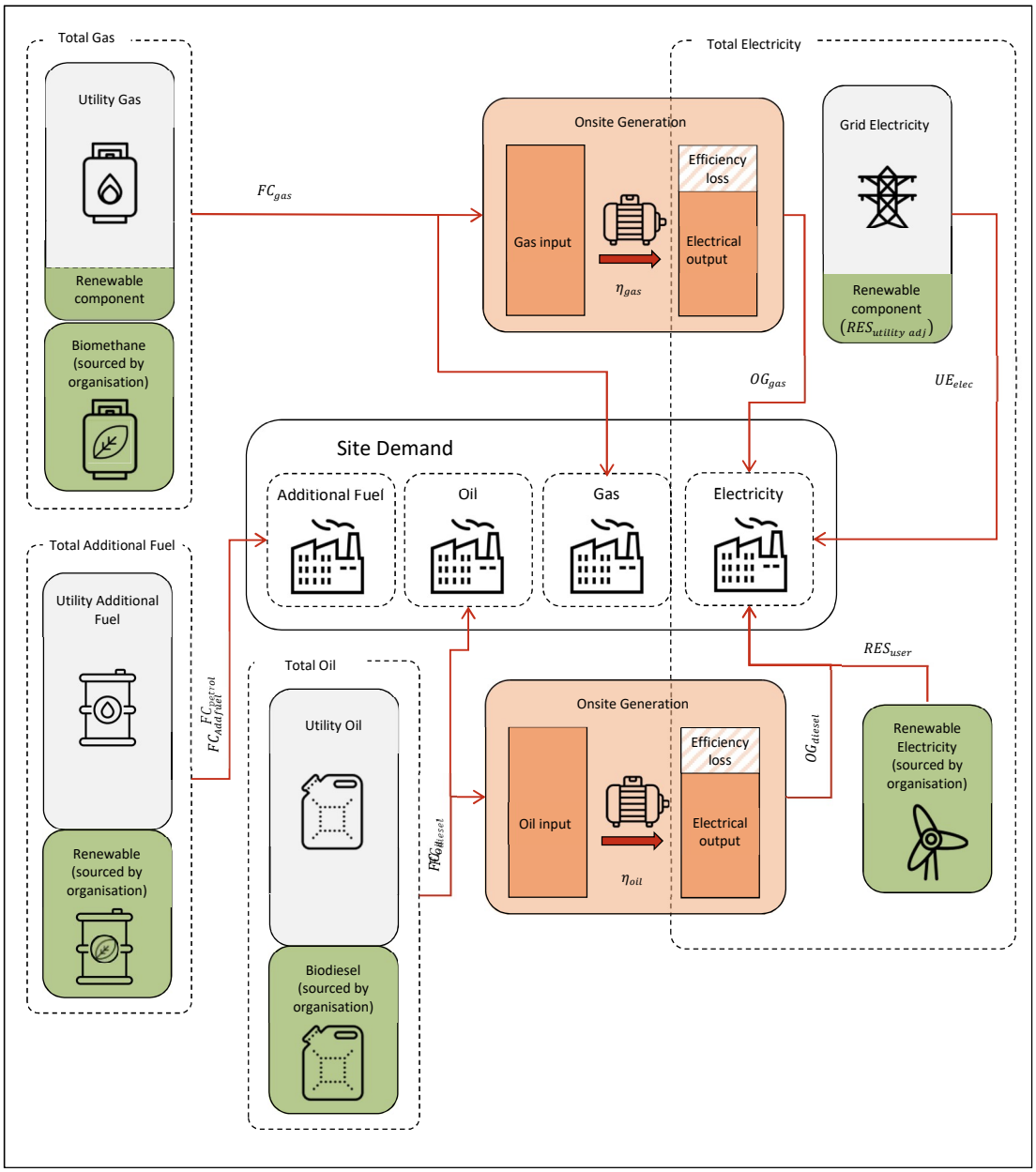


Figure 6.13: Energy source contributions to emissions factors

6.6 Model Simulation and Outputs – Carbon Emissions Waterfall

The carbon neutrality waterfall shows the reduction in emissions from the baseline year to the carbon neutrality target year. The time periods between the baseline year and the carbon neutrality start year are included as 'current time periods' to essentially update the carbon footprint for the start of the carbon neutrality timeline. Thus, the baseline year is considered as time period zero of the carbon neutrality roadmap.

Each waterfall step is divided into five sections—renewable energy, emissions-reduction measures, production changes, scope 3 emissions reduction, and planned carbon offsetting. There is some overlap between the emissions savings from renewable energy, production, and emissions-reduction measures since all three contribute to the emissions factors. The energy savings from the measures result in emissions savings; however, a portion of these emissions would be saved by the increased RES if the measures were not implemented. Similarly, emissions from increased production are dampened if there is a simultaneous increase in renewable energy. The approach in this modelling tool is to first consider the parameters affecting fuel consumption, i.e. the production changes and emissions-reduction measures. Finally, the renewable emissions savings are calculated on the updated fuel consumptions. The planned carbon offsetting and scope 3 emissions reductions are independent of the calculated emissions factors, and are added directly to calculate the total emissions savings. The mathematical model is used to generate the carbon neutrality waterfall is discussed in this section and is shown graphically in Figure 6.14.

6.6.1 Emissions savings attributed to production changes

The fuel consumption savings attributed to increased production is as discussed in section 6.5.2, and the resulting total emissions savings in time period tp_x from all energy sources is described by Eq. 71.

$$\underbrace{(ES_p)_{tp_x}}_{\text{Emissions savings from production increase}} = \underbrace{\left(\sum_{i=1}^{i=n} \underbrace{(FCS_p}_{\text{Fuel consumption savings from production increase}} \times \underbrace{EF_{tp_x})_i}_{\text{Emissions factor}}\right)_{tp_x}}_{\text{summed for all energy sources}} \qquad \textit{Eq. 71}$$

6.6.2 Emissions savings per measure

The total emissions savings per measure (from all energy sources) in the first time period following planned implementation is as shown in Eq. 72.

$$\underbrace{(ES_m)_{tp_x}}_{\text{Emissions savings from all measures}} = \sum_{i=1}^{i=n} \underbrace{\left((FCS_{m_total})_{tp_{x-1}}}_{\text{Fuel consumption savings from all measures implemented in previous time period}} \times \underbrace{EF_{tp_x}}_{\text{Emissions factor}}\right)_i \quad \text{summed for all energy sources} \qquad \textit{Eq. 72}$$

6.6.3 Emissions savings in time period tp_x from increased renewable energy share

The total emissions savings per time period attributed to an increase in total renewable energy (utility and user) for all energy sources is as per Eq. 73. The fuel consumption from the previous time period is used since the renewable energy component of the current time period is accounted for in the production increase and emissions-saving measures. The change in emissions factor since the previous time period is used to capture only the incremental savings.

$$\underbrace{(ES_r)_{tp_x}}_{\text{Emissions savings from increased RES}} = \sum_{i=1}^{i=n} \left(\underbrace{FC_{tp_{x-1}}}_{\text{Fuel consumption in previous time period}} \times \underbrace{\left(EF_{tp_x} - EF_{tp_{x-1}}\right)}_{\text{Change in emissions factor}}\right)_i \quad \text{summed for all energy sources} \qquad \textit{Eq. 73}$$

6.6.4 Total additional emissions savings in time period tp_x

The total additional emissions savings in time period tp_x represent the steps in the carbon neutrality waterfall (Eq. 74). These steps include the emissions savings attributed to changes in production, all emissions-reduction measures considered in the time period (implemented in the previous time period), changes in RES, planned carbon offsets, and scope 3 emissions reductions.

$$\underbrace{TES_{tp_x}}_{\text{Total emissions savings}} = \big(\underbrace{ES_p}_{\text{Emissions savings from production increase}} + \underbrace{\textstyle\sum_{m=1}^{m=k} ES_m}_{\text{Emissions savings from all measures}} + \underbrace{ES_r}_{\text{Emissions savings from renewables}} + \underbrace{ES_{co}}_{\text{Carbon offsets}} + \underbrace{ES_{s3}}_{\text{Scope 3 emissions savings}}\big)_{tp_x} \qquad \text{Eq. 74}$$

The remaining emissions in the carbon neutrality target year represents the balance that is to be addressed by carbon offsetting to achieve carbon neutrality; this balance is calculated as follows:

$$EB_{y_{cn}} = CF - \sum_{j=1}^{j=cn} TES_{tp_j}$$

Emissions balance = Carbon footprint − Sum of total emissions savings in each time period

Eq. 75

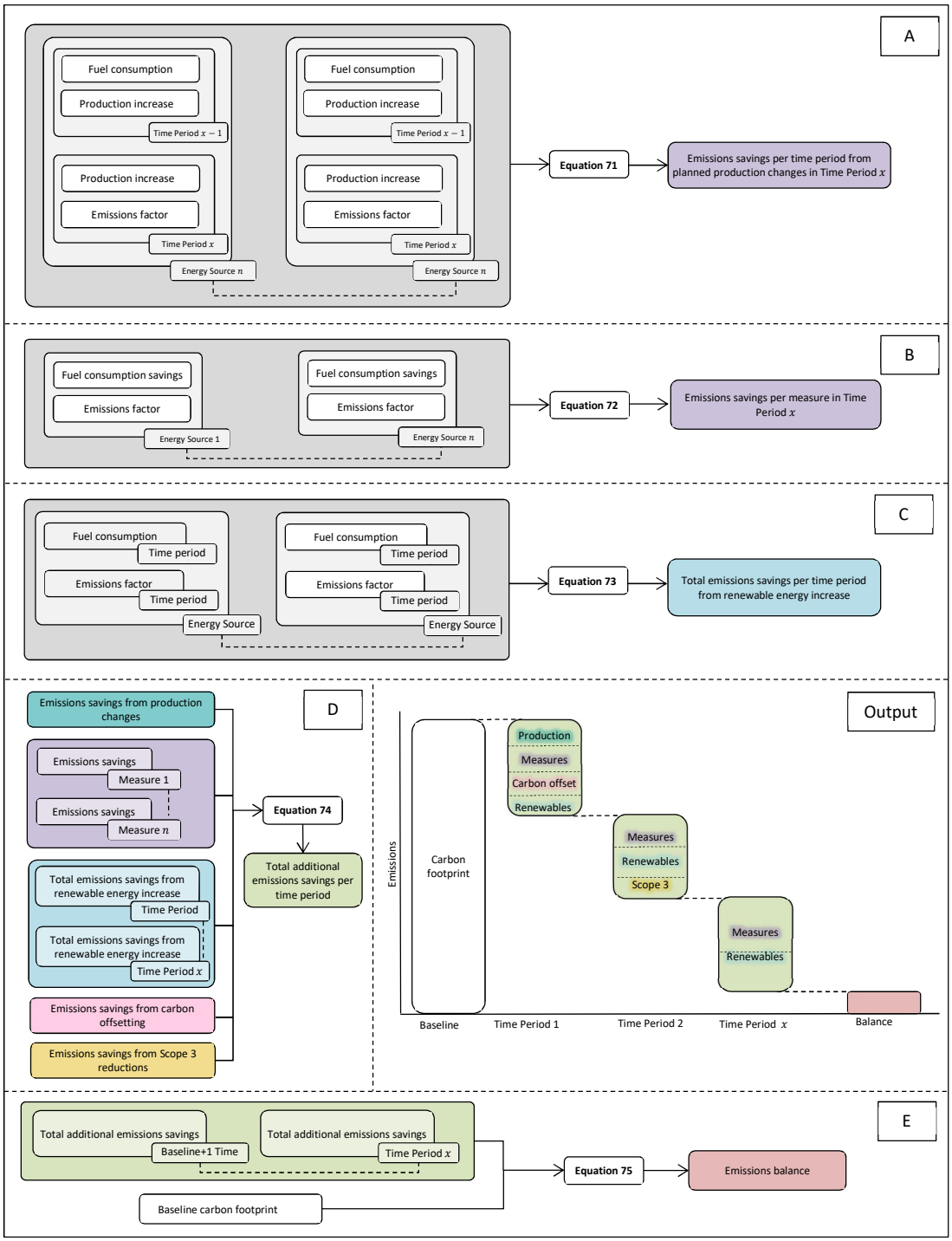


Figure 6.14: Graphical representation of carbon neutrality waterfall equations

6.7 Model Simulation and Outputs – Financial Analysis

The financial analysis is in the form of a graph that compares the cumulative costs and savings. The graph spans a maximum of 15 years regardless of whether the breakeven point is reached as this timeframe is deemed sufficient to indicate the financial effects of emissions reduction.

6.7.1 Financial savings

The equations used to determine the cumulative financial savings are discussed in this section, and are shown graphically in Figure 6.16. The total savings comprise operational savings attributed to fuel consumption, as well as savings from reduced carbon tax and carbon offset. It should be noted that carbon offset is considered a cost in the high-level modelling tool since it is an exploratory tool that provides an indication of the financial impact of targeting carbon neutrality where no commitment has yet been made. In contrast, the project-based modelling tool addressed in this chapter considers this a financial saving as there is a commitment in place which means that carbon offsetting is required and any emissions savings reduce the amount to be paid (carbon offset is not applicable to the scenario in which there is no commitment). The amounts are considered as future value since the annual growth rates of the various financial streams differ; the values are converted to present value in the final step.

6.7.1.1 *Fuel consumption per energy source in time period* tp_x

The fuel consumption savings are affected by all measures implemented or planned for implementation to date, as well as executed or forecasted production changes. However, in the business-as-usual scenario (BAU) in which no steps are taken towards carbon neutrality, the fuel consumption would increase with planned production changes in accordance with the percentage increase applied to the baseline fuel consumption. In the modelling tool, the planned production increase percentage is applied to the previous years' fuel consumption which is less since emissions-reduction measures have been applied (shown in Figure 6.10). To limit the financial effects in the modelling tool to those resulting from carbon neutrality planning, only the difference in fuel consumption between the BAU scenario and the

carbon neutrality plan is considered. This principle is illustrated in Figure 6.10. The fuels consumption savings in the BAU scenario and the savings attributed to the carbon neutrality plan are shown in Eq. 76 and Eq. 77, respectively. The fuel consumption savings per energy source in the time period of consideration are shown in Eq. 78.

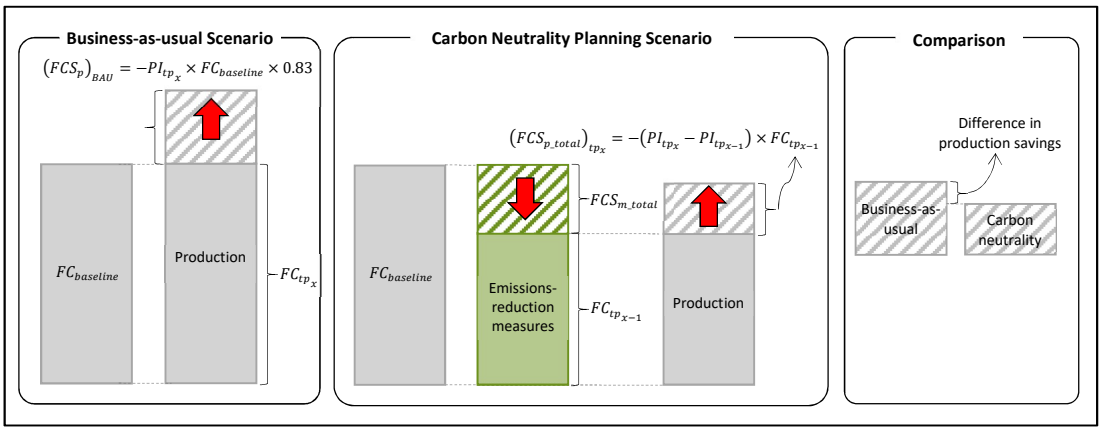


Figure 6.15: Production fuel consumption comparison

$$\underbrace{(FCS_{p_{BAU}})_{tp_x}}_{\text{Fuel consumption savings from production increase in in BAU}} = \underbrace{-}_{=} \underbrace{PI_{tp_x}}_{\text{Absolute production increase}} \times \underbrace{FC_{baseline}}_{\text{Baseline fuel consumption}} \times \underbrace{0.7}_{\text{Production scale factor}} \qquad \textit{Eq. 76}$$

$$\underbrace{(FCS_{\Delta p})_{tp_x}}_{\text{Production fuel consumption savings}} = \underbrace{-}_{=} \underbrace{\left(FCS_{p_{BAU}}\right.}_{\text{Absolute fuel consumption savings from production increase}} \underbrace{\left. - \sum_{j=1}^{j=x} (FCS_p)_{tp_j}\right)}_{\text{Sum of incremental savings from production increases}} \qquad \textit{Eq. 77}$$

$$\underbrace{(FCS_i)_{tp_x}}_{\text{Total fuel consumption savings}} = \underbrace{\left(\sum_{j=1}^{j=x} (FCS_{m_total} + FCS_{\Delta p})_{tp_j}\right)_i}_{\text{Fuel consumption savings from all measures} \; + \; \text{Fuel consumption savings from production increase}} \qquad \textit{Eq. 78}$$

6.7.1.2 *Operational financial savings in time period* tp_x

The operational financial savings are calculated using the fuel consumption savings, as well as the cost of renewable and utility energy fuels ($Cost_{renew}$ and $Cost_{utility}$, respectively). There are two input cost options:

- Advanced input option – value is input manually for each time period of the carbon neutrality timeline and these are used directly in the calculation of the operational financial savings.

- Simple input option – values are calculated using the compound annual growth rate equation, with the user-defined current cost and annual growth rate input (Eq. 79). This is a common economic metric that has been adjusted to account for the fact that the time period used in the modelling tool is a quarter rather than a year. In the future value factor exponent, the difference in time period is divided by four to express the time difference in years to align with the compound annual growth rate.

$$\underbrace{Cost_{tp_x}}_{\text{Cost in time period of consideration}} = \underbrace{Cost_{tp_c}}_{\text{Current cost}} \times \underbrace{(1 + CAGR_{cost})^{\left(\frac{tp_x - tp_c}{4}\right)}}_{\text{Future value factor based on compound annual growth rate}} \qquad \textit{Eq. 79}$$

The operational financial savings in the time period of consideration is shown in Eq. 80 for electricity and any additional fuels; the costs of the renewable energy sourced by the organisation and the utility energy portions are considered. Although onsite generation contributes to electricity used on site, the cost of the onsite generation portion of electricity is not considered since this is fuelled by gas and/or oil. The gas and oil consumption savings attributed to onsite electricity generation are as per Eq. 81 and Eq. 82, respectively. The resulting operational fuel savings are as per Eq. 83 and Eq. 84, respectively, where the renewable and utility energy portions are applied to the total fuel consumption comprising direct fuel use and that used for onsite electricity generation. The total operational financial savings is the sum off all fuel savings (Eq. 88).

$$\underbrace{(OFS_i)_{tp_x}}_{\text{Operational financial savings from fuel}} = \underbrace{\left(FCS_i \times \left(\left(Cost_{renew} \times \frac{RE_{user_adj}}{FC}\right)_i + \left(Cost_{utility} \times \frac{UE}{FC}\right)_i\right)\right)_{tp_x}}_{\text{Fuel consumption savings} \times \text{Cost portion attributed to renewable energy} + \text{Cost portion attributed to utility energy}} \qquad \textit{Eq. 80}$$

$$\underbrace{\left(FCS_{elec_gas}\right)_{tp_x}}_{\text{Gas consumption savings from electricity generation}} = \underbrace{\left(FCS_{elec} \times \left(\frac{OG_{gas}}{OG}\right)\left(\frac{1}{\eta_{gas}}\right) \times \left(\frac{OG}{FC_{elec}}\right)\right)_{tp_x}}_{\text{Electricity consumption savings} \times \text{Portion of onsite generation attributed to gas}} \qquad \textit{Eq. 81}$$

$$\underbrace{\left(FCS_{elec_oil}\right)_{tp_x}}_{\text{Oil consumption savings from electricity generation}} = \underbrace{\left(FCS_{elec}\right.}_{\text{Electricity consumption savings}} \times \underbrace{\left.\left(\frac{OG_{oil}}{OG}\right)\left(\frac{1}{\eta_{oil}}\right) \times \left(\frac{OG}{FC_{elec}}\right)\right)_{tp_x}}_{\text{Portion of onsite generation attributed to oil}} \quad \text{Eq. 82}$$

$$\underbrace{\left(OFS_{gas}\right)_{tp_x}}_{\text{Operational financial savings from gas}} = \underbrace{\left(FCS_{gas} + FCS_{elec_gas}\right)}_{\text{Total gas consumption savings}} \times \underbrace{\left(\left(Cost_{renew} \times \frac{RE_{user_adj}}{FC}\right)_{gas}\right.}_{\text{Cost portion attributed to renewable energy}} + \underbrace{\left.\left(Cost_{utility} \times \frac{UE}{FC}\right)_{gas}\right)_{tp_x}}_{\text{Cost portion attributed to utility energy}} \quad \text{Eq. 83}$$

$$\underbrace{\left(OFS_{oil}\right)_{tp_x}}_{\text{Operational financial savings from oil}} = \underbrace{\left(FCS_{oil} + FCS_{elec_oil}\right)}_{\text{Total oil consumption savings}} \times \underbrace{\left(\left(Cost_{renew} \times \frac{RE_{user_adj}}{FC}\right)_{oil}\right.}_{\text{Cost portion attributed to renewable energy}} + \underbrace{\left.\left(Cost_{utility} \times \frac{UE}{FC}\right)_{oil}\right)_{tp_x}}_{\text{Cost portion attributed to utility energy}} \quad \text{Eq. 84}$$

$$\underbrace{OFS_{tp_x}}_{\text{Total operational financial savings}} = \underbrace{\left(\sum_{i=1}^{i=n} OFS_i\right)_{tp_x}}_{\text{Sum of savings of all fuels}} \quad \text{Eq. 85}$$

6.7.1.3 *Cumulative operational financial savings in time period* tp_x

The cumulative operational financial savings from all measures implemented or planned for implementation to date and from all executed and forecasted production changes to date is shown in Eq. 86. It comprises the operational financial savings from the time period of consideration, and all savings from previous time periods adjusted to the same time period using the organisation's discount rate. Note that the carbon neutrality roadmap year (j) begins at zero to force the second term to zero in the first time period of the roadmap since no previous time periods' savings should be considered in the first time period.

$$\underbrace{COFS_{tp_x}}_{\text{Cumulative operational financial savings}} = \underbrace{OFS_{tp_x}}_{\text{Operational financial savings in time period}} + \underbrace{\sum_{j=0}^{j=x-1} COFS_{tp_j} \times (1+DR)^{\left(\frac{tp_x - tp_c}{4}\right)}}_{\text{Adjusted operational financial savings from previous time periods}} \quad \text{Eq. 86}$$

6.7.1.4 *Carbon tax savings in time period* tp_x

Carbon tax is payable on natural gas and oil, and is affected by increases in renewable gas share, all measures implemented and planned for implementation, and all

executed and forecasted production changes in excess of the BUA scenario. The total emissions savings relevant to the financial analysis is calculated as in Eq. 87 for gas and oil. The cumulative carbon tax savings per time period attributed to these sources in all previous years is as per Eq. 88.

$$\underbrace{\left((TES_i)_{tp_x}\right)_{financial}}_{\text{Total emissions savings for financial analysis}} = \underbrace{\left(\sum_{j=1}^{j=x}\left(\left(FCS_{m_total} \times EF\right) + ES_r\right)_{tp_j} + \left(FCS_{\Delta p} \times EF\right)_{tp_x}\right)_i}_{\text{Emissions savings from measures to date} + \text{Emissions savings from renewable energy increase to date} + \text{Emissions savings from increased production to date}} \quad \textit{Eq. 87}$$

$$\underbrace{CCTS_{tp_x}}_{\text{Carbon tax savings for time period}} = \underbrace{\left(Carbon\ tax_{tp_x} \times \sum_{j=1}^{j=x}(TES_{gas} + TES_{oil})_{tp_j}\right)}_{\text{Carbon tax for time period} \times \text{Cumulative natural gas and oil emissions to date}} + \underbrace{\left(\sum_{j=0}^{j=x-1} CTS_{tp_j} \times (1+DR)^{\left(\frac{tp_x - tp_c}{4}\right)}\right)}_{\text{Adjusted carbon tax savings from previous time periods}} \quad \textit{Eq. 88}$$

6.7.1.5 *Carbon offset savings in time period* tp_x

Carbon offset savings are only considered where carbon neutrality is a requirement since the offset has to be paid regardless in this case, and thus the savings are real and must be included. In this case, it is only considered in the years following the carbon neutrality target year. In contrast, carbon offset savings are not considered if the model is used only to explore the option of carbon neutrality as there is no offset to be paid if no commitment is made, and thus no real savings.

The carbon offset cost for the time period of consideration is calculated as follows for the simple and advanced cost inputs:

- Advanced input option – carbon offset is input manually for each time period of the carbon neutrality timeline and these values are used directly in the calculation.
- Simple input option – carbon offset is calculated as per Eq. 89 using the user-defined current offset and annual growth rate.

$$\underbrace{Carbon\ offset_{tp_x}}_{\text{Carbon offset in time period of consideration}} = \underbrace{Carbon\ offset_{y_c}}_{\text{Current carbon offset}} \times \underbrace{(1 + CAGR_{CO})^{\left(\frac{tp_x - tp_c}{4}\right)}}_{\text{Future value factor based on compound annual growth rate}} \quad \textit{Eq. 89}$$

The cumulative carbon offset in the time period of consideration is shown in Eq. 90.

$$\underbrace{CCOS_{tp_x}}_{\text{Carbon offset savings for time period}} = \underbrace{\left(\underbrace{Carbon\ offset_{tp_x}}_{\text{Carbon offset for time period}} \times \underbrace{\sum_{j=cn+1}^{j=x} TES_{y_j}}_{\text{Cumulative emissions savings attributed to date}} \right)}_{} + \underbrace{\sum_{j=cn}^{j=x-1} COS_{y_j} \times (1+DR)^{\left(\frac{tp_x - tp_c}{4}\right)}}_{\text{Adjusted carbon offset savings from previous time periods}} \qquad \textit{Eq. 90}$$

6.7.1.6 *Cumulative financial savings (present value)*

The cumulative financial savings at the present value is calculated as follows:

$$\underbrace{(CFS_{tp_x})_{PV}}_{\text{Present value of cumulative financial savings in time period}} = \underbrace{(COFS_{tp_x} + CCTS_{tp_x} + CCOS_{tp_x})}_{\text{Operational, carbon tax, and carbon offset savings}} \Big/ \underbrace{(1+DR)^{\left(\frac{tp_x - tp_c}{4}\right)}}_{\text{Future value factor}} \qquad \textit{Eq. 91}$$

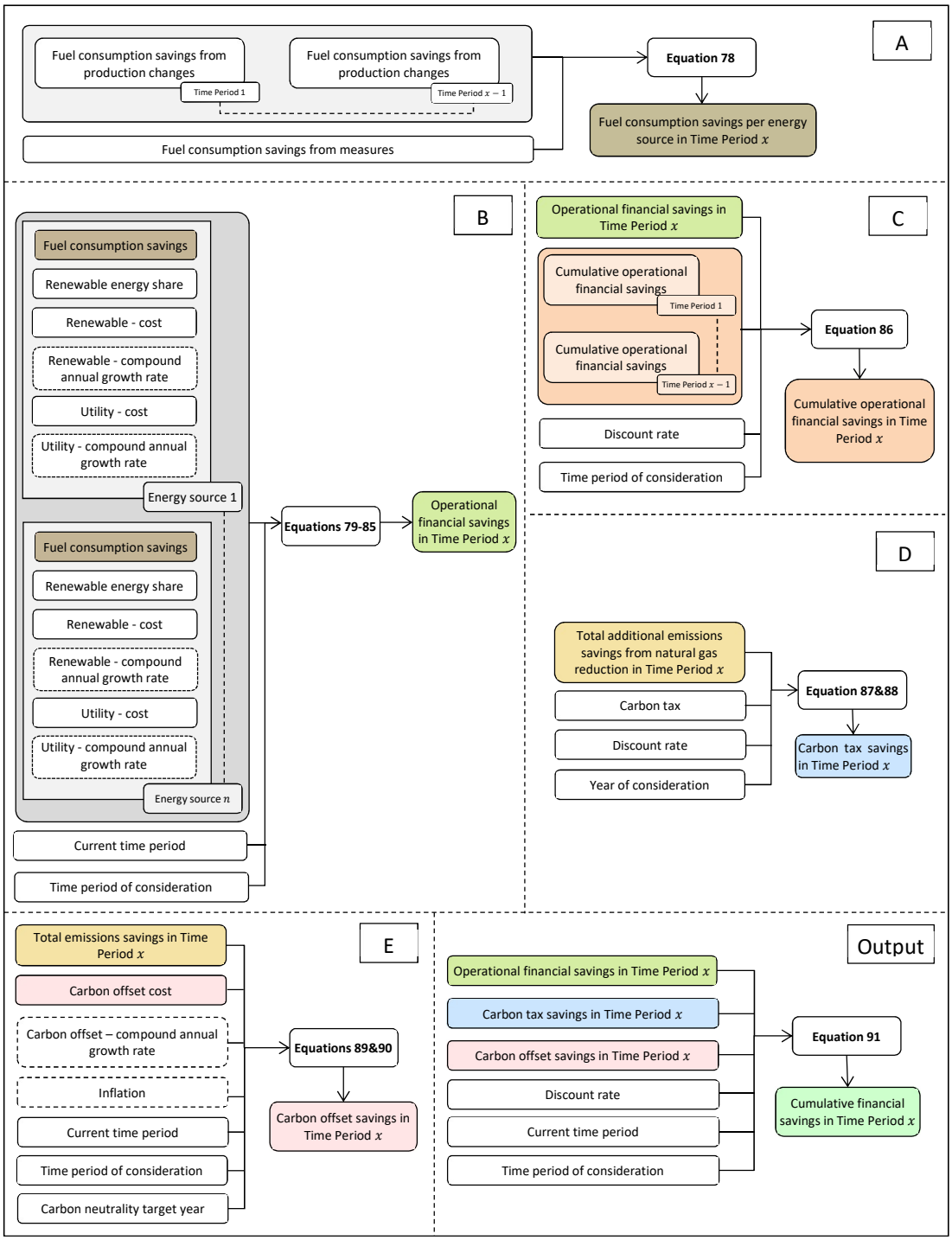


Figure 6.16: Graphical representation of financial savings equations

6.7.2 Financial Costs

The mathematical model used to determine the cumulative financial costs are discussed in this section, and are shown graphically in Figure 6.17. Note that all costs are depicted in present value.

6.7.2.1 *Total implementation cost in time period tp_x*

The total implementation cost from all measures planned for implementation in time period tp_x is as follows:

$$\underbrace{IMP_{tp_x}}_{\text{Implementation cost in time period}} = \underbrace{\sum_{m=1}^{m=k} (CC_{tp_x} - BG_{tp_x})_m}_{\text{Sum of all costs (capital less business grants) of all measures in time period}} \qquad \textit{Eq. 92}$$

Note that the implementation costs are considered in the time period of implementation, and the costs of current measures are not considered as they are already in the budget or have been settled financially.

6.7.2.2 *Total cumulative cost in in time period tp_x*

The total cumulative cost in time period tp_x is the sum of the implementation costs of all time periods, as follows:

$$\underbrace{CFC_{tp}}_{\text{Total cumulative cost in time period}} = \underbrace{\sum_{j=1}^{j=x} IMP_{tp_j}}_{\text{Sum of all implementation costs in time period}} \qquad \textit{Eq. 93}$$

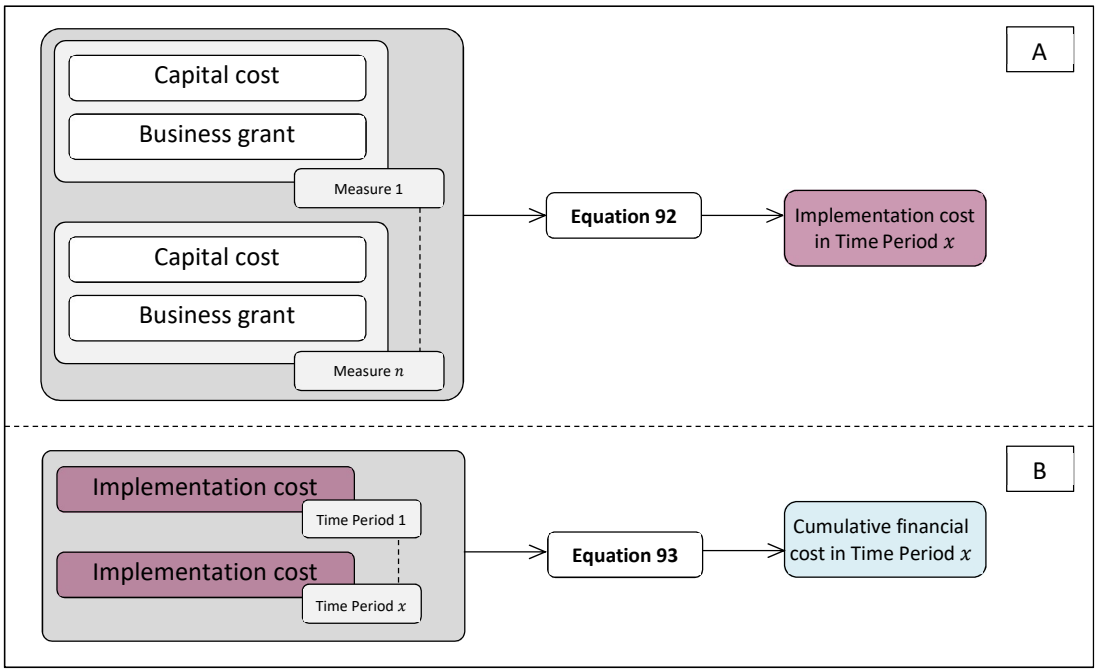


Figure 6.17: Graphical representation of financial cost equations

6.7.3 Key Financial Metrics

Three key financial analysis methods and metrics typically used in financial planning are used to assess the return on investment of projects—breakeven analysis, savings-return-on-investment (SIR), and the net present value (NPV). Breakeven analysis evaluates the cumulative costs and savings at present value along the carbon neutrality timeline and beyond, and determines the points at which they are equal (breakeven points). Note that there may be multiple breakeven points as the investment in the early years may begin to pay for itself before further capital investment is made in later years. The breakeven points are identified as in Eq. 94.

$$BE: CFS - CFC = 0 \qquad \textit{Eq. 94}$$

For the remaining metrics, the set of emissions-reduction measures and renewable energy increases are evaluated as a single investment in carbon neutrality to produce a single value based on a specific year for each metric. The SIR is the ratio of total savings to the total project investment, evaluated at a specific point in time, as shown in Eq. 95 for the time period of consideration. An SIR above unity indicates a cash-flow-positive project, i.e. the investment can be recovered. NPV considers the time value of money by discounting future cash flows at the organisation-specific discount rate. NPV is used to assess the long-term profitability of an investment to determine project viability, and is calculated as in Eq. 96.

$$SIR = \frac{Operating\ savings}{Cost\ of\ investment} = \left(\frac{CFS_{tp_x}}{CFC_{tp_x}}\right)_{PV} \qquad \textit{Eq. 95}$$

$$NPV = (Operating\ savings - Cost\ of\ investment) = \left(CFS_{tp_x} - CFC_{tp_x}\right)_{PV} \qquad \textit{Eq. 96}$$

The financial analysis outputs of the modelling tool are shown in Figure 6.18, where the graphical output is the breakeven analysis graph on which the cumulative savings, cumulative costs, and NPV are plotted on the left y-axis, and the SIR is plotted on the right y-axis.

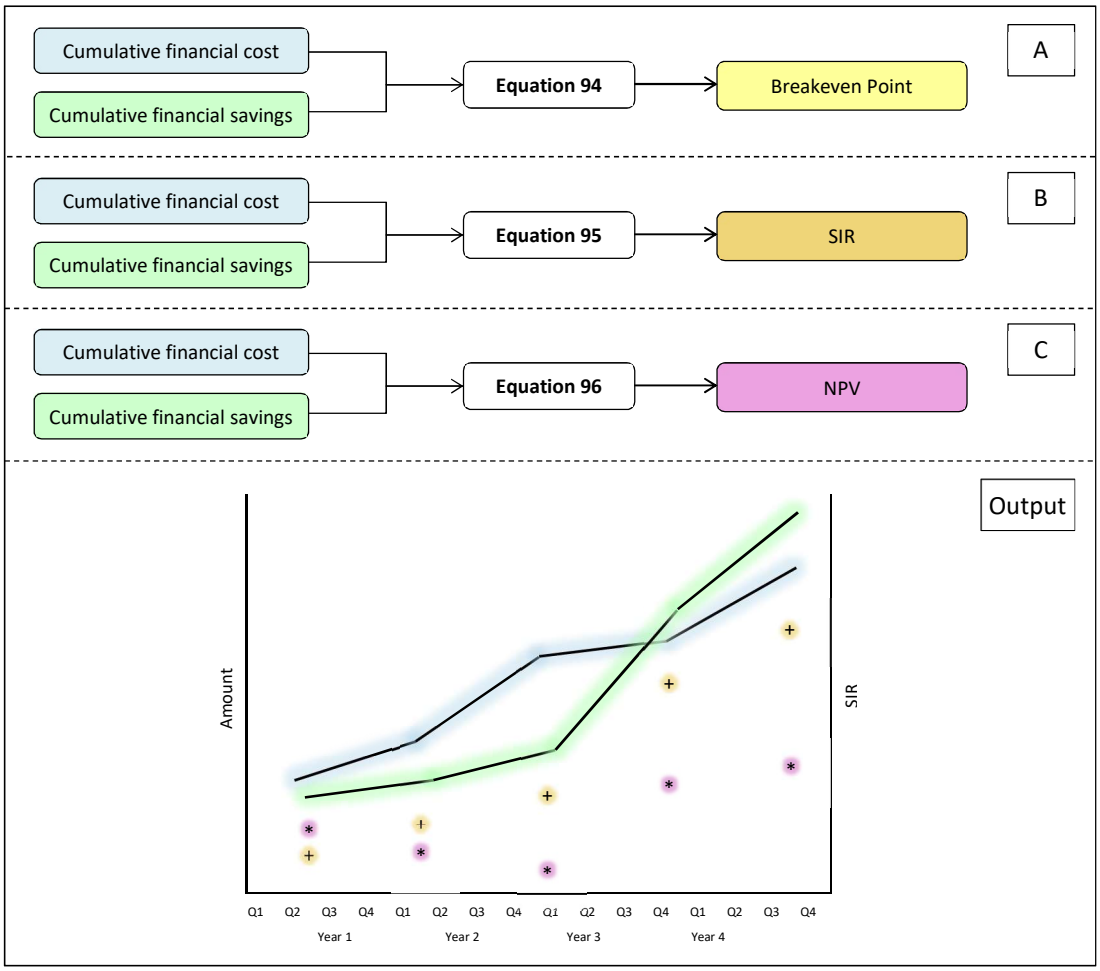


Figure 6.18: Graphical representation of the financial analysis

6.8 Modelling Tool Verification and Validation

The modelling tool was tested using the two software engineering principles of verification and validation to ensure accuracy and applicability, respectively [175]. The verification and validation process pertaining to this work is illustrated in Figure 6.19.

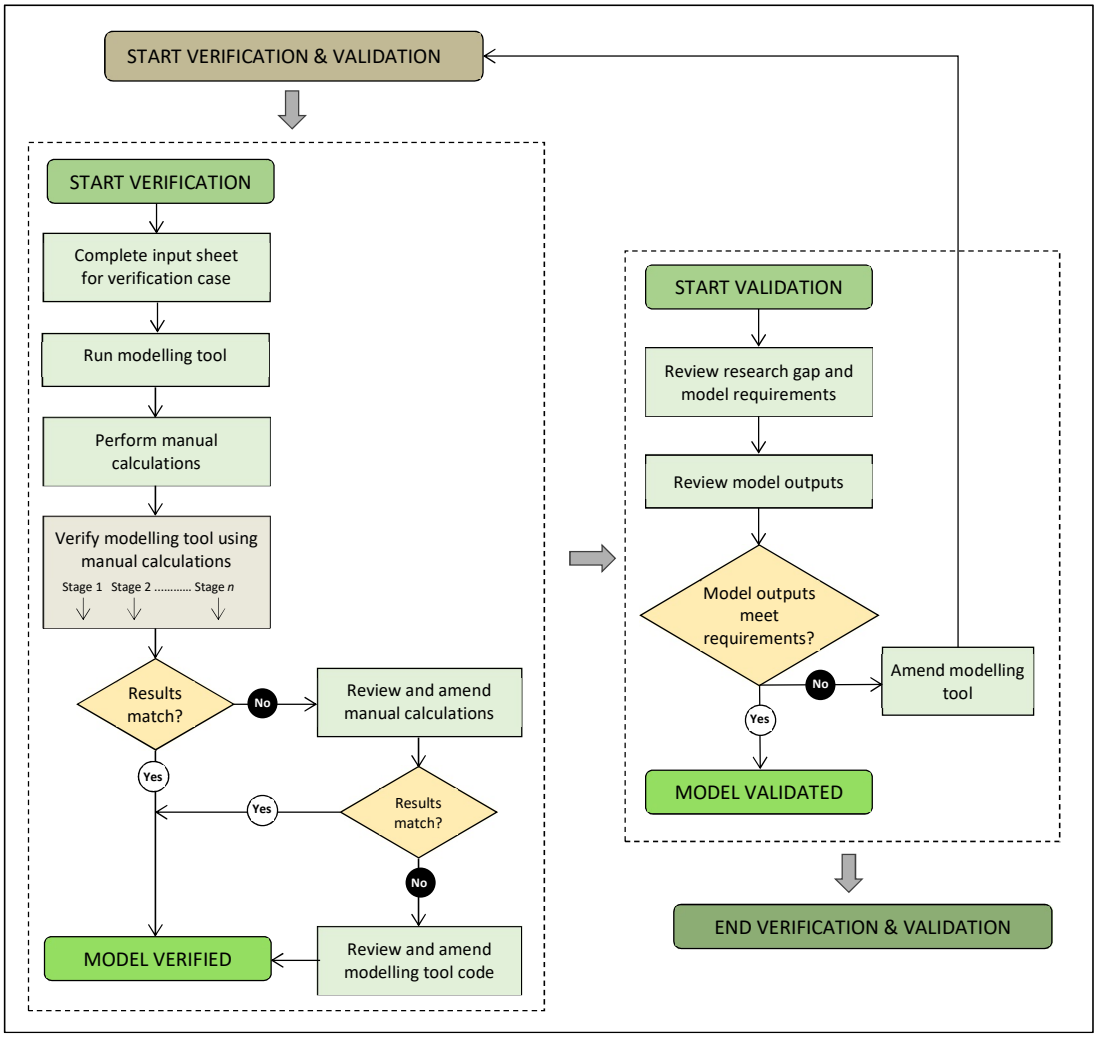


Figure 6.19: Verification and validation process

6.8.1 Modelling tool verification

6.8.1.1 *Verification approach*

The model was verified by means of a code review and manual calculations in Microsoft Excel (Microsoft Office Professional Plus 2016). Verification was conducted at various stages of development where new functionality was added, and the final model verification is discussed in this section. The verification case comprises representative industrial data created from an industry partner in the pharmaceutical manufacturing sector. Similar emissions-reduction projects were defined based on those considered by the industry partners, with additions and alterations to ensure that most of the modelling inputs were included for testing. As

such, this verification case is representative industrial data for which the modelling tool is designed.

6.8.1.2 *Verification case inputs*

The verification case has an energy breakdown and carbon footprint as shown in Figure 6.20.

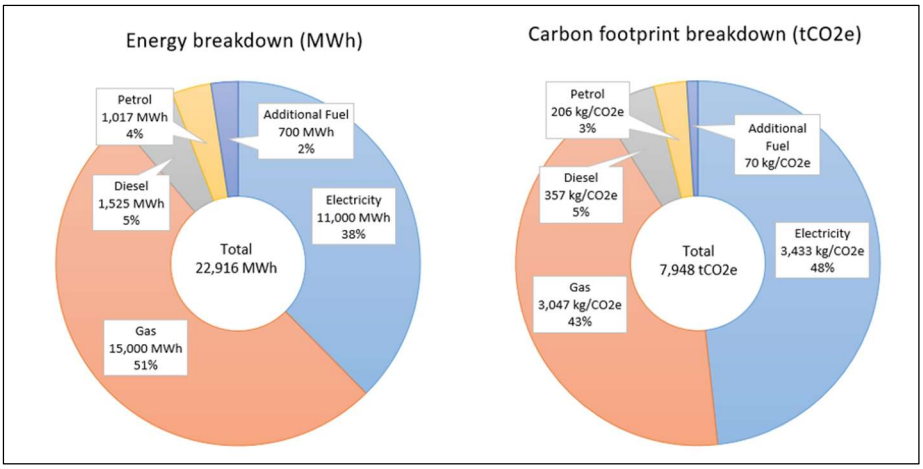


Figure 6.20: Verification case – Energy breakdown

The verification case includes an additional user-defined fuel, and contains sufficient current and optional projects such that each fuel type option is considered for reduction; it also excludes projects from the list; this ensures that the dropdown menus are accurately dealt with in the model. It further considers an increase in energy consumption owing to a forecasted production increase, and planned carbon offsetting within the carbon neutrality timeline to ensure that these items are considered in the calculations. In addition, it includes renewable energy share increases over the carbon neutrality timeline. The completed user input sheets are shown in Appendix B.

The verification case has the following scenarios:

- *No commitment to carbon neutrality* – the verification case uses the modelling tool to provide an indication of the costs and savings involved in implementing carbon emissions reduction measures.
- *Utility renewable share* – the verification case considers the renewable energy shares from the utility providers.

6.8.1.3 *Verification case results and discussion*

The model was verified according to the emissions equations in section 6.6 and the financial analysis in section 6.7, using Microsoft Excel (Microsoft Office Professional Plus 2016). The results for the carbon neutrality waterfall steps and the financial analysis are presented in this section.

6.8.1.3.1 Carbon neutrality waterfall

The carbon neutrality waterfall results from the manual calculations and the modelling tool implementation are shown in Figure 6.21 and Figure 6.22, respectively. The emissions values highlighted in the columns of the calculation table agree within 0.8% with those shown on the waterfall output from the modelling tool; this can be attributed to rounding errors.

Year of inclusion	Quarter	Waterfall steps - Production	Waterfall steps - Measures	Waterfall steps - Renewables	Waterfall steps - Offsets	Balance
2023	4	0	0	0	0	5500
2024	1	0	0	126	0	5374
2024	2	0	20	0	0	5354
2024	3	0	0	0	0	5354
2024	4	0	0	0	0	5354
2025	1	0	0	795	0	4559
2025	2	0	341	90	0	4128
2025	3	0	0	0	0	4128
2025	4	0	0	0	0	4128
2026	1	0	0	226	0	3902
2026	2	0	0	0	0	3902
2026	3	0	0	0	0	3902
2026	4	0	0	0	0	3902
2027	1	0	0	470	500	2932
2027	2	0	0	0	0	2932
2027	3	0	0	0	0	2932
2027	4	0	0	0	0	2932
2028	1	-197	0	504	0	2625
2028	2	0	845	0	0	1780
2028	3	0	0	0	0	1780
2028	4	0	0	0	0	1780
2029	1	0	0	0	700	1080
2029	2	0	0	0	0	1080
2029	3	0	456	0	0	623
2029	4	0	0	0	0	623
2030	1	0	0	159	0	464

Figure 6.21: Verification Case – Carbon Neutrality Waterfall: Manual calculation results

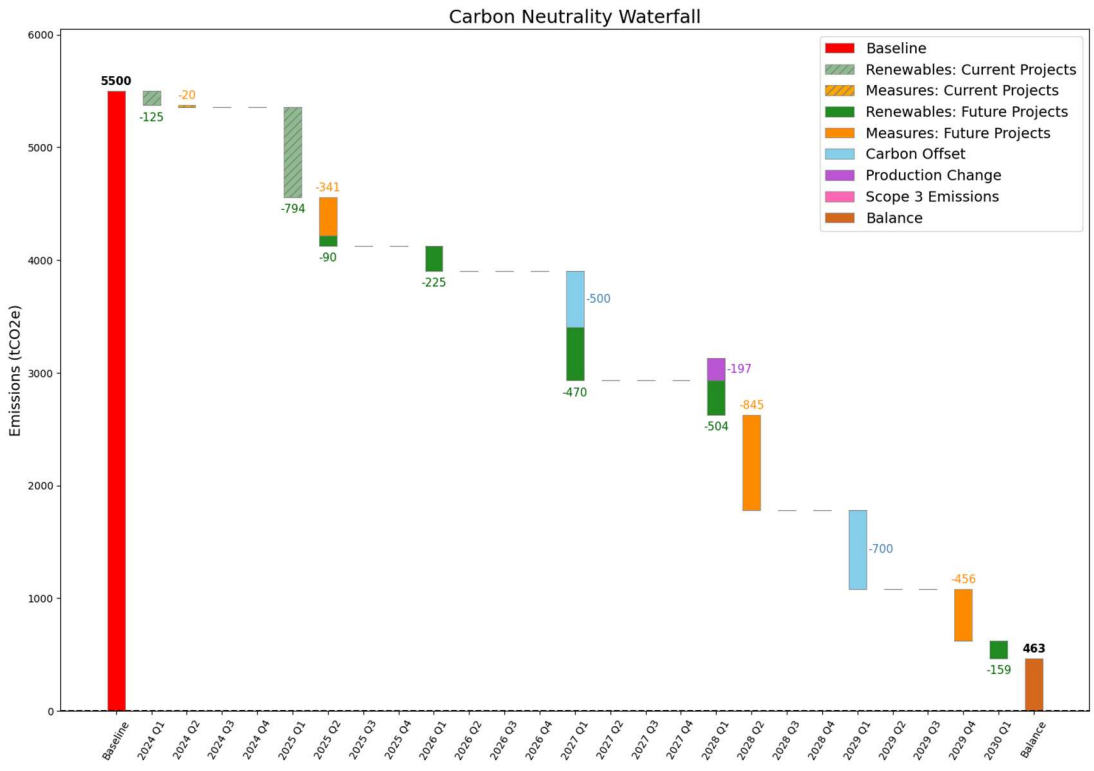


Figure 6.22: Verification Case – Carbon Neutrality Waterfall: Modelling tool results

6.8.1.3.2 Financial analysis

The present-value financial analysis from the manual calculations are shown in Figure 6.23 in the form of the present-value costs and savings, SIR, and NPV. The financial analysis output from the modelling tool is shown in Figure 6.24 in the form of a table of costs and savings, and a graph indicating the financial profile. The modelling tool considers a complete quarter as a single event by considering all measures in the quarter following their implementation to account for a full quarter of savings. This is a simplistic approach, with a far more complex real-world situation. Although the actual profile throughout the quarter may not be linear, this is assumed to be a sufficient representation of the real-world data as it makes some allowances for the consideration of measures being implemented throughout the quarter. Thus, the modelling tool represents the financial data as a piecewise linear graph. On the financial analysis graph, the red zones represent the years in which the costs outweigh the savings. Conversely, the green zones indicate the years in which the investment has paid off and there are net financial savings as a result of the implemented measures and increased renewable energy share. There are two breakeven points at which the financial savings exceed the costs after being lower in

the previous time period (highlighted in red); this is captured by the NPV becoming positive, indicting profitability in the investment at that point. The final cumulative savings and costs from the manual calculations agree within a 1.8×10^{-5} % error to those output from the modelling tool; this error is attributed to rounding errors. Thus, the financial analysis of modelling tool is considered verified.

Year of inclusion	Quarter	Total cumulative costs PV	Total cumulative savings PV	SIR	NPV
2025	1	€300,000	-€109,250	-0.364166408	-€409,250
2025	2	€300,000	-€129,106	-0.430352786	-€429,106
2025	3	€300,000	-€148,157	-0.493856247	-€448,157
2025	4	€300,000	-€166,414	-0.554712832	-€466,414
2026	1	€300,000	-€203,220	-0.677400974	-€503,220
2026	2	€300,000	-€238,996	-0.796652925	-€538,996
2026	3	€300,000	-€273,754	-0.912513056	-€573,754
2026	4	€420,000	-€307,508	-0.732160895	-€727,508
2027	1	€420,000	€189,456	0.451085679	-€230,544
2027	2	€420,000	€682,048	1.623923969	€262,048
2027	3	€420,000	€1,170,309	2.786450028	€750,309
2027	4	€420,000	€1,654,279	3.938758995	€1,234,279
2028	1	€2,420,000	€2,202,461	0.910107841	-€217,539
2028	2	€2,420,000	€2,217,001	0.916115938	-€202,999
2028	3	€2,420,000	€2,232,699	0.922602971	-€187,301
2028	4	€2,420,000	€2,249,539	0.929561665	-€170,461
2029	1	€2,420,000	€2,269,828	0.937945588	-€150,172
2029	2	€2,420,000	€2,291,202	0.946777494	-€128,798
2029	3	€2,620,000	€2,313,642	0.883069496	-€306,358
2029	4	€2,620,000	€2,372,677	0.905601968	-€247,323
2030	1	€2,620,000	€2,432,836	0.92856341	-€187,164
2030	2	€2,620,000	€2,493,666	0.951780745	-€126,334
2030	3	€2,620,000	€2,555,153	0.975249153	-€64,847
2030	4	€2,620,000	€2,617,285	0.998963871	-€2,715
2031	1	€2,620,000	€2,680,051	1.022920194	€60,051
2031	2	€2,620,000	€2,743,437	1.047113474	€123,437
2031	3	€2,620,000	€2,807,432	1.07153912	€187,432
2031	4	€2,620,000	€2,872,025	1.096192596	€252,025
2032	1	€2,620,000	€2,936,914	1.120959625	€316,914
2032	2	€2,620,000	€3,002,380	1.145946649	€382,380
2032	3	€2,620,000	€3,068,411	1.171149286	€448,411
2032	4	€2,620,000	€3,134,996	1.196563206	€514,996
2033	1	€2,620,000	€3,202,122	1.222184135	€582,122
2033	2	€2,620,000	€3,269,781	1.248007849	€649,781
2033	3	€2,620,000	€3,337,959	1.274030177	€717,959
2033	4	€2,620,000	€3,406,647	1.300246998	€786,647
2034	1	€2,620,000	€3,475,435	1.326501976	€855,435
2034	2	€2,620,000	€3,544,715	1.352944845	€924,715
2034	3	€2,620,000	€3,614,478	1.379571622	€994,478
2034	4	€2,620,000	€3,684,711	1.406378372	€1,064,711
2035	1	€2,620,000	€3,755,406	1.433361209	€1,135,406
2035	2	€2,620,000	€3,826,553	1.460516295	€1,206,553
2035	3	€2,620,000	€3,898,140	1.487839841	€1,278,140
2035	4	€2,620,000	€3,970,160	1.515328104	€1,350,160
2036	1	€2,620,000	€4,041,986	1.542742755	€1,421,986
2036	2	€2,620,000	€4,114,231	1.570317066	€1,494,231
2036	3	€2,620,000	€4,186,884	1.598047412	€1,566,884
2036	4	€2,620,000	€4,259,937	1.625930211	€1,639,937
2037	1	€2,620,000	€4,333,380	1.653961927	€1,713,380
2037	2	€2,620,000	€4,407,204	1.682139068	€1,787,204
2037	3	€2,620,000	€4,481,400	1.710458187	€1,861,400
2037	4	€2,620,000	€4,555,960	1.738915879	€1,935,960
2038	1	€2,620,000	€4,629,054	1.7668146	€2,009,054
2038	2	€2,620,000	€4,702,512	1.794851988	€2,082,512
2038	3	€2,620,000	€4,776,325	1.823024699	€2,156,325
2038	4	€2,620,000	€4,850,483	1.851329434	€2,230,483
2039	1	€2,620,000	€4,924,979	1.879762933	€2,304,979
2039	2	€2,620,000	€4,999,804	1.908321979	€2,379,804
2039	3	€2,620,000	€5,074,949	1.937003396	€2,454,949
2039	4	€2,620,000	€5,150,407	1.965804047	€2,530,407
2040	1	€2,620,000	€5,225,748	1.994560383	€2,605,748
2040	2	€2,620,000	€5,301,390	2.023431367	€2,681,390
2040	3	€2,620,000	€5,377,325	2.052413966	€2,757,325
2040	4	€2,620,000	€5,453,544	2.081505185	€2,833,544

Figure 6.23: Verification Case – Financial analysis: Manual calculation results

Quarter	Cumulative costs PV	Cumulative savings PV	SIR	NPV
2025.0 Q1.0	0	-109249	-inf	-109249
2025.0 Q2.0	300000	-129105	-0.43	-429105
2025.0 Q3.0	300000	-148156	-0.49	-448156
2025.0 Q4.0	300000	-166413	-0.55	-466413
2026.0 Q1.0	300000	-203220	-0.68	-503220
...	...	...	...	...
2039.0 Q4.0	2620000	5150406	1.97	2530406
2040.0 Q1.0	2620000	5225748	1.99	2605748
2040.0 Q2.0	2620000	5301390	2.02	2681390
2040.0 Q3.0	2620000	5377324	2.05	2757324
2040.0 Q4.0	2620000	5453543	2.08	2833543

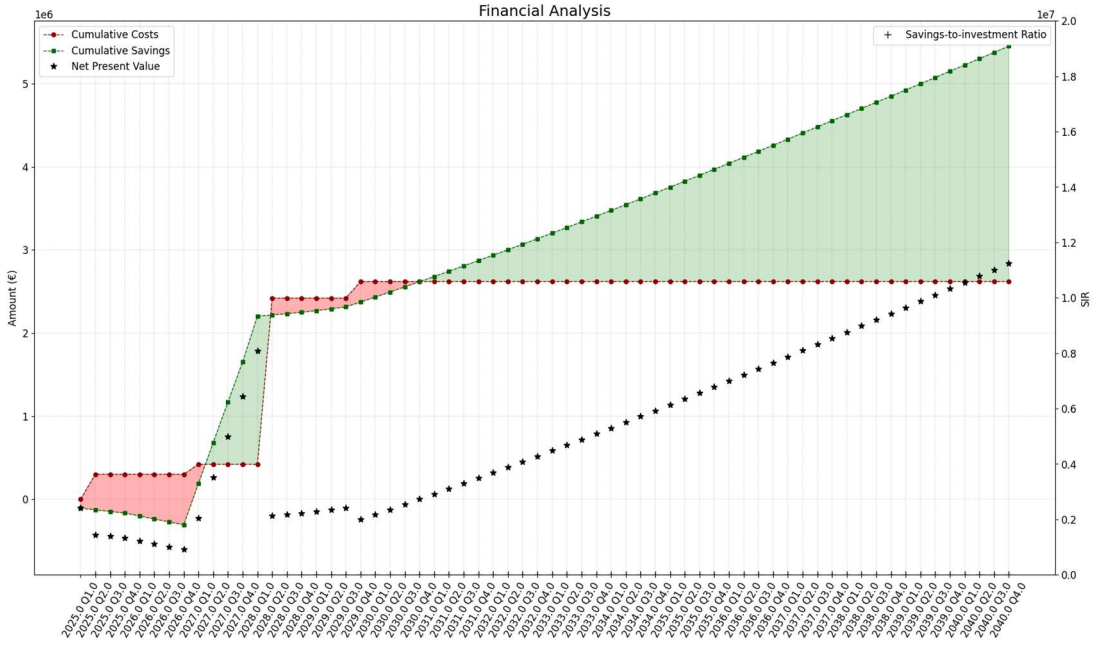


Figure 6.24: Verification Case – Financial analysis: Modelling tool results

6.8.2 Validation

6.8.2.1 *Validation approach*

The input requirements to the validation process are based on the literature review, research gap, and developed methodology in this work. Specifically, the modelling tool was validated against the two defined user requirements—a carbon neutrality waterfall and financial analysis. The applicability of the modelling tool to an industrial organisation was tested. An actual dataset from an industry partner in the medical device field was used to validate the model after verification to check its applicability.

This involved running the model with the user input sheet of the validation case and then evaluating the model outputs; no calculations were conducted since the accuracy of the model was verified previously.

6.8.2.2 *Validation case inputs*

The validation case uses actual industrial data from an organisation that has a commitment to carbon neutrality within five years. The emissions-reduction measures focus on reducing the thermal load since the organisation uses 100% renewable electricity sourced from a combination of onsite generation through wind energy and a fixed-price power purchase agreement to offset the remaining grid electricity. There is no significant production change forecasted, and no carbon offsetting has been planned prior to the carbon neutrality target year. In addition, the validation case has the following scenarios:

- *Commitment to carbon neutrality* – the validation case uses the modelling tool to provide an indication of the costs and savings involved in achieving carbon neutrality.
- *Utility renewable share* – the validation case does not consider the proposed renewable energy shares from the utility providers. This only affects the gas consumption since the full electrical load is supplied by renewable energy.
- *Costing* – the validation case uses the advanced costing methods for the carbon offset cost, and simple costing methods for the remaining costs.

The completed user input sheets are shown in Appendix C and the energy breakdown and carbon footprint are shown in Figure 6.25.

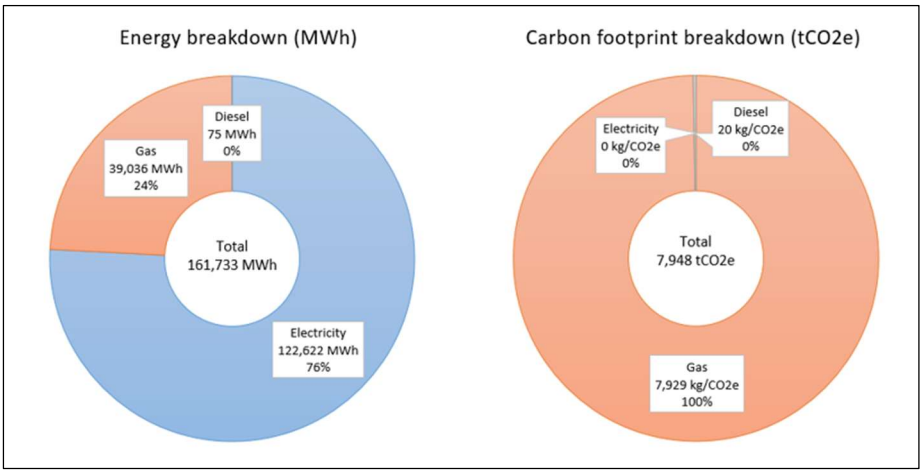


Figure 6.25: Validation – Energy and emissions breakdown

6.8.2.3 *Validation Case outputs and discussion*

The carbon neutrality waterfall and the financial analysis graph are presented in Figure 6.26 and Figure 6.27, respectively. The waterfall shows a negative balance in the carbon neutrality target year. This is clearly inaccurate as it is not possible to reduce emissions below zero through these measures alone since no additional carbon offsetting is planned within the carbon neutrality timeline. This anomaly is attributed to the fact that these emissions-reduction measures are considered independently in the modelling tool; in reality, there may be considerable interaction effects which cause the actual emissions reduction to be considerably lower than the theoretical. These inaccuracies spill over into the financial analysis. The costs are unaffected since these are implementation costs only and each measure is implemented as considered. However, the financial savings are overestimated owing to the inflated fuel savings and the corresponding emissions reduction on which the carbon tax and carbon offset are based. This results in a corresponding increase in the key financial metrics of SIR and NPV that are used for investment decisions. Therefore, consideration must now be given to alleviating the effects of project interactions.

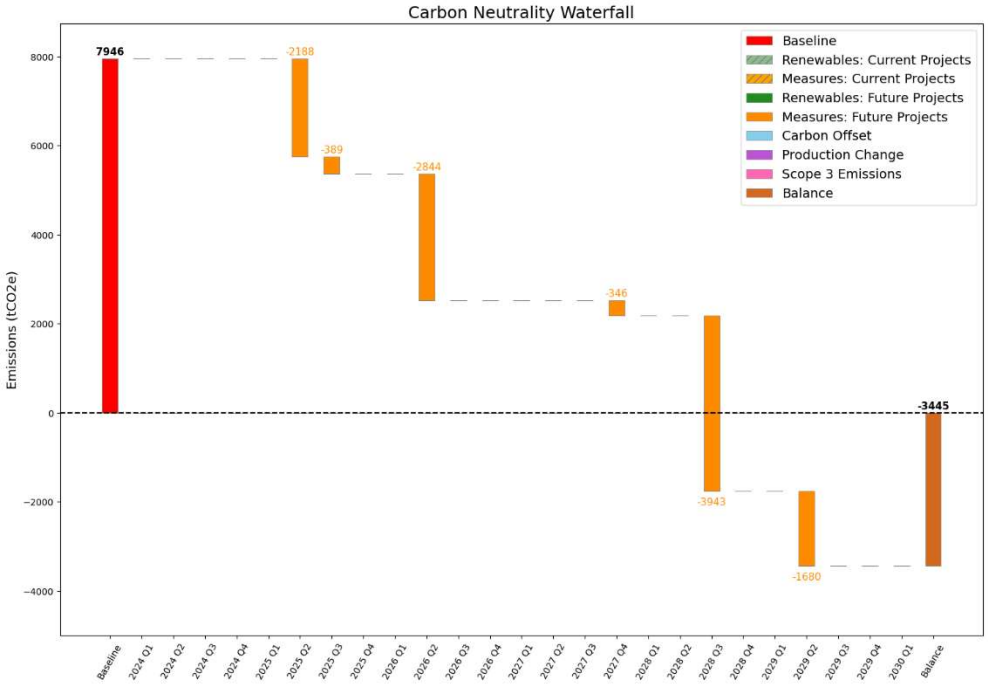


Figure 6.26: Validation Case – Carbon neutrality waterfall

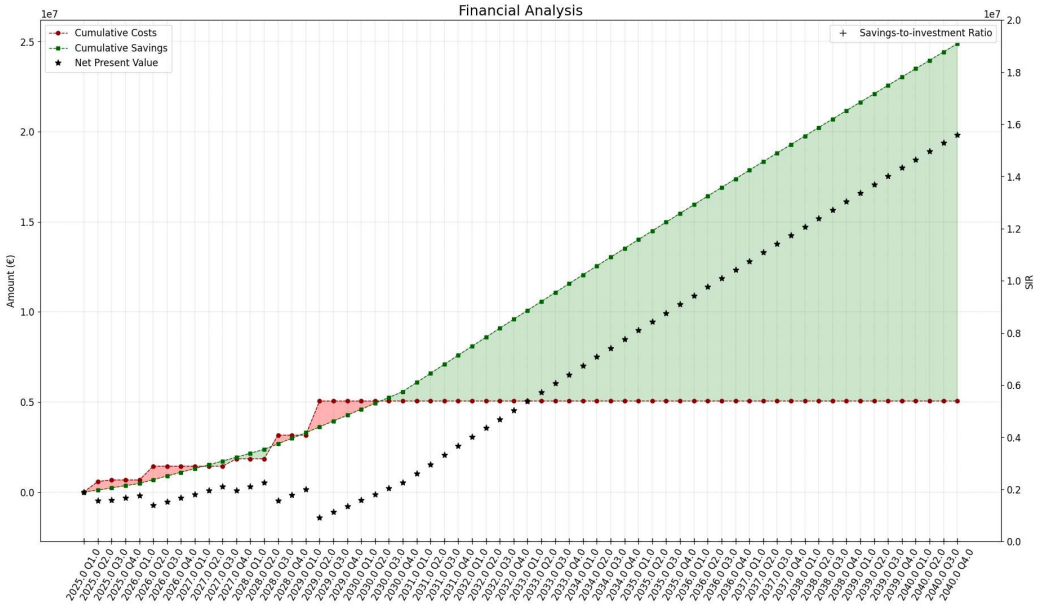
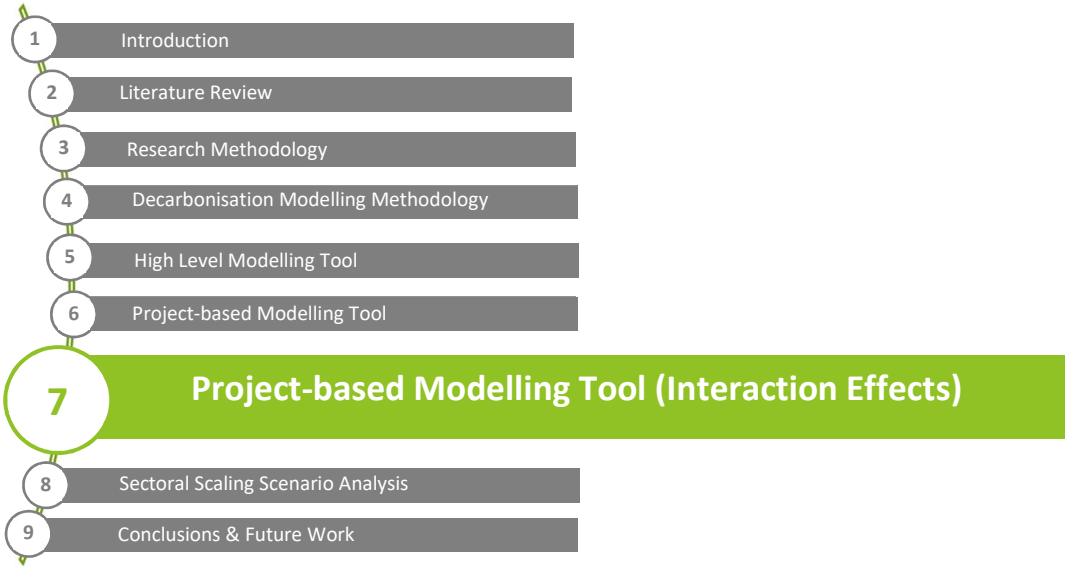


Figure 6.27: Validation Case – Financial analysis graph

6.9 Conclusions

A project-based modelling tool for carbon neutrality in non-EII industrial manufacturing is proposed in which the dynamic effects of changing emissions factors are considered. The required user inputs, inherent model inputs, and the mathematical model that underpins the modelling tool are presented. The modelling tool is verified against the mathematical model using representative synthetic data, and is deemed accurate. The validation process based on case study data indicates

that the modelling tool is applicable since the user requirements have been met in terms of the type of outputs. However, the carbon neutrality waterfall falls below zero, resulting in a negative balance. A possible cause of this is the inadvertent consideration of multiple emissions-reduction measures that address the same load such as an electric boiler and a heat pump for the full thermal load; this can occur since the modelling tool input is a list of all emissions-reduction opportunities which may include different options for the same load; this allows different options to be selected for ease of running multiple separate simulations. Another possible cause of the negative balance is planned carbon offsetting whereby the organisation may be undertaking voluntary offset projects. However, the case study does not consider redundant measures and does not include carbon offsetting, and consequently the negative balance is not representative of the real-world situation. Thus, the modelling tool is a verified and validated as a first working version; however, the interaction effects between emissions-reduction measures should be considered to enhance applicability.



This chapter addresses the following research objective:

'RO3 – Method for the resolution of interaction effects between emissions-reduction measures in a modelling tool to aid non-EII industrial organisations in planning carbon neutrality'

This method extends the project-based modelling tool to consider the interactions between emissions-reduction measures with the goal of improving the accuracy of the carbon neutrality waterfall and financial analysis. The flowchart in Figure 7.1 illustrates the integration of this method into the project-based modelling tool.

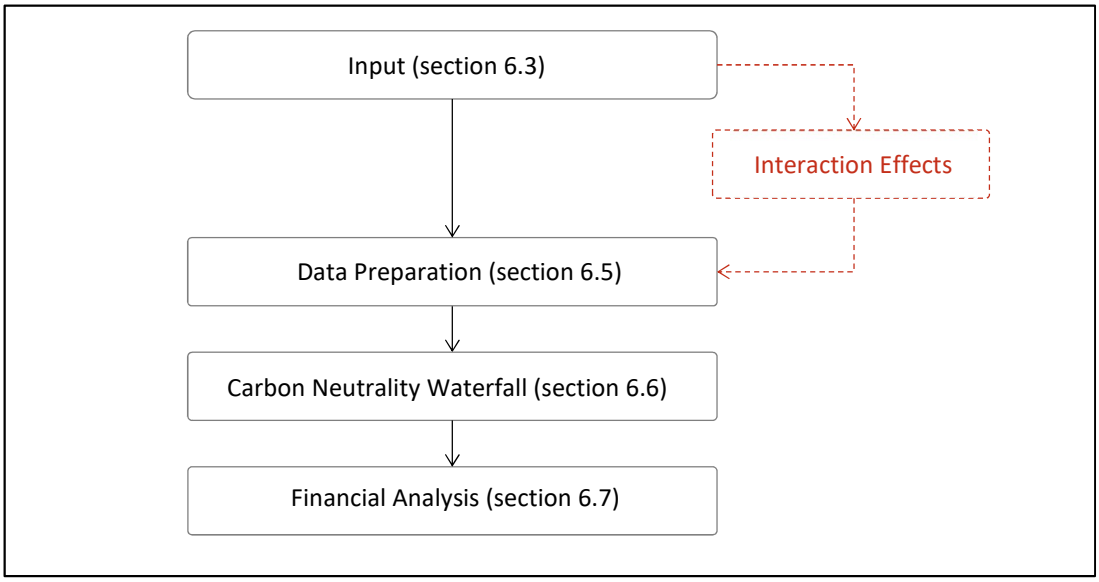


Figure 7.1: Flowchart of modelling methodology

The remainder of this chapter is as follows: Section 7.1 presents the development process of the incorporation of the interaction effects into the modelling tool. Section 7.2 provides an overview of the additional input data required for each emissions-reduction measure as well as the baseline data. Section 7.3 discusses the modelling approach used to generate the interaction-incorporated carbon neutrality waterfall, and presents the mathematical models applicable to each emissions-producing activity. Section 7.4 discusses the modelling approach used to generate the associated financial analysis graph. Section 7.5 details the validation process of the modelling tool using three case studies. Section 7.6.3 presents the conclusions, and discusses the limitations and threats to validity of the modelling tool.

7.1 Development process

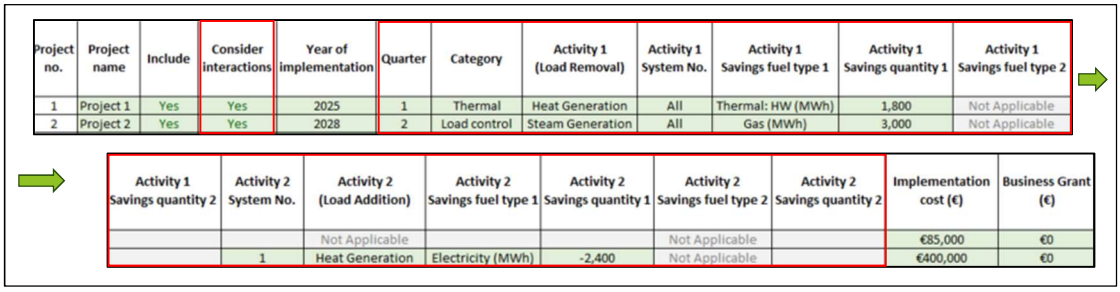
Three case studies of industrial manufacturing sites were leveraged as a basis from which to explore the interaction effects. First, the industrial processes at each site were analysed to determine typical sources of emissions in terms of equipment type, layout, and connections with other systems. Then, the relationships between these processes were explored to understand how they interact with each other and how changes in one process might affect another. Each process was further researched to explore other equipment types and layouts that could be used on other sites. Then, relevant carbon footprinting standards and emissions protocols were consulted to round out the research by seeking additional emissions sources**.** This lead to the development of a rule-based system of incorporating interaction effects in the modelling tool (as discussed in 2.6.2). The following sections detail the additional user input required for the consideration of the interaction effects in the project-based modelling tool.

7.2 Additional input data

7.2.1 Emissions-reduction measures

The additions to the input sections for the current and future projects are discussed in this section and highlighted in Figure 7.2. Additional information is required for each emissions-reduction measure in order to understand its potential interactions since emissions-producing activities may have interdependencies specific to the type

and layout of the equipment used on site. Three properties are deemed sufficient to understand the source of the emissions, the manner in which they are generated, and the scale of the emissions; these are Category, Activity, and System Number. Category is the type of emissions reduction which is chosen from a predefined list based on the energy hierarchy (section 7.2.1.2); Activity is the source of emissions reduction, chosen from a predefined list based on the GHG Protocol emissions-producing activities (section 7.2.1.3); and System number is a user-defined number that differentiates between various systems within an activity. The relationship between these three metrics is shown in Figure 7.3. The additional inputs, including these metrics, are discussed in more detail in the following subsections.



Project no.	Project name	Include	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings fuel type 1	Activity 1 Savings quantity 1	Activity 1 Savings fuel type 2
1	Project 1	Yes	Yes	2025	1	Thermal	Heat Generation	All	Thermal: HW (MWh)	1,800	Not Applicable
2	Project 2	Yes	Yes	2028	2	Load control	Steam Generation	All	Gas (MWh)	3,000	Not Applicable

Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings fuel type 1	Activity 2 Savings quantity 1	Activity 2 Savings fuel type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)
		Not Applicable			Not Applicable		€85,000	€0
	1	Heat Generation	Electricity (MWh)	-2,400	Not Applicable		€400,000	€0

Figure 7.2: Example input sheet for current & future projects – Project-based Modelling Tool (Interactions)

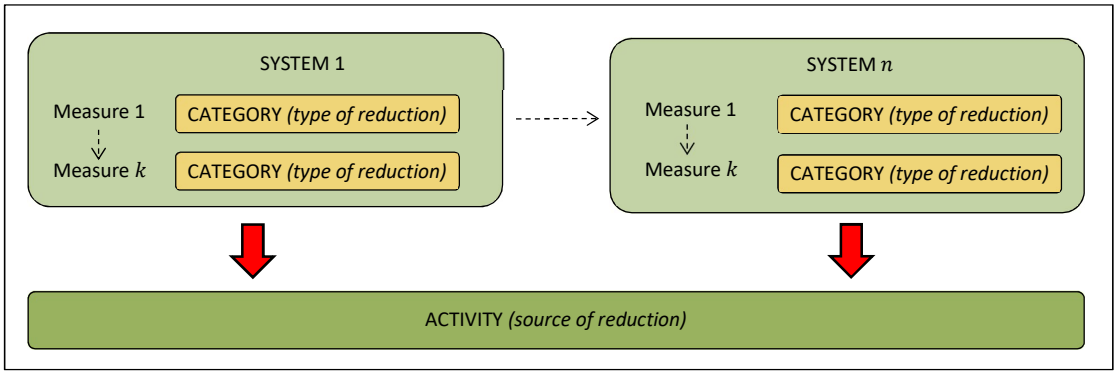


Figure 7.3: Relationship between Activity, Category, and System Number

7.2.1.1 *Inclusion of interaction effects*

The input sheet provides an option to turn off the interaction effect independently for each measure to consider its full effect. This is useful for atypical measures for which the assumptions of the modelling tool do not apply, as well as situations in which in-depth energy assessments have been conducted on site and potential emissions-reduction measures have been determined with some consideration of interactions.

7.2.1.2 *Category of emissions-reduction measure*

The category options for emission-reduction measures were chosen to align with tiers 1 to 4 of the energy hierarchy, with some adaption to facilitate the use of the rule-based interaction system (Table 7.1). Tier 1 relates to demand reduction, which is separated into load control and thermal categories in the modelling tool as these both act to reduce the load, but behave slightly differently in terms of interactions. Tier 2 is energy efficiency, which is considered a distinct category. Tiers 3 and 4 relate to the use of resources associated with no or low emissions, respectively, and these are both addressed by the new technology category. Tier 5 is not relevant to this modelling tool as it represents no change to the current situation, Consequently, each emissions-reduction measure is assigned to one of the following four categories—Efficiency, Load Control, Thermal, and New Technology (Figure 7.4).

- Efficiency - These measures directly reduce fuel consumption through equipment or control improvements without changing the energy demand or source. This category relates to the energy supply.
- Load control - These measures reduce the energy demand of the system by either behavioural changes such as reducing HVAC set points, improving the driving style of the transport fleet, and improving maintenance plans; system changes such as insulating pipework; and transferring the load from one activity to another. This category relates to energy demand.
- Thermal - These measures comprise additional and restructured waste heat recovery and heat exchange. This category relates to energy demand.
- New technology - These measures reduce emissions by replacing equipment with a different type—either equipment powered by a different fuel to take advantage of a lower emissions factor or a greater renewable energy share; or equipment that combines heating, cooling, and/or power generation. This category relates to energy supply.

Table 7.1: Defined Categories according to energy hierarchy

Energy Hierarchy		Category
Tier 1	Energy demand reduction	Load Control
		Thermal
Tier 2	Energy efficiency	Efficiency
Tier 3	Utilisation of renewable sustainable resources	New Technology
Tier 4	Utilisation of other, low-GHG-emitting resources	
Tier 5	Utilisation of resources as we do now	Not applicable

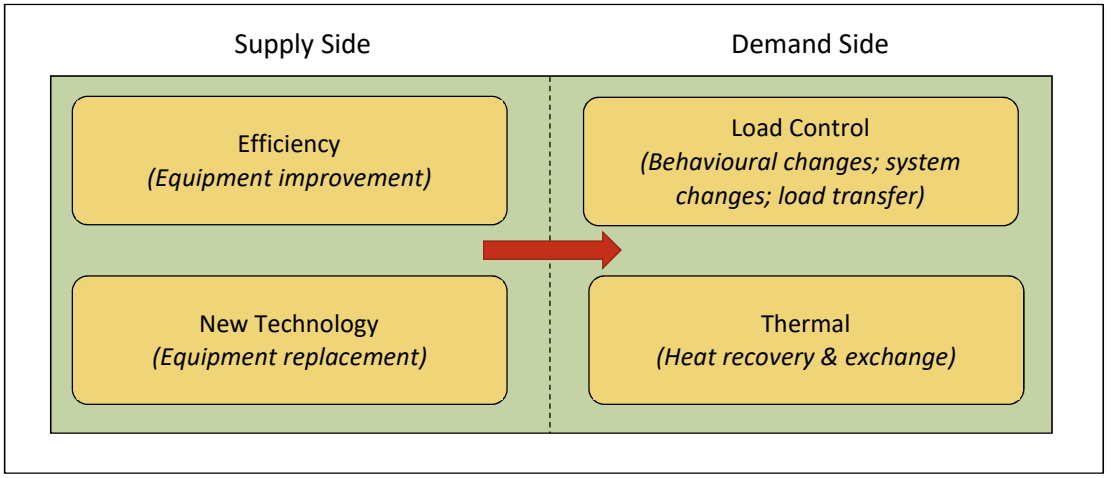


Figure 7.4: Emissions-reduction categories

7.2.1.3 *Activity and system*

The leading carbon footprinting methodology 'The Greenhouse Gas Protocol – A Corporate Accounting and Reporting Standard' defines principal emissions-producing activities (electricity, heat, or steam generation; physical or chemical processing; transportation; fugitive emissions; and purchased electricity) [37]. These activities form the basis of the activities in the modelling tool, where the following exceptions and additions are made to enhance the applicability to industrial manufacturing.

- Fugitive emissions are accidental or undesirable [37], and reduction measures directly reduce fuel or vapour instead of system loads. The emissions source may not be fuel, and thus cannot be converted to energy use. Savings in fugitive emissions can be entered directly as a negative value in the 'Carbon offsetting' input sheet, and no interaction effects are considered.

- The electrical equipment activity is reduced to lighting only as other electrical equipment may form part of larger systems that include equipment fuelled by alternate sources.
- Compressed air warrants an independent activity because of its high energy consumption of up to 10% of energy used in industry [176], and its consideration as 'the fourth utility' [177]. In addition, air compressors may be powered by alternate fuel and although this is not common, it further motivates for a separate activity.
- Production line equipment forms an independent activity as it consumes a significant proportion of energy, and there may be many different systems within this activity. This category includes equipment used for product manufacture, assembly, and testing, as well as laboratory activities.
- Chilled water generation forms an independent activity since it could comprise a significant proportion of energy consumption, it encompasses a range of equipment, and is linked to the HVAC systems.
- HVAC forms an independent activity since emissions-reduction measures cannot be categorised singularly as Heat or Chilled Water generation as they may affect both (or neither in the case of packaged HVAC units).
- Scope 3 covers emissions from sources not owned or controlled by the organisation, upstream and downstream of the organisation. Although all scope 3 emissions are not currently required for carbon neutrality certification, this option is built into the modelling tool as an option to future-proof it against tightening legislation, and because the tool is also used for information and planning purposes and there may be a need to determine the effect of reducing scope 3 emissions, (e.g. if using a science-based targets approach where scope 3 emissions are required to a greater extent).
- Other Activity covers all additional, undefined measures that are unlikely to yield an appreciable reduction in emissions.

Within each activity, each emissions-reduction measure can affect a number of systems; system numbers are included to differentiate between the applications of the measures. The activity options provided in the modelling tool are shown along

with example systems in Table 7.2, where the modelling tool activities that differ from those of the GHG protocol are the additional activities defined in this work.

Table 7.2: Defined Activities and System examples

GHG Protocol Activity	Modelling Tool Activity	System Examples
Electricity Generation	Electricity Generation	Generators; combined heating & power plant
Heat Generation	Heat Generation	LPHW plants & loops feeding HVAC, calorifiers
Steam Generation	Steam Generation	Steam plants & loops feeding HVAC, sterilisation cells
Physical/Chemical Processing	Physical/Chemical Processing	Ammonia production; cement production
Fugitive Emissions	(Excluded)	
Transport	Transport	Truck fleet; fork lifts
Electrical Equipment	Lighting	Lighting zones
-	Air Compression	Compressed air plants and loops
-	Production Line Equipment	Conveyors; moulding machines; packaging rigs; inspection equipment; plastic waste vacuums
-	Chilled Water Generation	HVAC chilled water; process water
-	HVAC	HVAC zones
-	Scope 3	n/a
	Other	n/a

On the input sheet within the tool, each measure must be assigned to at least one activity (from where the load is removed). Up to two activities can be assigned to account for cases of heat exchange or where a load is moved from one activity to

another, e.g. heat load moved from a HW system (Heat Generation) to a steam system (Steam Generation). In the case of load transfer, the interactions for both activities are governed by the rules of the load removal activity since that determines the load to be placed on the system.

7.2.1.4 *Energy source savings fuel type*

The energy source options are as per the project-based modelling tool excluding interaction effects, detailed in section 6.3.1.7. However, there are two additional options in the interaction effects modelling tool. 'HVAC' accounts for HVAC load control measures where the split between the heating and cooling load is undefined (discussed in more detail in section 7.3.6). 'CHW' accounts for the coefficient of performance (COP) of the chillers to relate load control measures on the demand to fuel on the supply side.

7.2.2 Additional input data - Baseline

The baseline fuel consumption and energy output of each energy source within each relevant Activity is required for the calculation of the interaction effects (**Error! Reference source not found.**). This data can be sourced from the carbon footprinting exercise required in the Define Step of the methodology. Alternatively, for relevant organisations in Ireland, some of this data may readily available from the LIEN questionnaire used to gather energy performance data.

Parameter	Value
Year of most recent carbon footprint	
Carbon footprint (tCO2e)	
Discount rate	
Footprint electricity consumption (MWh)	
Footprint gas consumption (MWh)	
Footprint oil consumption (kl)	
Any additional fuel to be considered?	
Footprint Additional Fuel consumption (unit)	
Footprint Additional Fuel emissions factor (tCO2e/unit)	
Electricity market-based emissions factor	
STEAM GENERATION	
Steam output (MWh) from gas boilers	
Steam output (MWh) from oil boilers	
Steam output (MWh) from electric boilers	
Steam boiler efficiency (gas)	
Steam boiler efficiency (oil)	
Steam boiler efficiency (electrode)	
HEAT GENERATION	
HW output (MWh) from gas boilers	
HW output (MWh) from oil boilers	
HW output (MWh) from electrode boilers	
HW output (MWh) from heat pumps	
HW output (MWh) from steam heat exchange	
HW boiler efficiency (gas)	
HW boiler efficiency (oil)	
HW boiler efficiency (electrode)	
HW heat pump efficiency	
Steam-HW heat exchange efficiency	
ONSITE GENERATION	
Onsite electrical generation by gas (MWh)	
Efficiency of gas-fuelled generators	
Onsite electrical generation by oil (MWh)	
Efficiency of oil-fuelled generators	
LIGHTING	
Electricity input (MWh)	
PRODUCTION LINE EQUIPMENT	
Electricity input (MWh)	
TRANSPORT	
Oil input (kl)	
Electricity input (MWh)	
AIR COMPRESSION	
Oil input (kl)	
Gas input (MWh)	
Electricity input (MWh)	
CHILLED WATER GENERATION	
Electricity input (MWh)	
Electric chiller COP	
Gas input (MWh)	
Gas chiller COP	
Oil input (kl)	
Oil chiller COP	
HVAC	
Electricity input (MWh)	
HW input (MWh)	
Is the energy consumption expected to increase owing to production increase or facility expansion over the carbon neutrality timline?	
Are any carbon offset programmes expected to be implemented within the carbon neutrality timeline?	

Figure 7.5: Example input sheet - Baseline – Project-based Modelling Tool (Interactions)

7.3 Modelling approach - Carbon neutrality waterfall

This section discusses the approach to the inclusion of the interaction effects in the modelling tool in relation to generating the carbon neutrality waterfall. Sub-section 7.3.1 presents an overview of general assumptions of the approach. Sub-sections 7.3.2 to 7.3.14 detail how the interaction effects of emissions-reduction measures for each activity are incorporated to more accurately depict the load reductions. Sub-section 7.3.15 describes the effect of the inclusion of the interaction effects on the emissions factors used in the calculation of the carbon emissions waterfall.

7.3.1 Overview

The following general assumptions and rules apply to the rule-based system of interaction effects in the modelling tool:

- Onsite electricity generation is evenly distributed across all electrical users, i.e. there is no consideration for a dedicated generation system for a specific load.
- Multiple measures assigned to the same time period of the carbon neutrality timeline are addressed in the order of entry.
- There is a backstop rule to prevent negative load since these rules cannot capture every situation and it is possible that interactions may be missed.

Two parameters are defined in the following sub-sections for use in the interaction effects equations, namely the systems approach and the new technology ratio.

7.3.1.1 *Systems approach*

The baseline load for each activity is provided in the user input sheets, but the breakdown of these loads into their systems (where applicable) is unknown. Since some measures act on more than one system, there must be a method of distributing the load between affected systems to scale future load reductions. Consequently, a systems approach is defined to adjust the savings from the current measure (*M*) to account for interactions with previous savings affecting the system. The ratio of the running total (incorporating applicable previous savings) to the baseline energy consumption of the activity is used as the 'systems ratio' to scale the current savings. The total savings attributed to applicable previous efficiency, load control, and

thermal measures fully or partially acting on the system are calculated as per Eq. 97, Eq. 98, and Eq. 99, respectively. The systems ratio is calculated as per Eq. 100. However, this equation is not consistent as it is governed by the rules defined for each Category within each Activity, and thus may not include all categories shown. The adjusted savings for current measure *M* are calculated as per Eq. 101.

$$Previous\ efficiency\ measures: \quad Eff_{prev} = \sum_{m=0}^{m=M-1} (FCS_{eff_{int}})_m \qquad \textit{Eq. 97}$$

$$Previous\ load\ measures: \quad Load_{prev} = \sum_{m=0}^{m=M-1} (FCS_{load_{int}})_m \qquad \textit{Eq. 98}$$

$$Previous\ thermal\ measures: \quad Therm_{prev} = \sum_{m=0}^{m=M-1} (FCS_{therm_{int}})_m \qquad \textit{Eq. 99}$$

$$SR_M = \frac{FC_{base} - (Eff_{prev} + Load_{prev} + Therm_{prev})}{FC_{base}} \qquad \textit{Eq. 100}$$

$$FCS_{int} = SR_M \times FCS_{orig} \qquad \textit{Eq. 101}$$

This systems approach is shown in Figure 7.6 with an example for clarity. The example depicts a lighting activity comprising two systems (zones), where the baseline energy consumption of the activity is known to be 6000 MWh. The contributions of systems 1 and 2 are 1500 and 4500 MWh, respectively; these are unknown in the modelling tool and are shown here to highlight the accuracy of the calculations based on the assumptions of the systems approach. The input table shows three measures—occupancy sensors in both systems which decrease the overall load by 15%, LED replacement in system 2 which improves the lighting efficiency by 55% in this zone only, and dimmer switches in system 2 which decreases the load by 20% in this system only. The proposed reductions in the modelling tool approach are calculated based on the systems approach, and the actual reductions are calculated for each system and are shown for comparison. The errors between the modelling tool calculation and the actual values are shown for each measure. The error for measure 1 is zero since there are no previous measures for interaction; the error for measure 2 is zero since the previous measure was applied to both systems; the error for

measure 3 is 32%, indicating an underestimation of the interaction effects. This approach will always underestimate the interaction effects as it is a pro-rata method that includes reductions in other systems. However, this allows for at least a minimum level of interaction to be considered in the absence of further information. As a comparison, the overall error for the balance of energy is calculated for the inclusion (-4%) and exclusion (-35%) of the interaction effects, and this highlights the importance of including these effects. (These errors are positive as they represent the overestimation of the remaining balance as a result of the underestimation of the reductions.)

Input

	Measure	Systems Affected	Category	Reduction (MWh)
1	Occupancy sensors (15% reduction)	1 & 2	Load control	900
2	Replacement with LED (55% reduction)	2	Efficiency	2475
3	Dimmer switches (20%)	2	Load control	900

Modelling Tool Approach

Baseline

6000 MWh electricity

Measure 1

Occupancy sensors in Systems 1 & 2

Load control measure

$FCS_{orig} = 900$

$SR_{M1} = 1$

$FCS_{int} = SR_{M1} \times FCS_{orig} = 900$

Measure 2

LED replacement in System 2

Efficiency measure

$FCS_{orig} = 2475\ MWh$

$SR_{M3} = \frac{(6000 - 900)}{6000} = 85\%$

$FCS_{int} = SR_{M3} \times FCS_{orig} = 2104\ MWh$

Measure 3

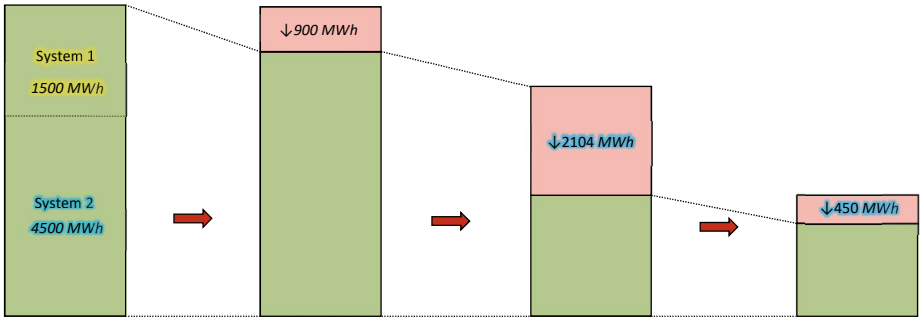
Dimmer switches in System 2

Load Control measure

$FCS_{orig} = 900\ MWh$

$SR_{M3} = \frac{(6000 - 900 - 2104)}{6000} = 50\%$

$FCS_{int} = SR_{M3} \times FCS_{orig} = 450\ MWh$



Actual Values - System 1

Baseline

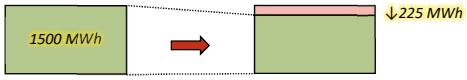
1500 MWh electricity

Measure 1

$FCS_{orig} = 15\% \times 1500 = 225\ MWh$

$SR_{M1} = 1$

$FCS_{int} = SR_{M1} \times FCS_{orig} = 225\ MWh$



Actual Values - System 2

Baseline

4500 MWh electricity

Measure 1

$FCS_{orig} = 15\% \times 4500 = 675\ MWh$

$SR_{M1} = 1$

$FCS_{int} = SR_{M1} \times FCS_{orig} = 675\ MWh$

Measure 2

$FCS_{orig} = 2475\ MWh$

$SR_{M2} = \frac{(4500 - 675)}{4500} = 85\%$

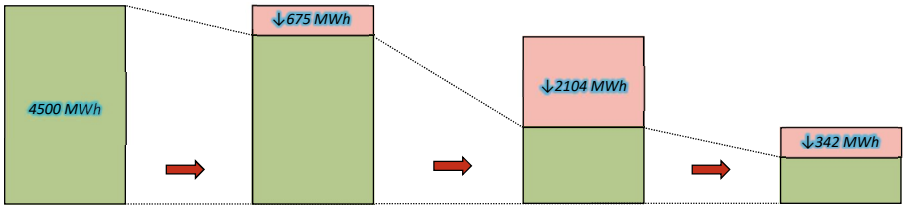
$FCS_{int} = SR_{M2} \times FCS_{orig} = 2104\ MWh$

Measure 3

$FCS_{orig} = 1125\ MWh$

$SR_{M2} = \frac{(4500 - 675 - 2104)}{4500} = 38\%$

$FCS_{int} = SR_{M2} \times FCS_{orig} = 342\ MWh$



Errors

Measure 1

$$Error = \frac{675 - 675}{675} = 0\%$$

Measure 2

$$Error = \frac{2104 - 2104}{2107} = 0\%$$

Measure 3

$$Error = \frac{450 - 342}{342} = 32\%$$

Overall model error:

$$Error = \frac{(6000 - 900 - 2104 - 450) - (6000 - 225 - 675 - 2104 - 342)}{(6000 - 225 - 675 - 2104 - 342)} = -4\%$$

Overall error of not including interaction effects:

$$Error = \frac{(6000 - 900 - 2475 - 900) - (6000 - 225 - 675 - 2104 - 342)}{(6000 - 225 - 675 - 2104 - 342)} = -35\%$$

Figure 7.6: Systems approach for measures applied to a system

7.3.1.2 *New technology ratio*

All efficiency, load control, and thermal measures must be adjusted following a change in technology so that the savings defined using the original technology remain applicable with the new energy source. Basically, this is an adjustment for the energy source and efficiency of the new equipment. In the user input sheet, the original energy source is shown as a positive savings value, indicating the removal of the load; the new energy source is shown as a negative value, indicating an energy increase to account for the additional load. The approach to new technology differs according to the activity type as follows, and a flow chart illustrating these approaches is shown in Figure 7.8

- *Lighting and Production Line Equipment* – New technology measures do not apply to these activities, as discussed in sections 7.3.2 and 7.3.3, respectively.
- *Transport, Air Compression, and Electricity Generation* – The savings attributed to the measures in these activities are input directly as fuel. Thus, changes in fuel as a result of new technologies can be dealt with directly within the activity. First, the interactions between all measures prior to the new technology measure are addressed according to the rules applicable to each activity (sections 7.3.4, 7.3.5, 7.3.7, and 7.3.10), using the systems ratio. The new technology measure follows the same rules to adjust the original savings of the old energy source ($\left(FCS_{tech_{orig}}\right)_{i_{old}}$) to include interactions ($(FCS_{tech_{int}})_{i_{old}}$). A 'technology ratio' is defined in Eq. 102 as the ratio between the original fuel savings of the old technology and new technology as a means to scale future fuel savings by accounting for differences in efficiency.

$$tech\ ratio = -\frac{\left(FCS_{tech_{orig}}\right)_{i_{new}}}{\left(FCS_{tech_{orig}}\right)_{i_{old}}} \qquad \textit{Eq. 102}$$

The technology ratio is applied to the adjusted fuel savings of the old fuel ($\left(FCS_{tech_{orig}}\right)_{i_{old}}$) to yield the adjusted fuel savings for the new fuel ($\left(FCS_{tech_{orig}}\right)_{i_{new}}$). Then, the fuel source of subsequent measures is changed to that of the new technology to ensure that they are incorporated using the correct fuel. Finally, the savings of these subsequent measures are adjusted

using the new technology ratio such that they represent fuel savings of the new technology. This approach assumes a total replacement strategy; in the case of partial replacement, smaller systems can be defined as these rules are applied for each system within an activity. As an example, in the case of the replacement of a number of diesel vehicles with electric vehicles within a fleet, the replaced vehicles can be defined as a system within the Transport activity.

- *HVAC, Chilled Water Generation, Heat Generation, Steam Generation* – These activities may contain parent-child relationships, and the energy savings are input as either energy source savings (e.g. 'Thermal: HW') or fuel savings. The energy sources are converted to fuels based on their relative contributions to the total energy output; for thermal savings, this occurs in the basic project-based modelling tool (section 6.5.1). For 'CHW' savings, the applicable fuel savings based on the same rationale are as follows:

$$\underbrace{FCS_{elec_{chw}}}_{\text{Electricity savings from CHW savings}} = \underbrace{ESS_{chw}}_{\text{CHW savings}} \times \underbrace{\frac{1}{CHP_{elec_{chw}}}}_{\text{Chiller COP}} \times \underbrace{\left(\frac{EO_{elec}}{EO_{gas} + EO_{oil} + EO_{elec}}\right)_{chw}}_{\text{Portion of total chw provided by elec chillers}} \quad \text{Eq. 103}$$

$$\underbrace{FCS_{gas_{chw}}}_{\text{Gas savings from CHW savings}} = \underbrace{ESS_{chw}}_{\text{CHW savings}} \times \underbrace{\frac{1}{CHP_{gas_{chw}}}}_{\text{Chiller COP}} \times \underbrace{\left(\frac{EO_{gas}}{EO_{gas} + EO_{oil} + EO_{elec}}\right)_{chw}}_{\text{Portion of total chw provided by gas chillers}} \quad \text{Eq. 104}$$

$$\underbrace{FCS_{oil_{chw}}}_{\text{Oil savings from CHW savings}} = \underbrace{ESS_{chw}}_{\text{CHW savings}} \times \underbrace{\frac{1}{CHP_{oil_{chw}}}}_{\text{Chiller COP}} \times \underbrace{\left(\frac{EO_{oil}}{EO_{gas} + EO_{oil} + EO_{elec}}\right)_{chw}}_{\text{Portion of total chw provided by oil chillers}} \quad \text{Eq. 105}$$

Then, the interactions between all measures prior to the new technology measure are addressed according to the activity rules (sections 7.3.6, 7.3.8, and 7.3.9), using the systems ratio. For new technology measures, the savings are input as fuel as they relate to the supply equipment. The savings from the original fuels of the new technology measure are adjusted according to these rules, and the savings from the new fuels are adjusted using the new technology ratio. However, future measures may be input as thermal savings

and these must be converted to fuel savings. Thus, the proportions of fuels providing the energy for the current measure (M) are updated with the implementation of new technologies, as per Eq. 106. The energy source savings are converted to fuel savings using these updated proportions, as in Eq. 107.

$$(EO_i)_M = EO_{i_{base}} - \sum_{m=1}^{m=M} ESS_m \qquad \textit{Eq. 106}$$

$$(FCS_i)_M = \frac{(EO_i)_M}{(EO_i)_{total}} \times ESS_M \qquad \textit{Eq. 107}$$

Finally, the interaction rules are applied to the fuel consumption savings, using the systems ratio.

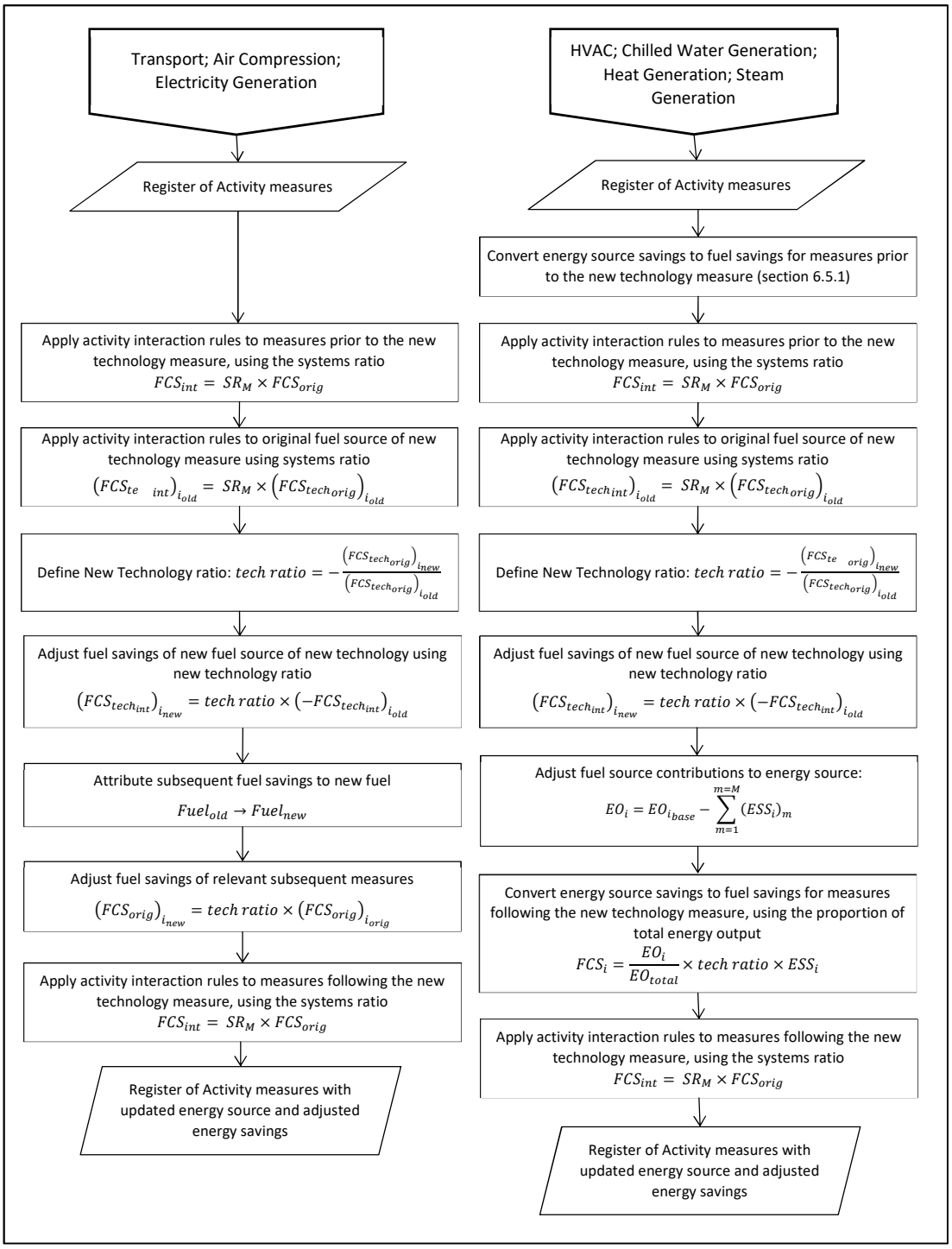


Figure 7.7: New technology approach

The following example within the Steam Generation Activity is provided for clarity. A natural gas boiler and an electrode boiler generate equal quantities of steam to supply the steam system, with different efficiencies. A register of possible emissions-reduction measures is defined; these are input as independent measures with no consideration of the sequence of implementation or of interactions. Measure 1 reduces demand on the steam system as a load control measure. It is treated as a

conversion of energy source savings (thermal) to fuel consumption savings, as detailed in section 6.5.1; this conversion process uses the baseline fuel contributions to steam generation and is applicable as no new technologies have yet been implemented. Measure 2 is the new technology measure where the gas boiler is replaced with an electrode boiler; first, the systems ratio is used to scale the gas savings to account for savings from measure 1, and then remaining gas is converted to electricity using the technology ratio. The gas and electricity contributions to the energy source are revised based on this, and are used to determine the fuel savings attributed to measure 3.

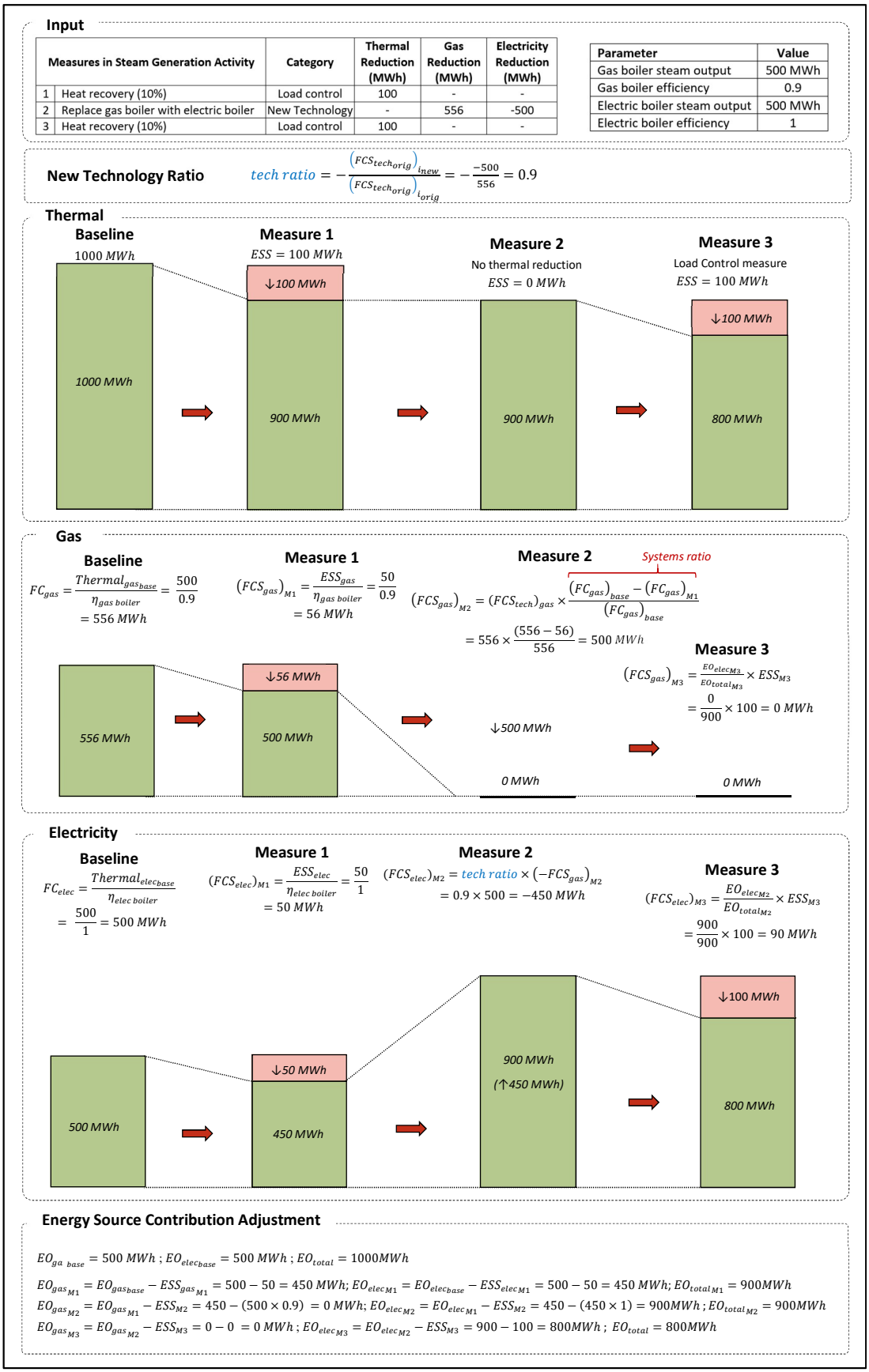


Figure 7.8: New technology ratio calculation for measures following a technology change

7.3.1.3 *Interaction effects process overview*

The modelling tool calculates the interactions for each activity in the following order: Lighting, Production Line Equipment, Transport, Air Compression, HVAC, Chilled Water Generation, Heat Generation, Steam Generation, and Electricity Generation. This is to account for parent-child relationships and load transfer between activities. Figure 7.9 shows an overview of the modelling tool process for consideration of the interaction effects, from the user inputs to the output register of adjusted emissions-reduction measures. The interaction effects between measures in a system are discussed in this order in the following sub-sections for the categories in each activity.

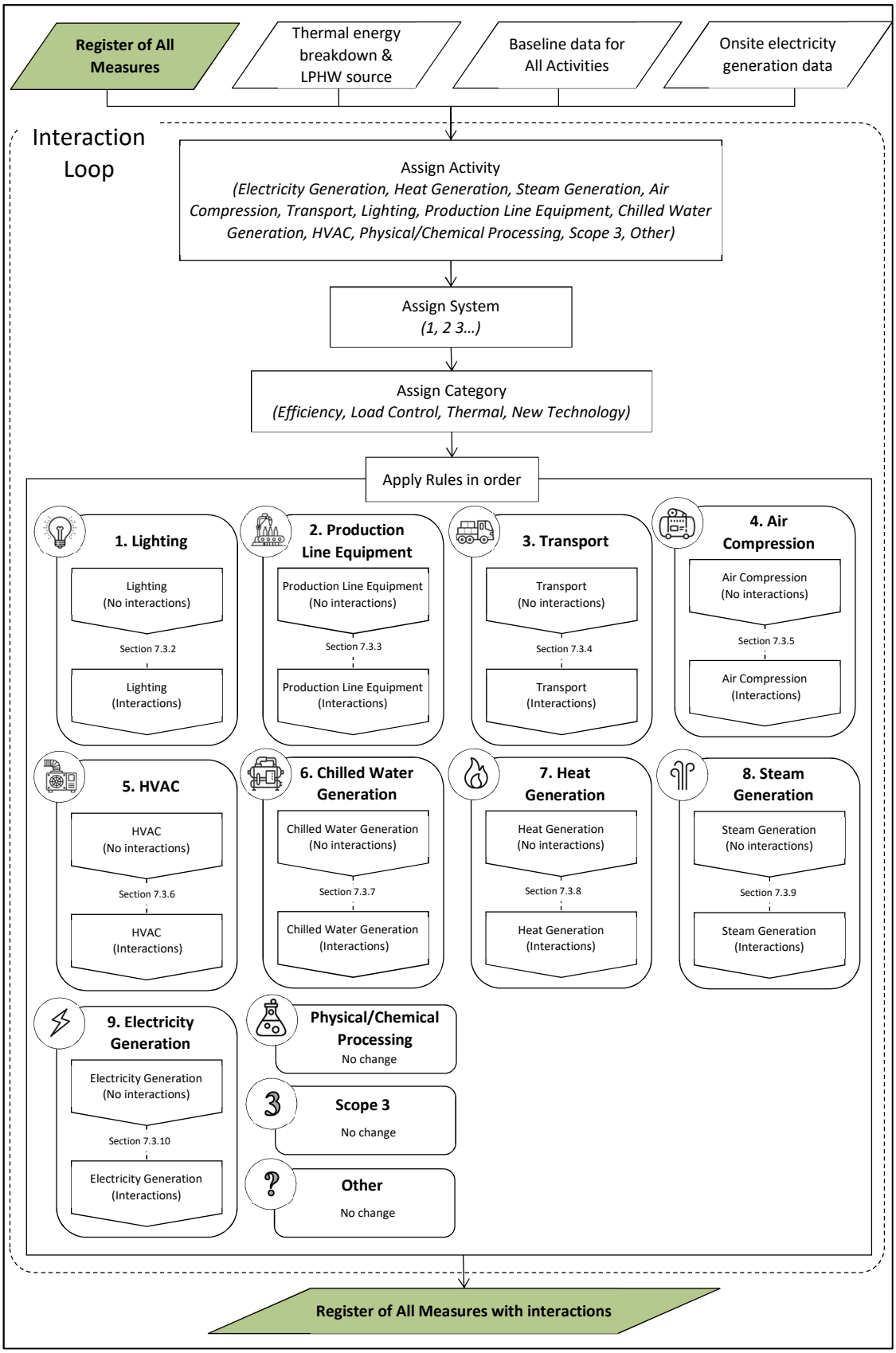


Figure 7.9: Interaction effects process

7.3.2 Lighting

Emissions-reduction measures in the efficiency and load control categories are applicable to lighting, where they reduce the lighting power density by reducing the energy intensity and demand, respectively. The thermal and new technology categories are not applicable since there is no thermal component and no change in energy source since all lighting is electrically powered. Examples of these measures for each applicable category are shown in Table 7.3.

Table 7.3: Example measures – Lighting

Category	Measures
Efficiency *(Energy intensity reduction)*	Replacement with more efficient lighting (e.g. LED)
Load Control *(Demand reduction)*	Occupancy sensors; motion sensors; dimmer switches; photosensors; timers

For lighting, the systems are the building's lighting zones. The following interaction effects between measures in a system are proposed for each category. The electrical savings attributed to each measure are adjusted to account for interactions; these equations are applicable to each system within the Lighting activity. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.10, and the final equations applicable to efficiency and load control measures are Eq. 108 and Eq. 109, respectively.

- Efficiency – Previous efficiency measures are ignored since the lighting type within a zone is unlikely to be changed more than once within the carbon neutrality timeline. All previous load control measures are considered as they reduce the total energy consumption, and the efficiency savings must be applied pro-rata to the adjusted total.
- Load control – Previous efficiency measures are considered since less energy is used to deliver the total load. If multiple load control measures are targeted, these are likely to be implemented together as a single control strategy. However, if these are implemented separately over a number of

years, there will be some non-linear interaction between these measures which is difficult to calculate without detailed data. As an approximation, a linear relationship is assumed, and the load savings are decreased pro-rata.

$$Efficiency: \quad FCS_{eff_{int}} = \left(\frac{FC_{lighting_{base}} - Load_{prev}}{FC_{lighting_{base}}}\right) \times FCS_{eff_{orig}} \qquad \textit{Eq. 108}$$

$$Load\ Control: \quad FCS_{load_{int}} = \left(\frac{FC_{lighting_{base}} - (Eff_{prev} + Load_{prev})}{FC_{lighting_{base}}}\right) \times FCS_{load_{orig}} \qquad \textit{Eq. 109}$$

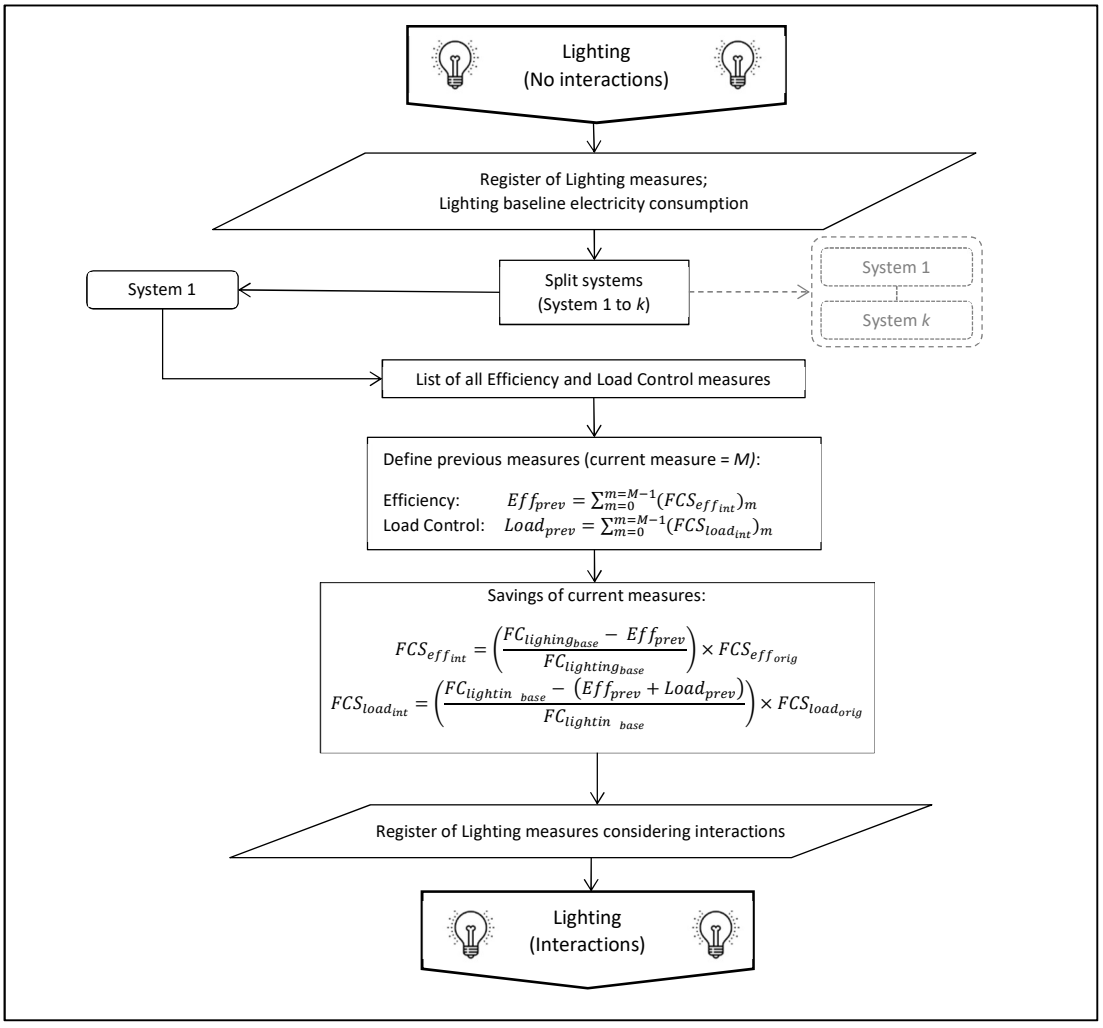


Figure 7.10: Graphical representation of Lighting interaction effects

7.3.3 Production Line Equipment

Production Line Equipment is limited to electrically powered, non-thermal equipment that operate independently. In this activity, systems are defined as sets of production lines manufacturing different products. Emissions-reduction measures in the efficiency and load control categories are applicable; the new technology

category is not applicable since these are strictly electrical activities and no change in energy source is possible.

Manufacturing operations management is evaluated by means of key performance indicators relating to production, maintenance, inventory, and quality. The benchmark key performance indicator used to evaluate production line efficiency is the overall equipment effectiveness, which is the product of the availability, effectiveness, and quality rate. [178] Availability is affected by equipment failure and by process failure in the form of setup and adjustment losses during production changeover and from tool positioning. Effectiveness relates to speed losses and stops from production interruption. Quality rate is determined by the level of product defects and reduced yield from unstable equipment start-up. [179] Although these metrics relate to production line efficiency, they are treated as load control measures since the streamlined operation of the production lines reduces the equipment load. The efficiency measures considered in the modelling tool relate specifically to the equipment efficiency. Examples of emissions-reduction measures for each category are shown in Table 7.4, where efficiency measures relate to equipment efficiency (supply side) and load control measures relate to operational and process efficiency (demand side).

Table 7.4: Example measures – Production Line Equipment

Category	Measures
Efficiency *(Supply reduction)*	Replacement with high-performance equipment
Load Control *(Demand reduction)*	Improve availability (improved maintenance procedure to reduce unplanned equipment downtime; optimise production schedules to reduce planned downtime); improve effectiveness (increase throughput); and improve quality rate (reduce defect rate and waste)

The following interaction effects between measures in a system are proposed for each category. The electrical savings attributed to each measure are adjusted to account for interactions; these equations are applicable to each system within the

Production Line Equipment activity. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.11, and the final equations applicable to efficiency and load control measures are Eq. 110 and Eq. 111, respectively.

- Efficiency – Previous efficiency measures represent improvements of different equipment along the production line, and are not considered as these are independent pieces of equipment. Previous load control measures are considered as they reduce the total energy consumption, and the efficiency savings are applied pro-rata to the adjusted total.
- Load control – Previous efficiency measures are considered since less energy is used to deliver the total load, and consequently the load savings decrease pro-rata. Previous load control measures are not considered for interactions since load reductions by different measures are additive.

$$Efficiency: \quad FCS_{eff_{int}} = \left(\frac{FC_{prod-line_{base}} - Load_{prev}}{FC_{prod-line_{base}}}\right) \times FCS_{eff_{orig}} \qquad \textit{Eq. 110}$$

$$Load\ Control: \quad FCS_{load_{int}} = \left(\frac{FC_{prod-line_{base}} - Eff_{prev}}{FC_{prod-line_{base}}}\right) \times FCS_{load_{orig}} \qquad \textit{Eq. 111}$$

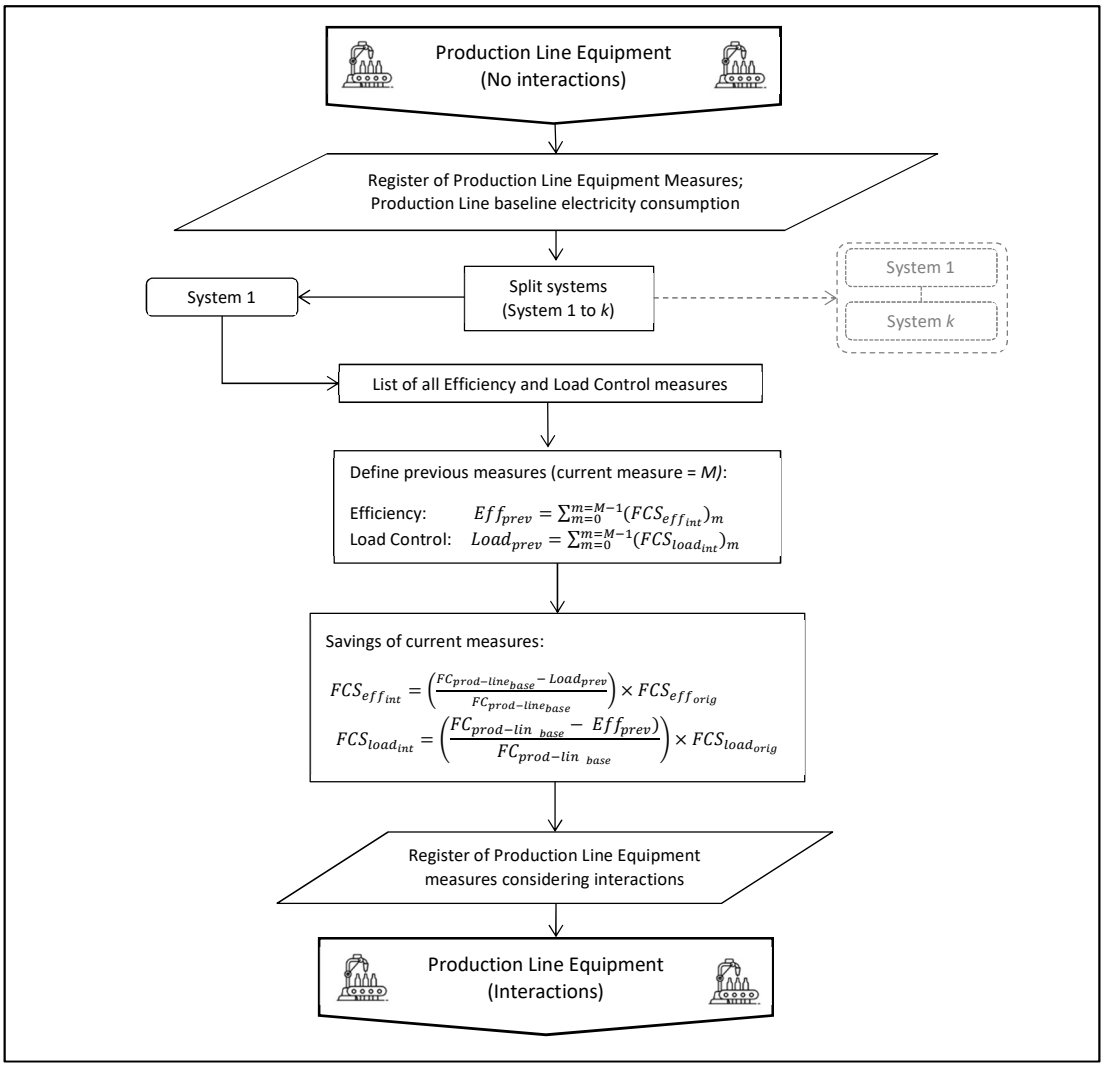


Figure 7.11: Graphical representation of Production Line Equipment interaction effects

7.3.4 Transport

Emissions-reduction measures in the efficiency, new technology, and load control categories are applicable to Transport. Efficiency encompasses measures that improve fuel economy through physical or behavioural changes. Load control relates to demand reduction, i.e. reduced distances driven. New technology refers to the replacement of existing vehicles with those with better fuel economy, as well as fuel replacement with greener alternatives. Examples of these measures for each category are shown in Table 7.5.

Table 7.5: Example measures – Transport

Category	Measures
Efficiency *(Fuel economy improvement)*	Physical changes: addition of aerodynamic devices; Behavioural changes: driver training
Load Control *(Demand reduction)*	Route optimisation
New Technology *(Fuel economy and/or emissions factor reduction)*	Replacement of petrol/diesel vehicles with electric vehicles; use of greener fuel

In the Transport activity, the systems are defined as different fleets (trucks, motorcycles, forklifts) or part thereof to which an emissions-reduction measure is applied. The following interaction effects between measures in a system are proposed for each category. The fuel consumption savings of each energy source affected by the measure are adjusted to account for interactions; these equations are applicable to each system within the Transport activity. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.12, and the final equations applicable to efficiency, load control, and new technology measures are Eq. 112, Eq. 113, and Eq. 114, respectively. Note that in all cases, where a new technology measure is implemented within the timeline, the savings of subsequent measures are first adjusted using the new technology to account for differences in efficiency of the conversion to kinetic energy. Then, the measures are grouped according to the revised energy source, and the following rules apply.

- Efficiency – All previous efficiency and load control measures are considered as they reduce the total fuel consumption, and the efficiency savings must be applied pro-rata to the adjusted total.
- Load control – Previous efficiency measures are considered since less energy is used to deliver the total load, and consequently the load savings decrease pro-rata. Previous load control measures are not considered for interactions since load reductions by different measures are additive.

- New technology – Previous efficiency and load control measures are considered since they affect the load to be supplied by the new technology. A total replacement strategy is assumed, and thus there are no previous new technology measures along the carbon neutrality timeline for each system.

$$Efficiency: \quad FCS_{eff_{int}} = \left(\frac{FC_{trans_{base}} - \left(Eff_{prev} + Load_{prev}\right)}{FC_{trans_{base}}}\right) \times FCS_{eff_{orig}} \qquad \textit{Eq. 112}$$

$$Load\ Control: \quad FCS_{load_{int}} = \left(\frac{FC_{trans_{base}} - Eff_{prev}}{FC_{trans_{base}}}\right) \times FCS_{load_{orig}} \qquad \textit{Eq. 113}$$

$$New\ Technology: \quad \left(FCS_{tec\ int}\right)_{i_{orig}} = \left(\frac{FC_{trans_{base}} - \left(Eff_{prev} + Load_{prev}\right)}{FC_{trans_{base}}}\right) \times \left(FCS_{tech_{orig}}\right)_{i_{old}}$$

$$\left(FCS_{tec\ int}\right)_{i_{new}} = tech\ ratio \times \left(FCS_{tech_{int}}\right)_{i_{old}} \qquad \textit{Eq. 114}$$

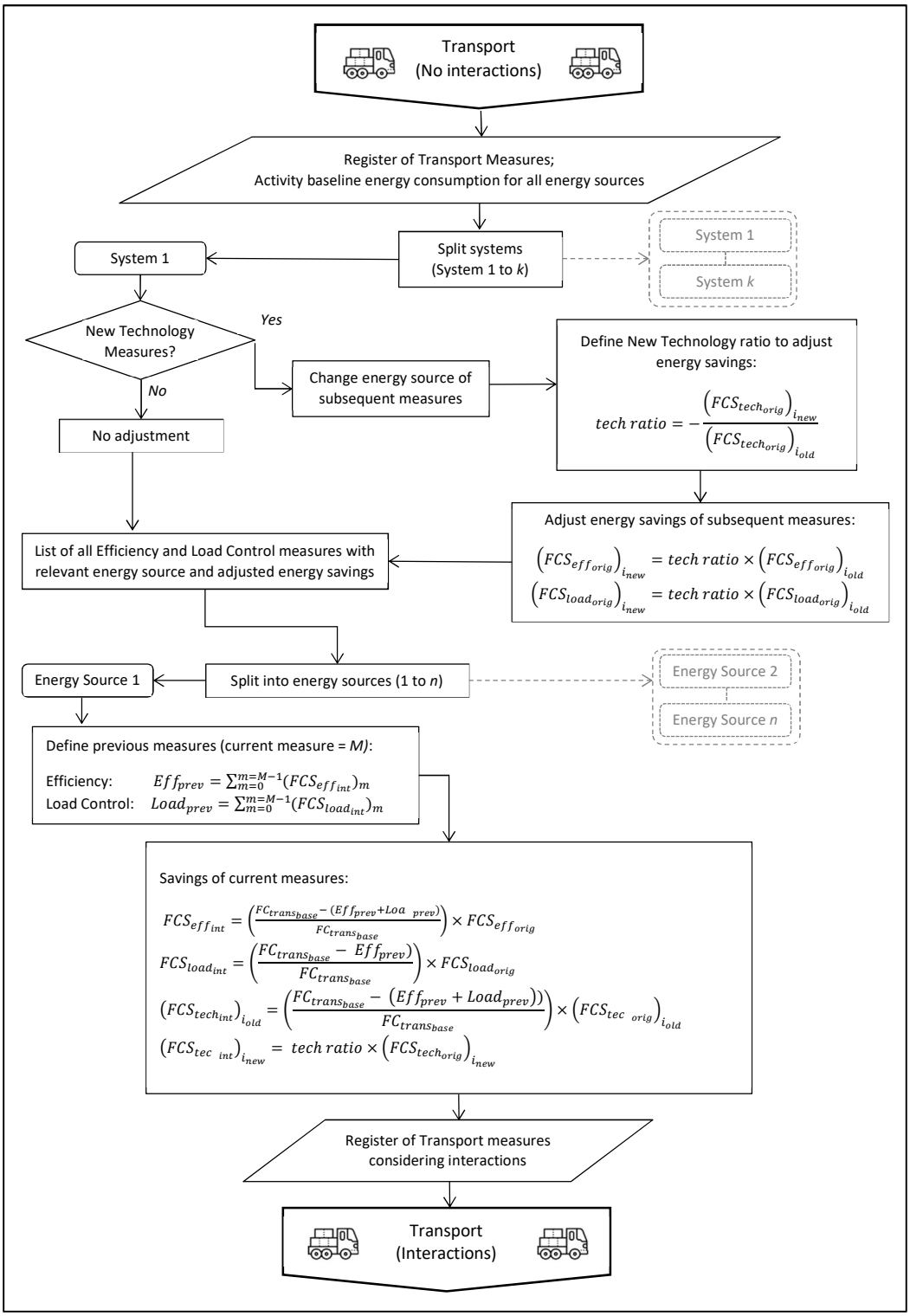


Figure 7.12: Graphical representation of Transport interaction effects

7.3.5 Air Compression

The air compression activity comprises all components of the compressed air system—typically the compressor, air cooler, wet air receiver tank, filters, air dryer, dry air tank, condensate trap, and the distribution system. Portable air compressors

contain the complete system in a single unit, and are typically used for small-scale applications. This activity predominantly addresses large industrial compressed air systems with varying degrees of distribution system complexity.

Emissions-reduction measures in the efficiency, load control, and new technology categories are applicable to Air Compression. Efficiency measures apply to the compressor itself, as well as the other components in the system. Compressors may be electrically, gas, or diesel powered, whereas all other equipment in the compressed air system (e.g. air dryers, air coolers) are electrically driven; consequently, the new technology category applies only to the compressor itself. Despite the thermal component to compressed air generation, the potential heat recovery is off of the compressor waste heat, and the emissions reduction is considered only in the activity that uses the recovered heat. The examples measures for each category as provided in the modelling tool input sheet are shown in Table 7.6. These measures are predominantly sourced from the British Compressed Air Society as part of their 'The 10% Taskforce' initiative to urge British manufacturers to reduce their compressed air generation by at least 10% [180].

Table 7.6: Example measures in each category – Air Compression

Category	Measures
Efficiency *(Energy intensity reduction)*	High efficiency motor on compressor; adjustable speed drive on compressor; compressor upgrade (same energy source); supporting equipment improvement or upgrade (dryers, air coolers)
Load Control *(Demand reduction)*	Improved leak detection, reduce production waste; more frequent filter replacement; optimise end-use devices; improve control strategy/system; redesign distribution system to reduce frictional pressure loss; reduce operating pressure band to optimal level
New Technology	Compressor upgrade (different energy source)

(Energy intensity and/or emissions factor reduction)	

The following interaction effects between measures in a system are proposed for each category. The fuel consumption savings of each energy source affected by the measure are adjusted to account for interactions; these equations are applicable to each system within the Air Compression activity. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.13, and the final equations applicable to efficiency, load control, and new technology measures are Eq. 115, Eq. 116, and Eq. 117, respectively. Note that in all cases, where a new technology measure is implemented within the timeline, the savings of subsequent measures are first adjusted using the new technology to account for differences in efficiency of the conversion to kinetic energy. Then, the measures are grouped according to the revised energy source, and the following rules apply.

- Efficiency – Efficiency measures apply to the compressor and other system components. If more than one efficiency measure is applied to the compressor, the energy savings from subsequent measures should be adjusted. In contrast, efficiency measures applied to different system components are independent. The user input sheets do not contain sufficient information to differentiate between components in the compressed air system. Since the compressor consumes the greatest amount of energy and has the highest potential for energy savings, it is assumed that all efficiency measures apply to it, and thus interactions between all efficiency measures are considered. However, this only holds true if there are no previous new technology measures. It is assumed that compressors would not be subject to efficiency measures after replacement along the carbon neutrality timeline. Since a total replacement strategy is assumed, previous new technology measures imply that the current efficiency measure applies only to other system components, and there is no interaction. All previous load control measures are considered as they reduce the total compressed air

demand, and the efficiency savings of all equipment is applied pro-rata to the adjusted total.

- Load control – Previous efficiency measures are assumed to apply directly to the compressor and are included, unless there are previous new technology measures which indicate that the efficiency measures apply to other system components. Previous load control measures are not considered for interactions since load reductions by different measures are additive.
- New technology – It is assumed that compressors would not be subject to efficiency measures prior to replacement along the carbon neutrality timeline as this is redundant. Since a total replacement strategy is assumed, all previous efficiency measures are considered to apply to other system components and are not considered for interaction. Previous load control measures are considered since they reduce the load on the compressor. There are no previous new technology measures along the carbon neutrality timeline for each system since a total replacement strategy is assumed.

$$Efficiency\text{: } FCS_{eff_{int}} = \begin{cases} \left(\frac{FC_{comp-air_{base}} - \left(Eff_{prev} + Load_{prev}\right)}{FC_{comp-air_{base}}}\right) \times FCS_{eff_{orig}} & No\ previous\ FCS_{tech} \\ \left(\frac{FC_{copm-air_{base}} - Load_{prev}}{FC_{chw_{base}}}\right) \times FCS_{eff_{orig}} & Previous\ FCS_{tech} \end{cases} \quad \textit{Eq. 115}$$

$$Load\ Control\text{: } FCS_{load_{int}} = \begin{cases} \left(\frac{FC_{comp-air_{base}} - Eff_{prev}}{FC_{comp-air_{base}}}\right) \times FCS_{load_{orig}} & No\ previous\ FCS_{tec} \\ FCS_{load_{orig}} & Previous\ FCS_{tech} \end{cases} \quad \textit{Eq. 116}$$

$$New\ Technology\text{: } \left(FCS_{tech_{int}}\right)_{i_{old}} = \left(\frac{FC_{comp-air_{base}} - Load_{prev}}{FC_{comp-air_{base}}}\right) \times \left(FCS_{tech_{orig}}\right)_{i_{old}}$$

$$\left(FCS_{tech_{int}}\right)_{i_{new}} = tech\ ratio\ \times \left(FCS_{tech_{int}}\right)_{i_{old}} \quad \textit{Eq. 117}$$

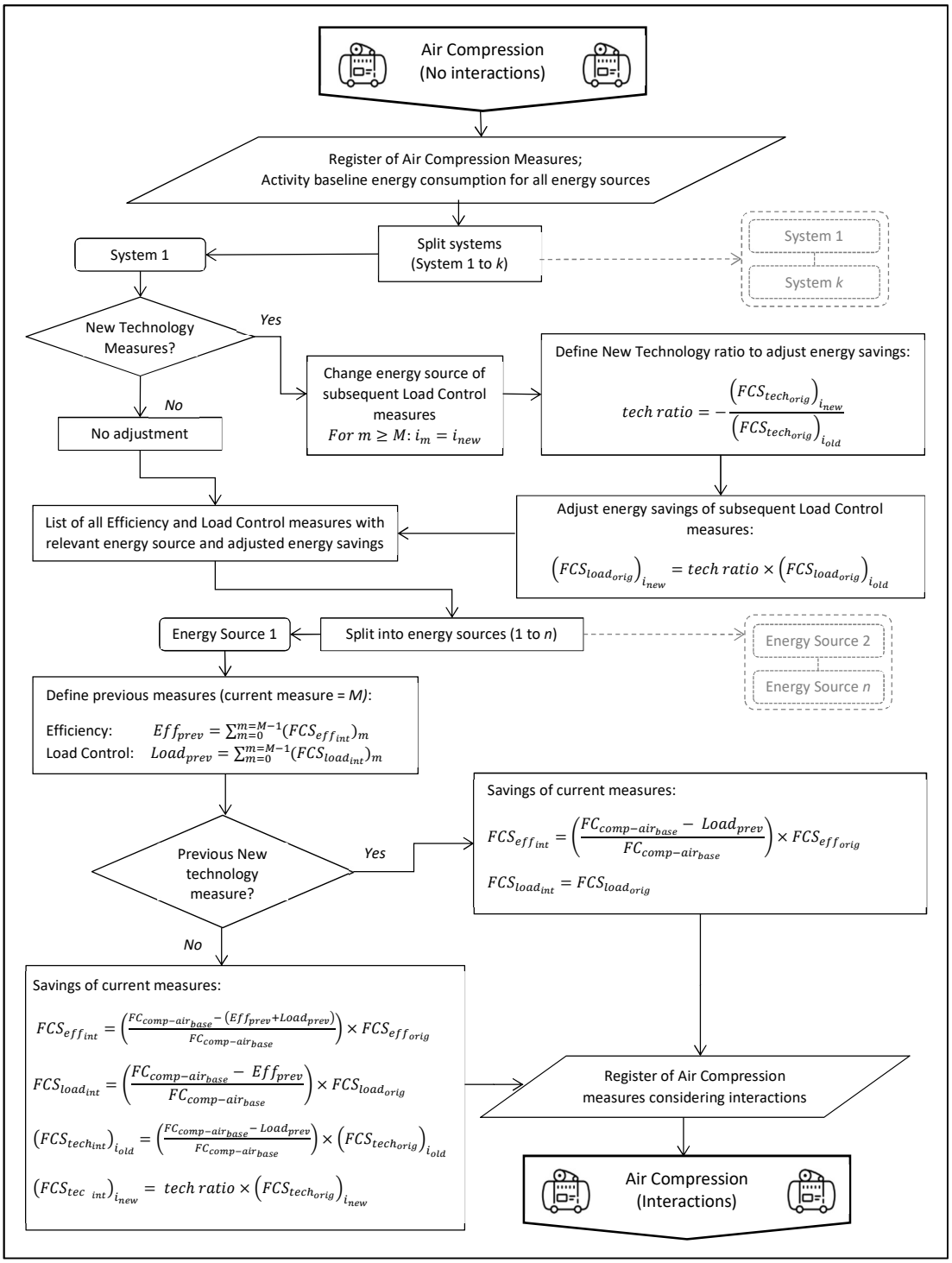


Figure 7.13: Graphical representation of Air Compression interaction effects

7.3.6 HVAC

The HVAC activity encompasses all equipment and networks used to supply the conditioned air for all HVAC types. The HVAC activity does not include the conditioning of the air from air handling units and their water heating and cooling networks, where heating is either generated directly by HW generation equipment

such boilers and heat pumps (Heat Generation activity) or indirectly through heat recovery off the steam network (Steam Generation activity) and cooling is generated through the Chilled Water Generation activity. Thus, the HVAC activity can either function as a standalone activity; or as a sub-activity for the Heat Generation, Steam Generation, and Chilled Water Generation activities, where it has a load control function. Since it may affect both heating and cooling simultaneously, it cannot always be entered directly into these activities without prior adjustment and data manipulation. To properly consider the interaction effects of load control and thermal measures, the type of HVAC system and its control strategy for the space must be identified.

7.3.6.1 *HVAC System and Control Strategy*

The Sustainable Energy Authority of Ireland analysed HVAC control strategies by simulating an AHU (constant air volume (CAV); supply air temperature range of 20-22 °C; air flow rate of 1m^3/s) over one year with the most common control strategies and structural configurations nationwide [181]. The average heating/cooling ratios for systems with full fresh air, 15% fresh air, and modulating fresh air are 95/5, 87/13, and 85.5/14.5, respectively. These ratios are used to proportion the CAV AHU load reductions into heating and cooling loads that are sent to the HW/Steam Generation and CHW Generation activities for processing. Further control strategies are defined to account for variable air volume (VAV) AHUs and packaged units. VAVs deliver a variable volume of air at a constant temperature and thus the fresh air proportion is variable for a fixed occupancy. As such, it can be considered a modulating FA strategy, and the heat is supplied by HW or steam. Packaged units (heat pumps and packaged AHUs) condition the air directly without reliance on other activities; although they can be CAV or VAV, there is no need to differentiate these since changes in demand are dealt with directly in the activity. Consequently, nine HVAC types based on the control strategy and heat source are provided as HVAC activity options in the input sheet:

- HVAC: AHU CAV Full FA – HW
- HVAC: AHU CAV Full FA – Steam
- HVAC: AHU CAV 15% FA – HW

- HVAC: AHU CAV 15% FA – Steam
- HVAC: AHU CAV Modulating FA – HW
- HVAC: AHU CAV Modulating FA – Steam
- HVAC: AHU VAV – HW
- HVAC: AHU VAV – Steam
- HVAC: Packaged

7.3.6.2 *Example Measures*

Emissions-reduction measures in the efficiency category relate to equipment and system improvements, and are applicable to all HVAC Activities. Load control measures are operational and behavioural measures that affect the heating and cooling loads supplied. Thermal measures are those that involve heat recovery where the heat recovered is used within the activity. New technology measures represent changes between HVAC activity types. Note that the load control, thermal, and new technology measures are not relevant for standalone HVAC supply equipment such as ventilation fans since these are electrical and any improvements are considered to be efficiency measures. The examples measures for each category as provided in the modelling tool input sheet are shown in Table 7.7.

Table 7.7: Example measures in each category – HVAC

Category	Measures
Efficiency *(Supply reduction)*	Clean/replace filters (reduces pressure drop)
Load Control *(Demand reduction)*	Occupancy sensors; economisers; re-zoning
Thermal *(Demand reduction)*	Heat recovery wheels/coils
New Technology *(Energy intensity and/or emissions factor reduction)*	Transfer to another HVAC Activity

7.3.6.3 *Interaction Effects*

The following interaction effects between measures in a system are proposed for each category. The fuel consumption savings of each energy source affected by the measure are adjusted to account for interactions; these equations are applicable to each system within the HVAC activity. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.14, and the final equations applicable to efficiency, load control, thermal, and new technology measures are Eq. 118, Eq. 119, Eq. 120, and Eq. 121, respectively. In the case of a new technology measure, the HVAC activity of all subsequent measures is first revised to that of the new technology. Then, the load control and thermal savings are adjusted and then sent to the relevant Steam, Heat, and Chilled Water Generation activities (where applicable) for processing. The following rules apply to all measures including those transferred to new HVAC activities.

- Efficiency – Efficiency measures are treated as follows according to the activity type in which they are applied.
    - AHU CAV & VAV - Previous efficiency measures are ignored since they are likely independent measures affecting the functioning of different components within the system. Previous load control and thermal measures are not considered directly within this activity as they relate to the Heat Generation activity, and efficiency measures are unaffected. This is clear in CAV systems since the air flow is independent of the load. Although the VAV principle is based on variable air flow rather than variable temperature in response to changing loads, this is intended for fluctuating loads in different HVAC zones; where considerable load reductions and thermal measures have been implemented, the temperatures of the heat stream are likely to shift in response and the VAV function is maintained to tailor the supply air temperature to different zones.
    - Packaged unit – Packaged units consider all previous efficiency, load control, and thermal measures as all components (compressor, condenser, evaporator, fans) are contained within a single unit.

- Load Control – The load reduction is first adjusted according to the activity type in which the load is serviced, and then either addressed directly in the HVAC activity or sent to the parent activity (Steam/Heat Generation and Chilled Water Generation). For the AHU control strategies, previous efficiency measures are not considered for interaction since they act on the supply equipment, whereas the load is met by the Heat or Steam Generation and Chilled Water Generation activities. For packaged units, previous efficiency measures are considered pro-rata. For all control strategies, previous load control measures are not considered as load reductions are independent and thus additive. For the AHU control strategies, previous thermal measures are ignored since they do not affect the supply air volume; these measures are sent directly to the Heat or Steam Generation and Chilled Water Generation activities for consideration at the source. For packaged units, previous thermal measures are considered pro-rata as they affect the load to be supplied by the unit. In all cases, no further action is taken for previous new technology measures as the change in activity is captured prior to implementing these interaction rules. Following these adjustments, the load control measures are treated as follows according to the control strategy:
    - HVAC – Packaged: Load reductions from load control measures are considered directly in the HVAC activity.
    - HVAC – CAV & VAV AHU: Load reductions from load control measures are sent to the relevant Heat/Steam Generation and CHW Generation activities in the ratios shown in Table 7.8 if the energy source savings are input in the form of 'HVAC'. However, there is the option to input the savings directly as 'Thermal: HW' or 'Thermal: Steam' and 'Electricity (MWh)' if the heating and cooling split is known.

Table 7.8: Load control strategy

Control Strategy	Heat/Steam Generation	CHW Generation
HVAC – AHU Full FA	95%	5%
HVAC – AHU 15% FA	87%	13%
HVAC – AHU Modulating FA	85.5%	14.5%

- Thermal – Thermal measures are first adjusted according to the activity type to which they are applied, and then either addressed directly in the HVAC activity or sent to the parent activities (Steam/Heat Generation and Chilled Water Generation). For all HVAC activities, previous efficiency measures are not considered for interaction since they are unrelated to the loads on the supply equipment. Previous load control and thermal measures may reduce the requirement for waste heat, but not the availability. Since it is unlikely that the thermal measure involves heat recovery to exceed the full load, previous measures can be ignored in all cases with low risk of double-counting these savings. No further action is taken for previous new technology measures as the change in activity is already captured. Following these adjustments, the thermal measures are treated as follows according to the control strategy:
    - HVAC – Packaged: Thermal load reductions are considered directly in the HVAC activity.
    - HAVC – CAV & VAV AHU: Thermal load reductions are sent to the relevant Heat/Steam Generation activity as load control measures since this is where the heat load is generated.
- New Technology – New technology measures represent a change in control strategy with existing equipment or a change from an AHU to packaged unit or vice versa. The interaction effects are treated as follows according to the type of technology replacement.
    - AHU → AHU: No previous measures are considered since efficiency measures may refer to other system components, and previous load

control and thermal measures are addressed in the Heat/Steam and CHW Generation activities.

- AHU → Package: No previous efficiency measures are considered since they may refer to other system components. Previous load control and thermal measures are considered since they reduce the load to be supplied by the new technology.
- Package → AHU: It is unlikely that efficiency measures would be applied to a unit that is to be replaced along the carbon neutrality timeline, and thus these are assumed to apply to other system components. As such, they are not considered for interaction. Previous load control and thermal measures are not considered since they decrease the load to be supplied by the new technology, but this is not addressed by the supply equipment in this activity.

$$Efficiency: \quad AHU: \quad FCS_{eff_{int}} = FCS_{eff_{orig}}$$

$$Package: \quad FCS_{eff_{int}} = \left(\frac{FC_{hvac_{base}} - Eff_{prev} - Load_{prev} - Th_{prev}}{FC_{hvac_{base}}}\right) \times FCS_{eff_{orig}} \qquad \textit{Eq. 118}$$

$$Load\ Control: \quad AHU: \quad FCS_{load_{int}} = FCS_{load_{orig}}$$

$$Package: \quad FCS_{load_{int}} = \left(\frac{FC_{hva\ \ base} - Eff_{prev} - Th_{prev}}{FC_{hvac_{base}}}\right) \times FCS_{load_{orig}} \qquad \textit{Eq. 119}$$

$$Thermal: \quad AHU: \quad FCS_{th_{int}} = FCS_{th_{orig}}$$

$$Package: \quad FCS_{th_{int}} = FCS_{th_{orig}} \qquad \textit{Eq. 120}$$

$$New\ Technology: \quad \left(FCS_{tech_{int}}\right)_{i_{orig}} = \left(FCS_{tech_{orig}}\right)_{i_{orig}}$$

$$\left(FCS_{tech_{int}}\right)_{i_{new}} = tech\ ratio \times \left(FCS_{tech_{orig}}\right)_{i_{new}} \qquad \textit{Eq. 121}$$

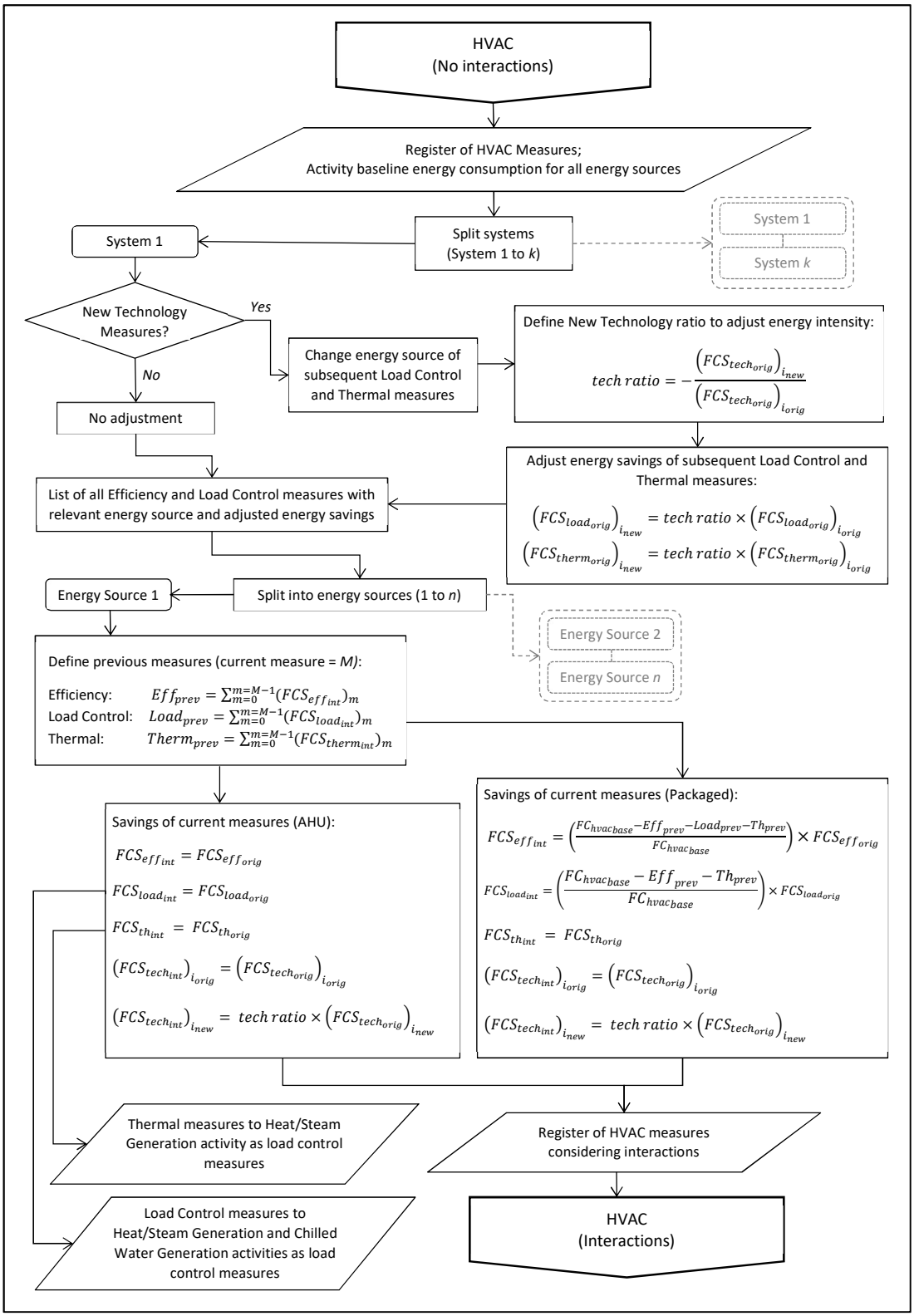


Figure 7.14: Graphical representation of HVAC interaction effects

7.3.7 Chilled Water Generation

Chilled Water Generation encompasses chilled water systems based on the following two working principles—vapour compression and vapour absorption.

- Vapour compression chillers use mechanical or magnetic bearing compressors to drive the refrigerant around the system. They can be air- or water-cooled, where the latter includes cooling towers in the chilled water generation system. These chillers powered can be powered by electricity, gas (turbines or reciprocating engines), or diesel (engines). The components of the associated cooling towers (fans, motors, pumps) are electrically powered.
- Vapour absorption chillers use heat instead of compressors to drive the refrigerant around the system; this heat can be from an external source (waste heat or steam) or it can be generated directly within the chiller from the burning of gas or oil (direct-fired chillers). Vapour absorption chillers are water-cooled by means of cooling towers, the components of which are electrically powered.

Chilled Water Generation is subject to efficiency measures in the form of improved maintenance procedures and replacement of equipment within the same working principle; load control measures indirectly through the HVAC activity or directly from other sources such as process water; and new technology measures in the form of equipment replacement with a different working principle. Although absorption chillers have a thermal component, the heat source is typically waste heat which has no direct interactions with other activities. In the case of direct-fired chillers, any thermal modifications can be considered efficiency measures since they improve the chiller output with no interactions with other activities. Examples of these measures for each applicable category are shown Table 7.7.

Table 7.9: Example measures – Chilled Water Generation

Category	Measures
Efficiency *(Supply reduction)*	Improved maintenance plan (reduce tube fouling and refrigerant leakage, control water temperature and velocity); replacement of constant-speed drive

	with variable-speed drive on compressor; replacement of chiller with more efficient one of same working principle
Load Control *(Demand reduction)*	Reduced HVAC loads; reduced process water requirement
New Technology *(Energy intensity and/or emissions factor reduction)*	Replacement of chiller with that of a different working principle

The following interaction effects between measures in a system are proposed for each category. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.15, and the final equations applicable to efficiency, load control, and new technology measures are Eq. 122, Eq. 123, and Eq. 124, respectively, for each energy source affected by the measure. Note that in all cases, where a new technology measure is implemented within the timeline, the savings of relevant subsequent measures are first adjusted using the technology ratio to account for differences in efficiencies of the technologies. The following rules apply to the all measures including those adjusted to the new energy source.

- Efficiency - Efficiency measures apply to the chiller and other system components. If more than one efficiency measure is applied to the chiller, the energy savings from subsequent measures should be adjusted. In contrast, efficiency measures applied to different system components are independent. The user input sheets do not contain sufficient information to differentiate between components in the chilled water system. Since the chiller consumes the greatest amount of energy and has the highest potential for energy savings, it is assumed that all efficiency measures apply to it, and thus interactions with previous efficiency measures are considered. However, this only holds true if there are no previous new technology measures. It is assumed that the chillers would not be subject to efficiency measures after replacement along the carbon neutrality timeline. Since a total replacement strategy is assumed, previous new technology measures imply that the

current efficiency measure applies only to other system components, and there is no interaction. All previous load control measures are considered as they reduce the total chilled water demand, and the efficiency savings of all equipment is applied pro-rata to the adjusted total.

- Load control – Previous efficiency measures are assumed to apply directly to the chiller and are included, unless there are previous new technology measures which indicate that the efficiency measures apply to other system components. Previous load control measures are not considered for interactions since load reductions by different measures are additive.
- New technology – It is assumed that chillers would not be subject to efficiency measures prior to replacement along the carbon neutrality timeline as this is redundant. Since a total replacement strategy is assumed, all previous efficiency measures are considered to apply to other system components and are not considered for interaction. Previous load control measures are considered since they reduce the load on the chiller. There are no previous new technology measures along the carbon neutrality timeline since a total replacement strategy is assumed.

$$Efficiency\text{:}\quad FCS_{eff_{int}} = \begin{cases} \left(\dfrac{FC_{chw_{base}} - \left(Eff_{prev} + Load_{prev}\right)}{FC_{chw_{base}}}\right) \times FCS_{eff_{orig}} & No\ previous\ FCS_{tech} \\ \left(\dfrac{FC_{chw_{base}} - Load_{prev}}{FC_{chw_{base}}}\right) \times FCS_{eff_{orig}} & Previous\ FCS_{tech} \end{cases} \qquad \textit{Eq. 122}$$

$$Load\ Control\text{:}\quad FCS_{load_{int}} = \begin{cases} \left(\dfrac{FC_{chw_{base}} - Eff_{prev}}{FC_{chw_{base}}}\right) \times FCS_{load_{orig}} & No\ previous\ FCS_{tech} \\ FCS_{load_{orig}} & Previous\ FCS_{tech} \end{cases} \qquad \textit{Eq. 123}$$

$$New\ Technology\text{:}\quad \left(FCS_{tech_{int}}\right)_{i_{orig}} = \left(\frac{FC_{chw_{base}} - Load_{prev}}{FC_{chw_{base}}}\right) \times \left(FCS_{tech_{orig}}\right)_{i_{orig}}$$

$$\left(FCS_{tech_{int}}\right)_{i_{new}} = tech\ ratio\ \times \left(FCS_{tech_{int}}\right)_{i_{orig}} \qquad \textit{Eq. 124}$$

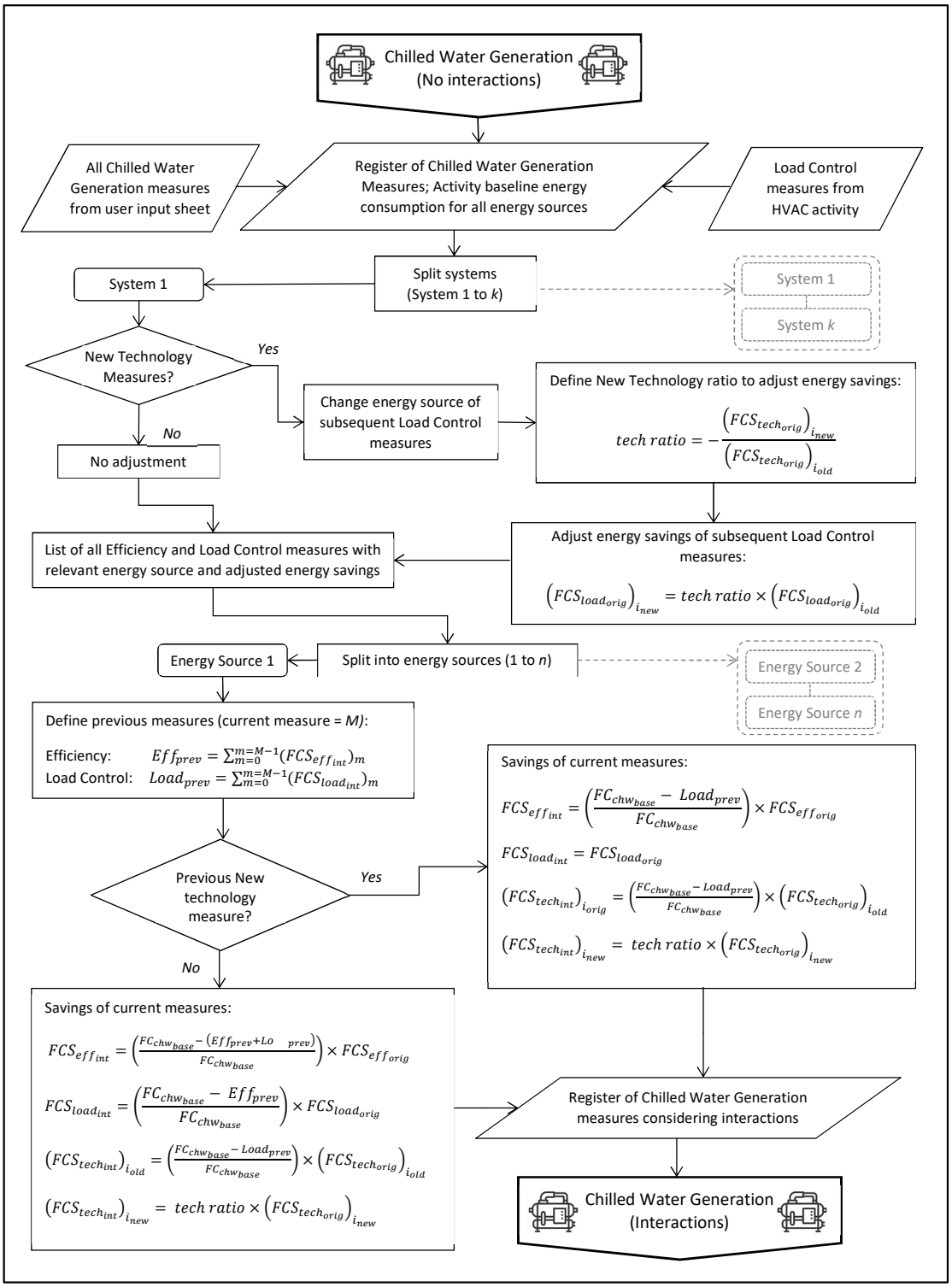


Figure 7.15: Graphical representation of Chilled Water Generation interaction effects

7.3.8 Heat Generation

Heat Generation encompasses hot water generated directly, e.g. by means of boilers, direct-fired water heaters, electric water heaters, and heat pumps, and hot water generated through heat exchange with the steam system; it also includes other components in the HW distribution system, such as pumps. Direct Heat Generation

is subject to efficiency measures in the form of better equipment of the same energy source, new technology measures in the form of equipment replacement with a different energy source, thermal measures in the form of recovered heat, and load control measures in the form of reduced process heating loads and reduced heating loads from HVAC (HVAC load control and thermal measures). Indirect Heat Generation from heat exchange with steam system is subject to efficiency measures in the form of improved heat exchange, as well load control and thermal measures. Examples of these measures for each applicable category are shown in Table 7.10.

Table 7.10: Example measures – Heat Generation

Category	Measures
Efficiency *(Supply reduction)*	*Direct HW Generation* - Regular tuning to optimise air intake; regular cleaning of boiler tubes to prevent soot build-up; preheat combustion air; install automatic blowdown valves
	Heat Exchange with Steam – Optimise heat exchange sizing; install turbulators to enhance heat transfer
Load Control *(Demand reduction)*	All HVAC load reductions (HVAC load control & thermal measures); direct HW demand reduction; transfer between dedicated HW boiler (Heat Generation activity) and HW generation from steam system (Steam Generation activity); valve insulation in boiler room
Thermal *(Energy reduction)*	Flue gas heat recovery; blowdown heat recovery; heat recovery off other equipment
New Technology *(Energy intensity and/or emissions factor reduction)*	Replacement of gas boiler with electrode boiler

The following interaction effects between measures in a system are proposed for each category. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.16, and the final equations

applicable to efficiency, load control, thermal, and new technology measures are Eq. 125, Eq. 126, Eq. 127, and Eq. 128, respectively, for each energy source affected by the measure. Note that the load and thermal measures are input as energy source savings ('Thermal: HW') rather than fuel since they reduce the demand on the heating system. Note that where a new technology measure is implemented within the timeline, the savings of all subsequent efficiency, load control, and thermal measures are first adjusted using the new technology ratio and the contributions of the energy sources to the total energy output of the activity. The following rules apply to the all measures including those adjusted to the new energy source.

- *Efficiency* – Efficiency measures are processed as follows according to the source of heat generation.
    - Dedicated HW source – Efficiency measures apply to the HW generator and other system components. If more than one efficiency measure is applied to the HW generator, the energy savings from subsequent measures should be adjusted. In contrast, efficiency measures applied to different system components are independent. The user input sheets do not contain sufficient information to differentiate between components in the HW system. Since the HW generator consumes the greatest amount of energy and has the highest potential for energy savings, it is assumed that all efficiency measures apply to it, and thus interactions with previous efficiency measures are considered. However, this only holds true if there are no previous new technology measures. It is assumed that the HW generators would not be subject to efficiency measures after replacement along the carbon neutrality timeline. It is further assumed that the same replacement strategy applies to multiple HW generators feeding a single distribution system, i.e. if one HW generator is replaced with that of a different energy source, then the remaining HW generators would be planned for replacement at some point and would not be subject to efficiency measures in the interim. Consequently, previous new technology measures imply that the

current efficiency measure applies only to other system components, and there is no interaction. All previous load control and thermal measures are considered as they reduce the total HW demand, and the efficiency savings of all equipment is applied pro-rata to the adjusted total.

- HW generated from steam – Previous efficiency measures not are considered as these relate only to the heat exchange efficiency. Previous load control measures are not considered as they are independent measures. Previous thermal and new technology measures are not applicable since the load is handled in the Steam Generation activity. When the current efficiency value has been revised with the interaction rules, the activity type is changed from 'Heat Generation' to 'Steam Generation' and the category is changed from 'Efficiency' to 'Load Control' to prepare it for processing within the Steam Generation activity.

- *Load control* – Load control measures are processed as follows according to the source of heat generation.
  - Dedicated HW source – Previous efficiency measures are assumed to apply directly to the hot water generator and are included, unless there are previous new technology measures which indicate that the efficiency measures apply to other system components. Previous load control measures are not considered for interactions since load reductions by different measures are additive and do not interact. Previous thermal measures are considered since less energy is used to deliver the total load, and consequently the load savings decrease pro-rata.
  - HW generated from steam – Previous efficiency measures are considered since less energy is used to deliver the total load, and consequently the load savings decrease pro-rata. Previous load control measures are not considered for interactions since load reductions by different measures are additive and do not interact. Previous thermal and new technology measures are not applicable

since the load is handled in the Steam Generation activity. When the current load control value has been revised with the interaction rules, the activity type is changed from 'Heat Generation' to 'Steam Generation' to prepare it for processing within the Steam Generation activity.

- *Thermal* – Thermal measures are applicable only to heat generated by direct HW sources. They act on the supply side to reduce the energy consumption of the hot water generator, and are not affected by measures applied to the generator itself and those that affect the demand. It is noted that the heat recovery potential off of the boiler flue and blowdown is dependent on the boiler output; however, not all thermal measures represent heat recovery from the hot water generator itself as heat may be recovered from other industrial equipment and systems. Consequently, previous efficiency and load control measures are ignored. Previous thermal measures are not considered for interaction since they are independent and are thus additive.
- *New Technology:* This category applies only to the replacement of the HW generator and this is unlikely to occur more than once per generator along the carbon neutrality timeline. Thus, previous new technology measures refer to replacement of other generators within the same system, and are ignored. It is assumed that HW generators would not be subject to efficiency measures prior to replacement along the carbon neutrality timeline as this is redundant. It is further assumed that the same replacement strategy applies to multiple HW generators feeding a single distribution system, i.e. if one HW generator is replaced with that of a different energy source, then the remaining HW generators would be planned for replacement at some point and would not be subject to efficiency measures in the interim. Consequently, all previous efficiency measures are considered to apply to other system components and are not considered for interaction. Previous load control and thermal measures are considered as they reduce the load to be supplied by the new technology.

Dedicated HW source:

$$Efficiency:\ FCS_{eff_{int}} = \begin{cases} \left(\frac{FC_{HW_{base}} - \left(Eff_{prev} + Th_{prev} + Load_{prev}\right)}{FC_{HW_{base}}}\right) \times FCS_{eff_{orig}} & No\ previous\ FCS_{tech} \\ \left(\frac{FC_{HW_{base}} - \left(Th_{prev} + Load_{prev}\right)}{FC_{HW_{base}}}\right) \times FCS_{eff_{orig}} & Previous\ FCS_{tech} \end{cases} \quad \textit{Eq. 125}$$

$$Load\ Control:\ FCS_{load_{int}} = \begin{cases} \left(\frac{FC_{HW_{base}} - \left(Eff_{prev} + Th_{prev}\right)}{FC_{HW_{base}}}\right) \times FCS_{load_{orig}} & No\ previous\ FCS_{tech} \\ \left(\frac{FC_{HW_{base}} - Th_{prev}}{FC_{HW_{base}}}\right) \times FCS_{load_{orig}} & Previous\ FCS_{tech} \end{cases} \quad \textit{Eq. 126}$$

$$Thermal:\quad FCS_{th_{int}} = FCS_{th_{orig}} \quad \textit{Eq. 127}$$

$$New\ Technology:\quad \left(FCS_{tech_{int}}\right)_{i_{orig}} = \left(\frac{FC_{HW_{base}} - \left(Load_{prev} + Th_{prev}\right)}{FC_{HW_{base}}}\right) \times \left(FCS_{tech_{orig}}\right)_{i_{orig}}$$
$$\left(FCS_{tech_{int}}\right)_{i_{new}} = tech\ ratio\ \times \left(FCS_{tech_{int}}\right)_{i_{orig}} \quad \textit{Eq. 128}$$

HW from steam heat exchange:

$$Efficiency:\ FCS_{eff_{int}} = \left(\frac{FC_{HW_{base}} - Eff_{prev}}{FC_{HW_{base}}}\right) \times FCS_{eff_{orig}} \quad \textit{Eq. 129}$$

$$Load\ Control:\quad FCS_{load_{int}} = \left(\frac{FC_{HW_{base}} - Eff_{prev}}{FC_{HW_{base}}}\right) \times FCS_{load_{orig}} \quad \textit{Eq. 130}$$

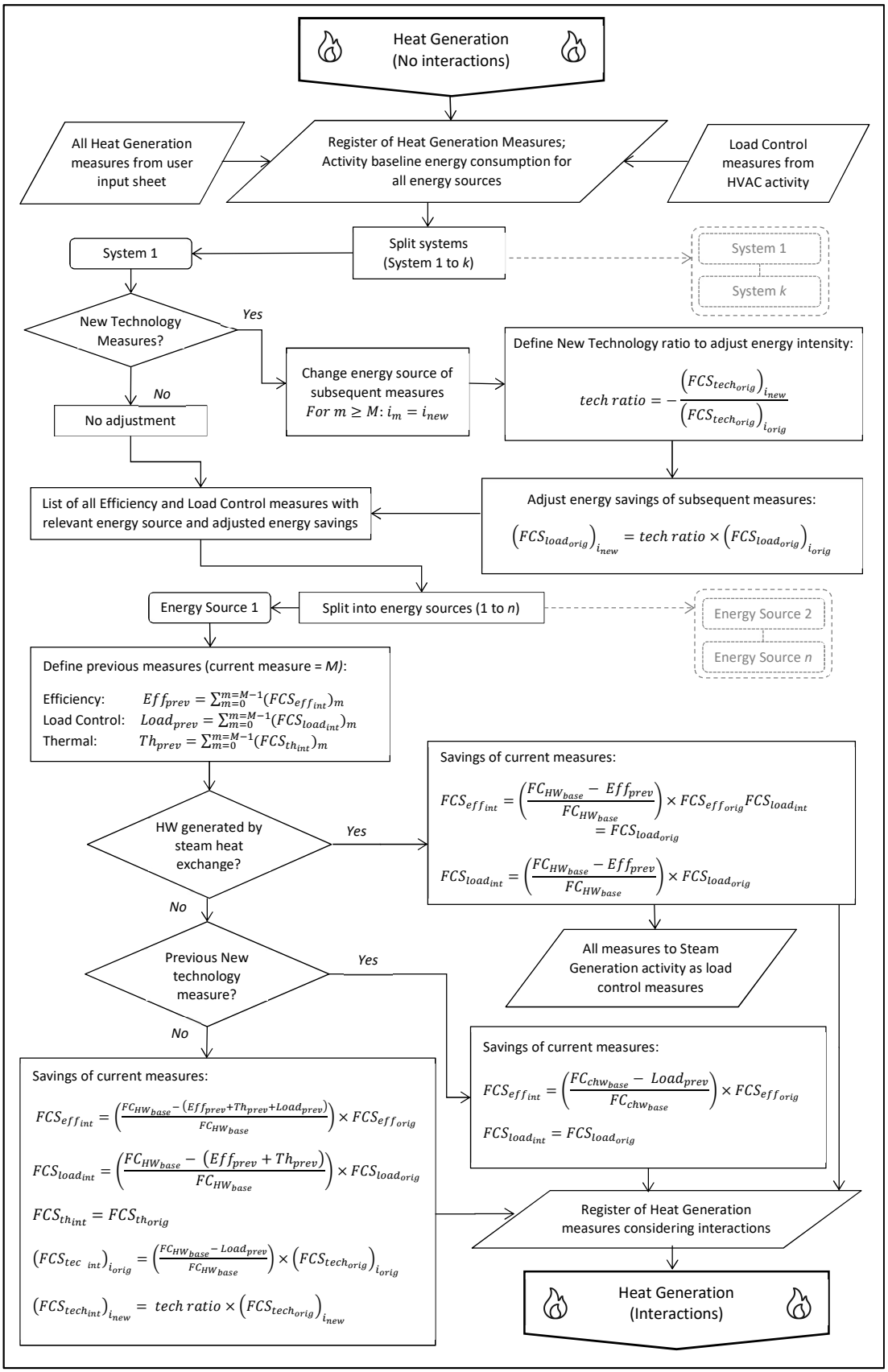


Figure 7.16: Graphical representation of Heat Generation interaction effects

7.3.9 Steam Generation

Steam generation is subject to efficiency measures in the form of better equipment of the same energy source, new technology measures in the form of equipment replacement with a different energy source; thermal measures in the form of recovered heat; and load control measures in the form of reduced process steam loads, reduced heating loads from HVAC (HVAC load control and thermal measures), and reduced HW heating loads in the case where the HW is generated through heat exchange with the steam network. Examples of these measures for each applicable category are shown in Table 7.11.

Table 7.11: Example measures – Steam Generation

Category	Measures
Efficiency *(Energy intensity reduction)*	Regular tuning to optimise air intake; valve insulation in boiler room; regular cleaning of boiler tubes to prevent soot build-up; preheat combustion air; install automatic blowdown valves; condensate recovery
Load Control *(Demand reduction)*	All HVAC load reductions (HVAC load control and thermal measures); all HW load reductions (Heat Generation load control and thermal measures); direct steam demand reduction; transfer of HW load between dedicated HW boiler (Heat Generation activity) and HW generation from steam system (Heat Generation activity); valve insulation in boiler room
Thermal *(Energy reduction)*	Flue gas heat recovery; blowdown heat recovery; heat recovery off other equipment
New Technology *(Energy intensity and/or emissions factor reduction)*	Replacement of gas boiler with electrode boiler

The following interaction effects between measures in a system are proposed for each category. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.17, and the final equations applicable to efficiency, load control, thermal, and new technology measures are Eq. 131, Eq. 132, Eq. 133, and Eq. 134, respectively, for each energy source affected by the measure. Note that where a new technology measure is implemented within the timeline, the savings of all subsequent efficiency, load control, and thermal measures are first adjusted using the new technology ratio and the contributions of the energy sources to the total energy output of the activity. The following rules apply to the all measures including those adjusted to the new energy source.

- *Efficiency* – Efficiency measures apply to the boiler and other system components. If more than one efficiency measure is applied to the boiler, the energy savings from subsequent measures should be adjusted. In contrast, efficiency measures applied to different system components are independent. The user input sheets do not contain sufficient information to differentiate between components in the steam system. Since the boiler consumes the greatest amount of energy and has the highest potential for energy savings, it is assumed that all efficiency measures apply to it, and thus interactions with previous efficiency measures are considered. However, this only holds true if there are no previous new technology measures. It is assumed that the boiler would not be subject to efficiency measures after replacement along the carbon neutrality timeline. It is further assumed that the same replacement strategy applies to multiple boilers feeding a single distribution system, i.e. if one boiler is replaced with that of a different energy source, then the remaining boilers would be planned for replacement at some point and would not be subject to efficiency measures in the interim. Consequently, previous new technology measures imply that the current efficiency measure applies only to other system components, and there is no interaction. All previous load control and thermal measures are considered as they reduce the total steam demand, and the efficiency savings of all equipment is applied pro-rata to the adjusted total.

- *Load control* – Previous efficiency measures are assumed to apply directly to the boiler and are included, unless there are previous new technology measures which indicate that the efficiency measures apply to other system components. Previous load control measures are not considered for interactions since load reductions by different measures are additive. Previous thermal measures are considered since less energy is used to deliver the total load, and consequently the load savings decrease pro-rata.
- *Thermal* – Thermal measures act on the supply side to reduce the energy consumption of the boiler, and are not affected by measures applied to the boiler itself and those that affect the demand. It is noted that the heat recovery potential off of the boiler flue and blowdown is dependent on the boiler output; however, not all thermal measures represent heat recovery from the boiler itself as heat may be recovered from other industrial equipment and systems. Consequently, previous efficiency and load control measures are ignored. Previous thermal measures are not considered for interaction since they are independent and are thus additive.
- *New Technology:* This category applies only to the replacement of the boiler and this is unlikely to occur more than once per boiler along the carbon neutrality timeline. Thus, previous new technology measures refer to replacement of other boilers within the same system, and are ignored. It is assumed that boilers would not be subject to efficiency measures prior to replacement along the carbon neutrality timeline as this is redundant. It is further assumed that the same replacement strategy applies to multiple boilers feeding a single distribution system, i.e. if one boiler is replaced with that of a different energy source, then the remaining boilers would be planned for replacement at some point and would not be subject to efficiency measures in the interim. Consequently, all previous efficiency measures are considered to apply to other system components and are not considered for interaction. Previous load control and thermal measures are considered as they reduce the load to be supplied by the new technology.

$$Efficiency: FCS_{eff_{int}} = \begin{cases} \left(\frac{FC_{steam_{base}} - \left(Eff_{prev} + Th_{prev} + Load_{prev}\right)}{FC_{steam_{base}}}\right) \times FCS_{eff_{orig}} & No\ previous\ FCS_{tech} \\ \left(\frac{FC_{steam_{base}} - \left(Th_{prev} + Load_{prev}\right)}{FC_{steam_{base}}}\right) \times FCS_{eff_{orig}} & Previous\ FCS_{tech} \end{cases} \quad \textit{Eq. 131}$$

$$Load\ Control: \quad FCS_{load_{int}} = \begin{cases} \left(\frac{FC_{steam_{base}} - \left(Eff_{prev} + Th_{prev}\right)}{FC_{steam_{base}}}\right) \times FCS_{load_{orig}} & No\ previous\ FCS_{tech} \\ \left(\frac{FC_{steam_{base}} - Th_{prev}}{FC_{steam_{base}}}\right) \times FCS_{load_{orig}} & Previous\ FCS_{tech} \end{cases} \quad \textit{Eq. 132}$$

$$Thermal: \quad FCS_{th_{int}} = FCS_{th_{orig}} \quad \textit{Eq. 133}$$

$$New\ Technology: \quad \left(FCS_{tech_{int}}\right)_{i_{orig}} = \left(\frac{FC_{steam_{base}} - \left(Load_{prev} + Th_{prev}\right)}{FC_{steam_{base}}}\right) \times \left(FCS_{tech_{orig}}\right)_{i_{old}}$$

$$\left(FCS_{tech_{int}}\right)_{i_{new}} = tech\ ratio \times \left(FCS_{tech_{int}}\right)_{i_{old}} \quad \textit{Eq. 134}$$

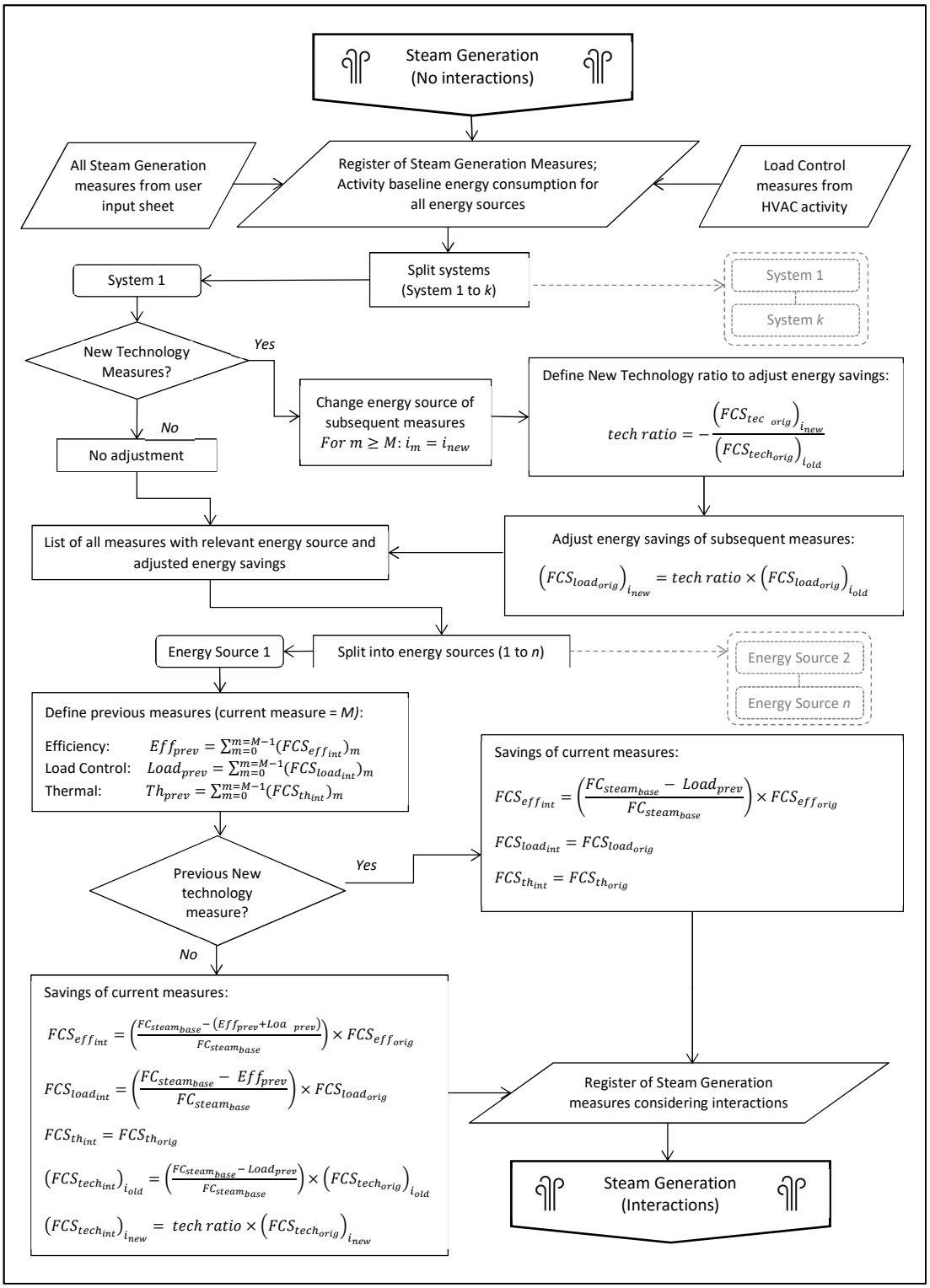


Figure 7.17: Graphical representation of Steam Generation interaction effects

7.3.10 Electricity Generation

Inclusion of the interaction effects within the Electricity Generation activity has a compound effect in that the adjustments to the savings are considered directly, and the accuracy of the electricity emissions factor applied to all electrical savings from

all activities is increased. Electricity Generation is subject to efficiency measures in the form of improvements to onsite plant with no change in energy source, and new technology measures in the form of additional equipment to replace grid electricity or equipment replacement with a different energy source. No thermal measures are considered since heat is not consumed in this activity (it is a by-product of some forms of onsite electricity generation and acts as a heat source for HW systems, steam systems, and absorption chillers). No load control measures are considered directly in this activity. There is a possible interaction between the Electrical Generation activity and the electrical load control measures from all other activities; however, these only take effect if the total site electrical requirement is met by a combination of onsite generation and renewable energy since electrical load reductions from the grid are prioritised (this is discussed in section 6.5.3.1]). The examples measures for each category as provided in the modelling tool input sheet are shown in Table 7.12.

Table 7.12: Example measures in each category – Electricity Generation

Category	Measures
Efficiency *(Supply reduction)*	Regular maintenance
Load Control *(Demand reduction)*	Electrical savings from all other activities
New Technology *(Energy intensity and/or emissions factor reduction)*	Additional CHP; CCHP; CCP; generators

In the case of co-generation plant, the reduction in electrical supply from onsite generation leads to a reduction in by-products; heat for CHPs, cooling for CCPs, and heat and cooling for CCHPs. Although this impacts the Heat Generation, Steam Generation, and Chilled Water Generation activities, these interaction effects are not considered as the level of detail required to determine these effects is deemed too complex for the user input sheets. Electricity Generation is treated as a single system that contributes to addressing the total electrical load of the site, with the remainder

supplied by the grid and/or independent renewable energy sources. A graphical representation of the derivation of the equations used to account for these interaction effects is shown in Figure 7.18. The interactions between the measures are calculated as per Eq. 135 and Eq. 136, and are described as follows.

- *Efficiency* – Any previous efficiency measures is deemed to apply to other onsite generators in the plant, with no interactions between independent equipment. Load control measures are all measures from all activities that consume electricity; however, they are only considered if they reduce the total requirement of onsite generation. In terms of new technology measures, it is assumed that onsite generators would not be subject to efficiency measures after replacement along the carbon neutrality timeline; thus, interaction effects with previous new technology measures are ignored. Consequently, the efficiency savings are not subject to interactions.
- *New technology* – It is assumed that the same replacement strategy applies to multiple generators feeding the site's electrical distribution system, i.e. if one generator is replaced with that of a different energy source, then the remaining generators would be planned for replacement at some point and would not be subject to efficiency measures in the interim. Thus, interaction effects with previous efficiency measures are ignored. Previous new technology measures are deemed to apply to the replacement of other onsite generators in the plant, with no interactions between independent equipment. Previous load control measures are not considered for interaction as new technology replacing existing onsite generation equipment can be sized for additional load as it then takes up grid supply.

$$Efficiency: \quad FCS_{eff_{int}} = FCS_{ef\ orig} \qquad \textit{Eq. 135}$$

$$New\ Technology: \quad \left(FCS_{tech_{int}}\right)_{old} = \left(FCS_{tech_{orig}}\right)_{i_{orig}} \qquad \textit{Eq. 136}$$

$$\left(FCS_{tech_{int}}\right)_{i_{new}} = tech\ ratio \times \left(FCS_{tech_{int}}\right)_{i_{old}}$$

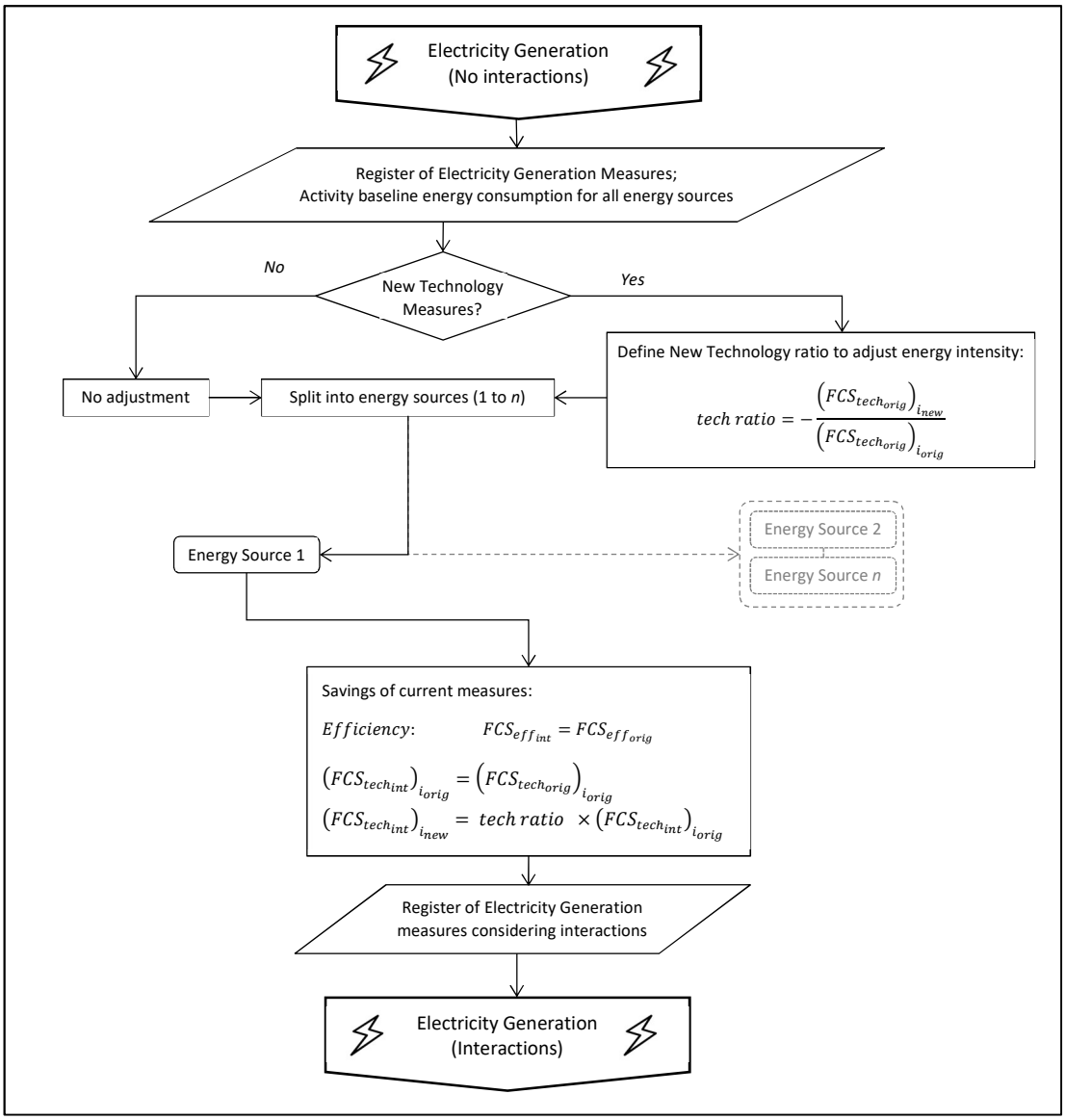


Figure 7.18: Graphical representation of Electricity Generation interaction effects

7.3.11 Physical/Chemical Processing

Physical and chemical processing activities are those that produce materials or chemicals. The measures considered in this category are those that reduce the emissions released as by-products of this production only; other measures are considered in the production line equipment activity. Physical and chemical processing activities are more likely to be associated with energy-intensive industries, which typically follow suggested guidance from industry associations to reduce emissions across the process cycle; these are likely to be independent, industry-specific measures. For non-energy-intensive industries, chemical and physical processing is likely to have a negligible contribution to total emissions, and

similarly, these are expected to be independent measures with no interactions. Consequently, no interaction effects are considered for systems within these activities.

7.3.12 Scope 3

The Greenhouse Gas Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard defines the following eight upstream emissions-producing activities: purchased goods and services, capital goods, fuel- and energy-related activities not included in scope 1 or scope 2, upstream transportation and distribution, waste generated in operations, business travel, employee commuting, and upstream leased assets; and the following seven downstream emissions-producing activities: downstream transportation and distribution, processing of sold products, use of sold products, end-of-life treatment of sold products, downstream leased assets, franchises, and investments [43]. These are assumed to be independent measures that address different parts of the supply chain, and are not considered for interaction.

7.3.13 Other

Other activities encompass activities that do not fit into the better-defined categories. These are expected to be independent measures with no interactions with a low total contribution to emissions. Consequently, no interaction effects are considered for systems within these activities.

7.3.14 Summary

These interactions between activities are illustrated in Figure 7.19.

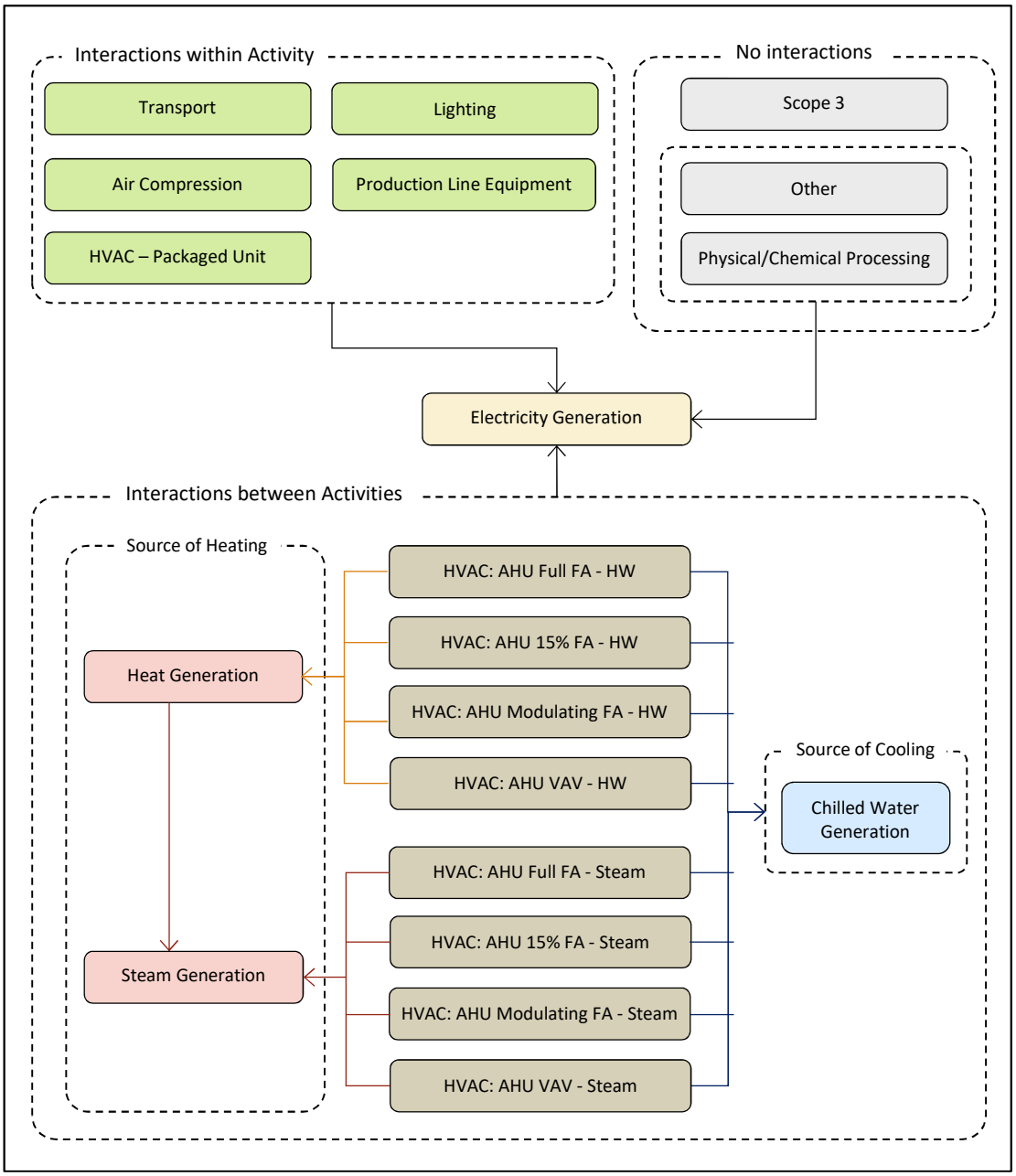


Figure 7.19: Relationship between activities

7.3.15 Emissions Factors

In the project-based modelling tool described in Chapter 6, the emissions factors for the site are calculated using the built-in emissions factors for each fuel, the projected renewable energy share for each fuel, and the reduced loads from the emissions-reduction measures. These demand reductions from the measures are prioritised in the order of utility, onsite generation, and renewable energy. This results in variable proportions of the energy sources, which alters the emissions factors (Figure 6.12). The inclusion of the interaction effects in the modelling tool allows improves the

accuracy of the emissions factors by more realistically quantifying the energy reductions for efficiency, load control, and thermal measures, and by adjusting the energy outputs of the old and new fuels in the case of new technology implementation.

7.4 Modelling approach - Financial analysis

The financial analysis presents the cumulative costs and savings over the carbon neutrality timeline and beyond until the breakeven point.

7.4.1 Financial costs

A conservative approach is taken for the implementation costs, where only those for new technology measures are considered for interaction since they are typically the highest. The interactions between measures means that new equipment implemented further along the timeline could be sized smaller than planned since previous measures may have decreased the load. However, there are a number of factors that affect the potential reduced implementation costs:

- It is not known where the original load lies within the operating range of the equipment, and thus at what point the equipment size can be reduced.
- Load reductions are expressed as annual reductions in MWh, whereas equipment may be sized according to peak load in MW and the effect on this is not captured for each measure.
- Implementation costs of new technologies include costs associated with distribution, electrical, and control systems, as well as enabling works; the proportion of these costs vary according to the site layout and complexity [182].

Consequently, the modelling tool considers no change in implementation cost for reductions under 20% to account for operating ranges, peak load contributions, and associated costs. Thereafter, the costs are scaled pro-rata.

7.4.2 Financial savings

The financial savings (operational, carbon tax, and carbon offset) are reliant on fuel type and consumption. Thus, the interaction effects need only be considered in the

carbon neutrality waterfall section of the modelling tool where the fuel consumption and emissions are calculated; no change to the financial analysis is required.

7.5 Case Study Validation

Three case studies are analysed to clarify the effectiveness of the proposed method of including interaction effects. For each case study, the modelling tool is first run without considering interactions to determine the theoretical emissions reduction. Then, it is run considering the interactions to quantify the emissions reduction with interaction effects. In each case, the organisation has undergone a site assessment, energy audit, heat study, and renewable energy study to generate a detailed report which includes a register of emissions-reduction opportunities. The output graphs are compared on the basis of the total emissions reduction, cumulative implementation cost, and cumulative financial savings at the 5-, 10-, and 15-year points of the carbon neutrality timeline.

7.5.1 Case study A

7.5.1.1 *Background*

Organisation A is a medical device manufacturer that employs over 1400 staff and has a revenue of approximately €1.2 billion. Organisation A aims to reduce its site energy consumption by 20% by 2025 and be carbon neutral by 2030. The significant energy users in descending order are the electrical production lines (24% of total energy consumption), steam system fuelled by natural gas (17% of total energy consumption), and compressed air system fuelled by electricity (14% of total energy consumption). All electricity used on site is renewable sourced through a corporate PPA. Consequently, their focus is on the reduction of their thermal load and their reliance on natural gas, and all of the proposed emissions-reduction measures address the thermal load.

7.5.1.2 *Modelling tool input*

Organisation A has an energy and carbon footprint breakdown as shown in Figure 7.20 for their baseline year. The proposed emissions-reduction measures are described in Table 7.13 with a graphical representation in Figure 7.21, and the completed user input sheets are shown in Appendix C1.

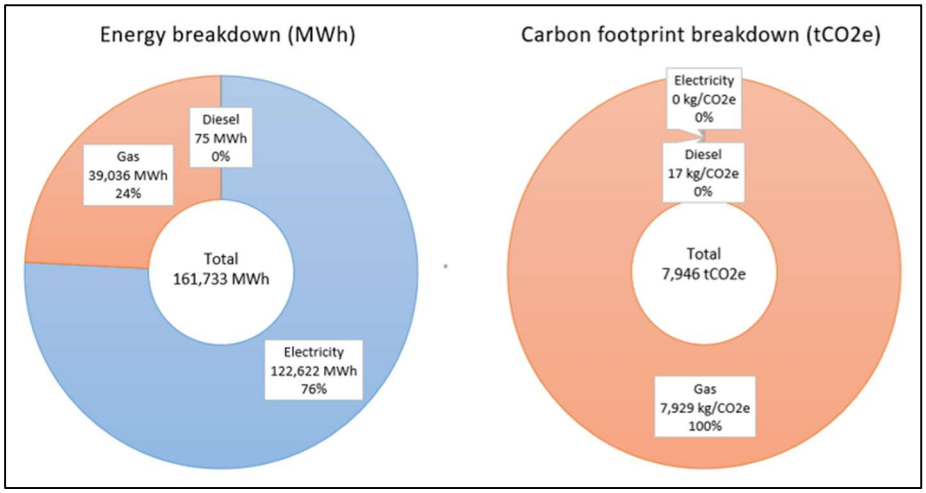


Figure 7.20: Organisation A – Energy and carbon footprint breakdown

Table 7.13: Organisation A – Description of emissions-reduction measures

No.	Description	Category	Activity	System	Notes
M1	Increase waste heat recovery off of the air compressor system to the HW system	Thermal	Heat Generation	1	Recovered waste heat for use in current medium-temperature heat applications on the HW system
M2	Implement waste heat recovery off of the thermal oxidiser stack to the HW system	Thermal	Heat Generation	2	Recovered waste heat for use in current medium-temperature heat applications on the HW system
M3	Deionised water return to be heated by heat pump instead of steam	Load Control	Steam Generation	3	Load transfer from steam system to heat pump
M4	Feed water to the steam system to be preheated by a heat pump fed off the condenser	Load Control	Steam Generation	All	Load transfer from steam system to heat pump

	water in the chilled water plant, instead of the steam system				
M5	Replace the HW duty boiler with a heat pump fed off the condenser water in the chilled water plant	New Technology	Heat Generation	All	Heat pump takes up the remaining medium-temperature load on the HW system
M6	Replace steam boilers with high-temperature heat pump fed off the fridge plant waste heat	New Technology	Steam Generation	All	Heat pump takes up the remaining high-temperature load on the steam system

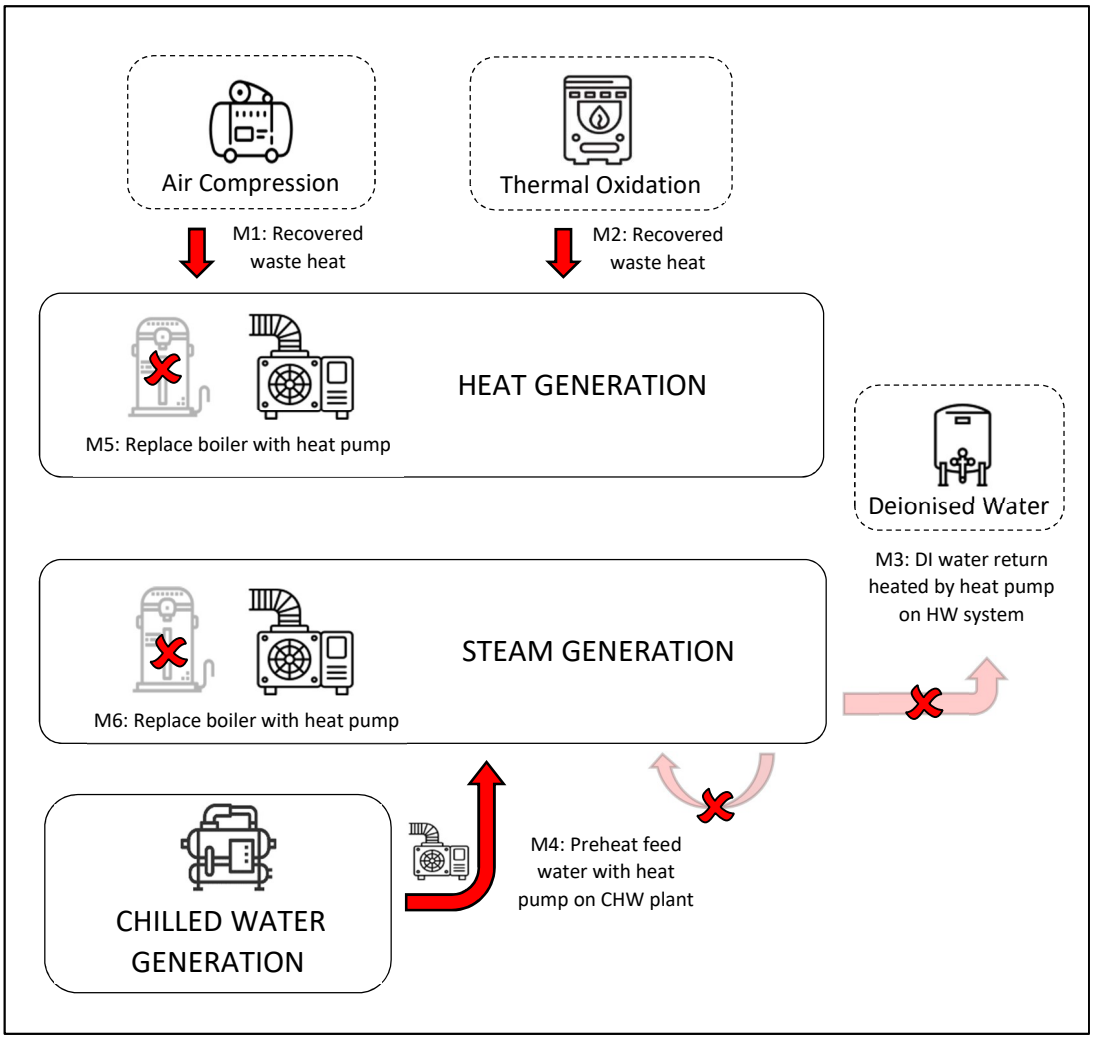


Figure 7.21: Organisation A – Illustration of emissions-reduction measures

The modelling tool approach to resolve these interaction effects is described as follows. Note that each measure only affects a single activity in this case study as there is no transfer of savings between activities, and there is no need to define systems.

- *Measure 1 – Heat recovery off air compressor*: Since this is the first measure in the Heat Generation activity, there are no interactions and the energy savings are not adjusted.
- *Measure 2 – Heat recovery off thermal oxidiser stack*: There are no interaction effects within the Heat Generation activity as measure 1 is a thermal measure and previous thermal measures are not considered for interaction.
- *Measure 3 – Load transfer from steam to heat pump*: There are no interactions since this is the first measure within the Steam Generation activity.

- *Measure 4 – Load transfer from steam to heat pump*: There are no interactions within the Steam Generation activity since the previous measure in this activity (measure 3) has a load control function, and load control measures are independent.
- *Measure 5 – Hot water heat pump:* The energy savings of the original energy source (Thermal: HW) are adjusted by subtracting all load control measures within the Heat Generation activity through the use of the systems ratio, which encompasses measures 1 and 2. The energy savings of the new energy source (Electricity) as well as the implementation cost are adjusted using the new technology ratio.
- *Measure 6 – Steam heat pump:* The energy savings of the original energy source (Thermal: Steam) are adjusted by subtracting all load control measures within the Steam Generation activity through the use of the systems ratio, which encompasses measures 1 and 2. The energy savings of the new energy source (Electricity) as well as the implementation cost are adjusted using the new technology ratio.

7.5.1.3 *Results comparison*

The carbon neutrality waterfalls and financial analyses output from the modelling tool for the simulations without and with the interaction effects are shown in Figure 7.22 and Figure 7.23, respectively, with the generated reports shown in Appendix D2. It is clear that consideration of the interaction effects impacts both the emissions balance and the financial analysis. The carbon neutrality waterfall without interaction effects exhibits a negative balance as a result of the planned implementation of two measures—a heat pump to address the full load of HW stream, and a high-temperature heat pump to address the full steam load. These heat pumps are sized according to the full loads to be replaced at the time of the energy audit and heat study, and these design loads are captured in full in this model. However, the measures implemented prior to the adoption of the heat pumps act to reduce the loads to be taken up by these heat pumps. Consequently, the emissions savings attributed to the heat pumps are lower in the carbon neutrality waterfall output when the interaction effects are considered in the time periods following

implementation (2028 Q3 and 2029 Q2). This results in a considerably smaller negative emissions balance of -80 tCO2e, which more closely represents the real scenario (this is shown as a zero emissions balance on the graph as the modelling tool does not allow negative balances). This slightly negative emissions balance may be attributed to differences in emissions factors used by the organisation in calculating their baseline carbon footprint, and the modelling tool not being able to capture every interaction. In the financial analysis, the only changes in the cost graph are the implementation costs of the final two measures (replacement heat pumps) in 2028 Q2 and 2029 Q1 since the revised loads are greater than 20% lower than the original loads. The financial savings graphs of both models are identical until the HW and steam heat pumps are considered in 2028 Q3 and 2029 Q2 (first time period after implementation), respectively. From the carbon neutrality target year, the financial savings difference is compounded by the carbon offset cost which is shown by the slight change in gradient of the savings graph.

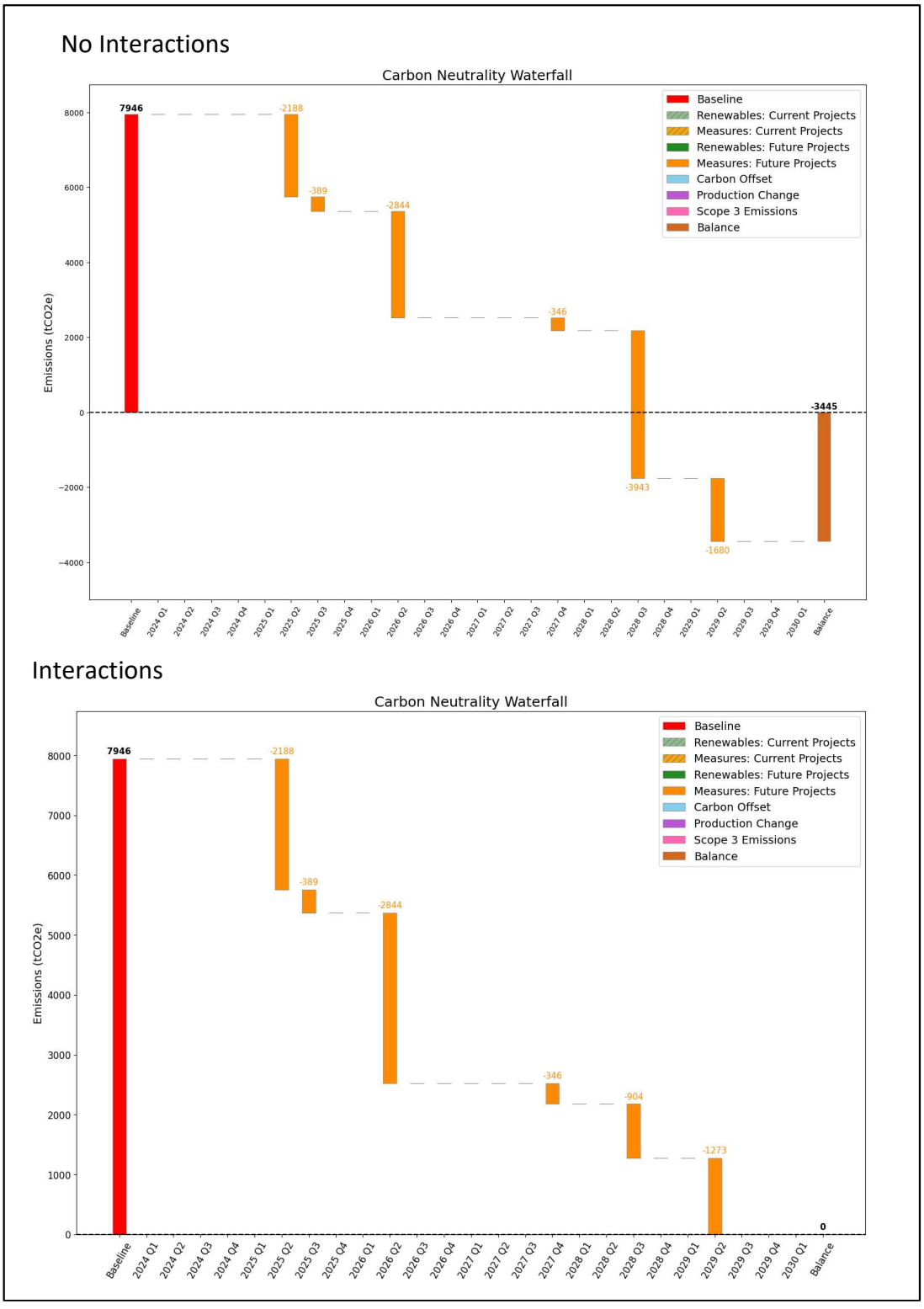


Figure 7.22: Organisation A – Modelling tool outputs – Carbon neutrality waterfall

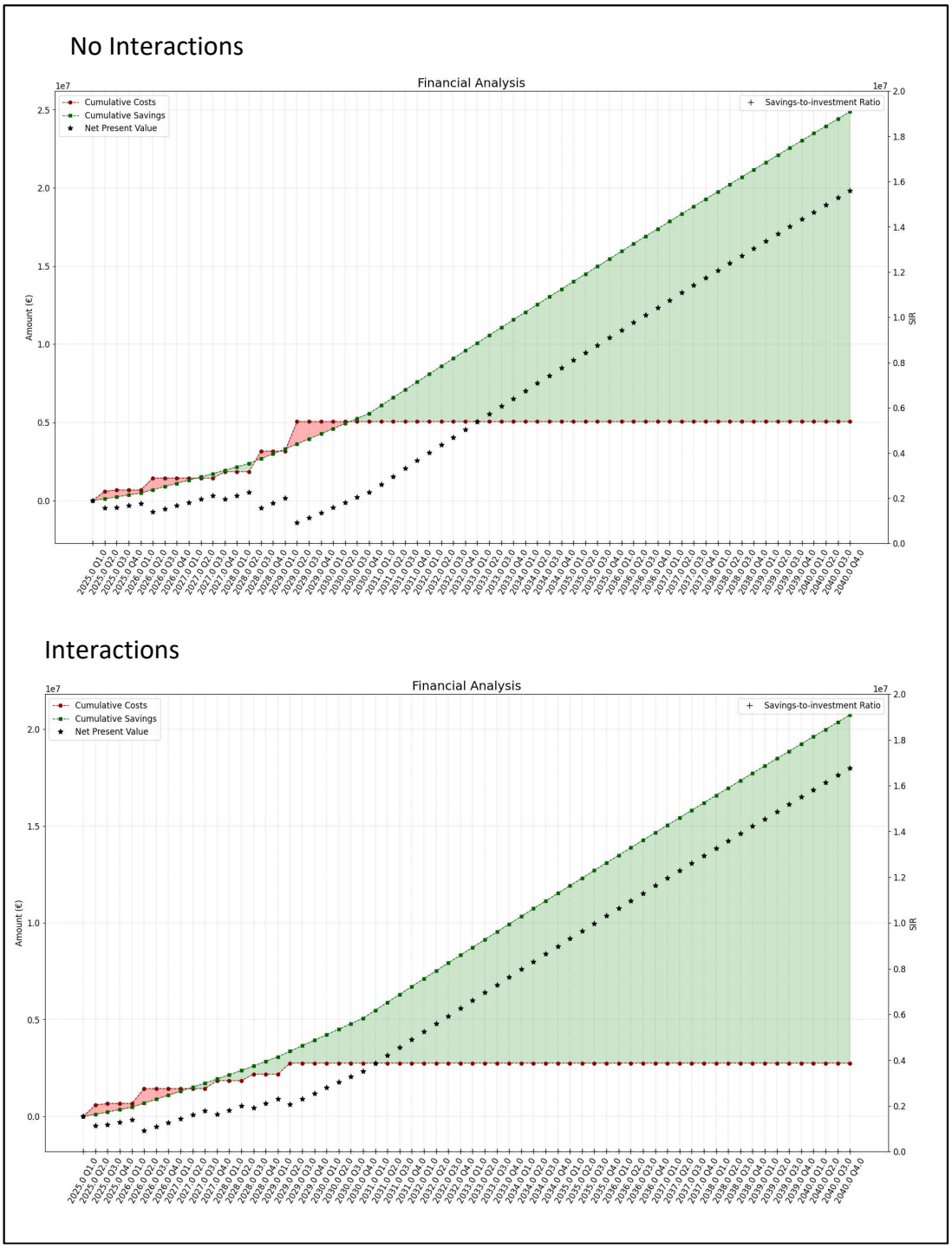


Figure 7.23: Organisation A – Modelling tool outputs – Financial Analysis

7.5.2 Case study B

7.5.2.1 *Background*

Organisation B is a pharmaceutical manufacturer that employs approximately 1200 staff and has a revenue of over €11 billion. Organisation B aims to increase its electrical RES from 50% in 2023 to 100% by 2025, and to achieve carbon neutrality by 2030. The significant energy users in ascending order are comfort heating and

ventilation (50% of useful energy), sterilisation fuelled by natural gas (19% of useful energy), and the clean-in-place system fuelled by electricity (15% of useful energy). Natural gas generates thermal energy in the form of steam which is converted to HW through multiple heat exchanger skids. Consequently, their focus is on the reduction of their thermal load and reliance on natural gas, and many of the proposed emissions-reduction measures involve heat recovery.

7.5.2.2 *Modelling tool input*

Organisation B has an energy and carbon footprint breakdown as shown in Figure 7.24 for their 2023 baseline year. The proposed emissions-reduction measures are described in Table 7.14 with a graphical representation in Figure 7.25, and the completed user input sheets are shown in Appendix E1.

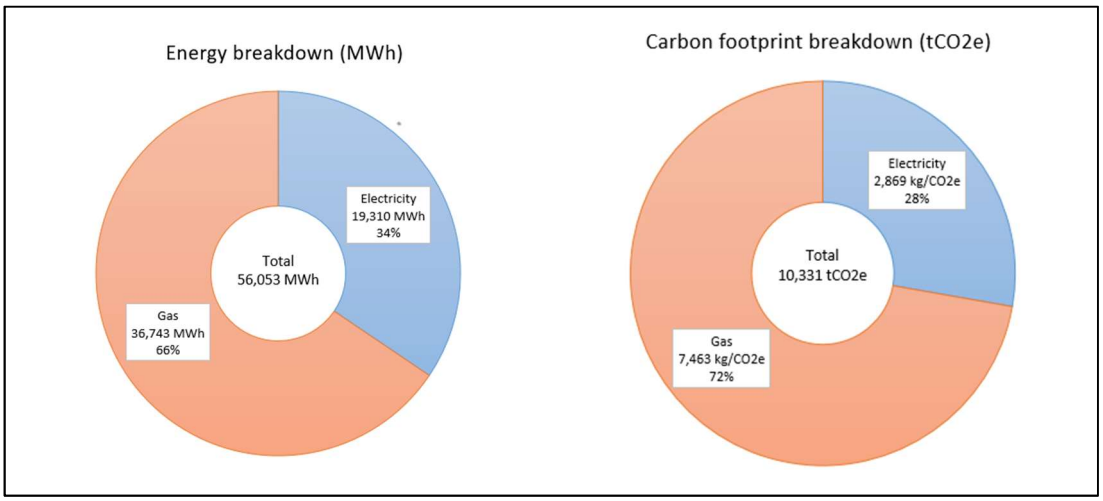


Figure 7.24: Organisation B – Energy and carbon footprint breakdown

Table 7.14: Organisation B – Description of emissions-reduction measures

No.	Description	Category	Activity	System	Notes
1	Implement HVAC heat recovery wheels	Thermal	HVAC	All	Waste heat recovery which reduces the heat generation required from the HW heating coil

2	Install heat recovery coils on AHUs	Thermal	HVAC	All	Waste heat recovery which reduces the heat generation required from the HW heating coil
3	Replace thermal system with ozone for sanitation	Load Control	Steam Generation	All	Load transferred from the steam system to electrical equipment
4	Recover clean-in-place system final rinse for use as pre-rinse	Load Control	Steam Generation	All	Clean-in-place system uses water-for-injection generated by steam, and this measure reduces the volume of water required to be heated
5	Use most efficient stills in priority	Load Control	Steam Generation	All	Water-for-injection is generated electrically by vapour compression distillation instead of with steam through multiple effect distillation; this is load control and not new technology because it is governed by how the measure relates to the activity

6	Increase regeneration on heat inactivation skid preheaters	Thermal	Steam Generation	All	Increased heat regeneration decreases thermal energy to be supplied by steam system
7	Use cooling tower to cool water-for-injection	Load Control	Chilled Water Generation	All	Water-for-injection is cooled by the chilled water instead of electrically; this is load control and not new technology because it is governed by how the measure relates to the activity
8	Recover waste heat from air compressor system	Thermal	Heat Generation	All	Recovered waste heat for use in current medium-temperature heat applications on the HW system
9	Install heat pump on chilled water system	New Technology	Heat Generation	All	Heat pump run off CHW waste heat to supply the remaining medium-temperature thermal applications on HW system
10	Install thermal energy store unit for the steam load	New Technology	Steam Generation	All	Thermal energy store to take up remaining high-temperature load on steam system

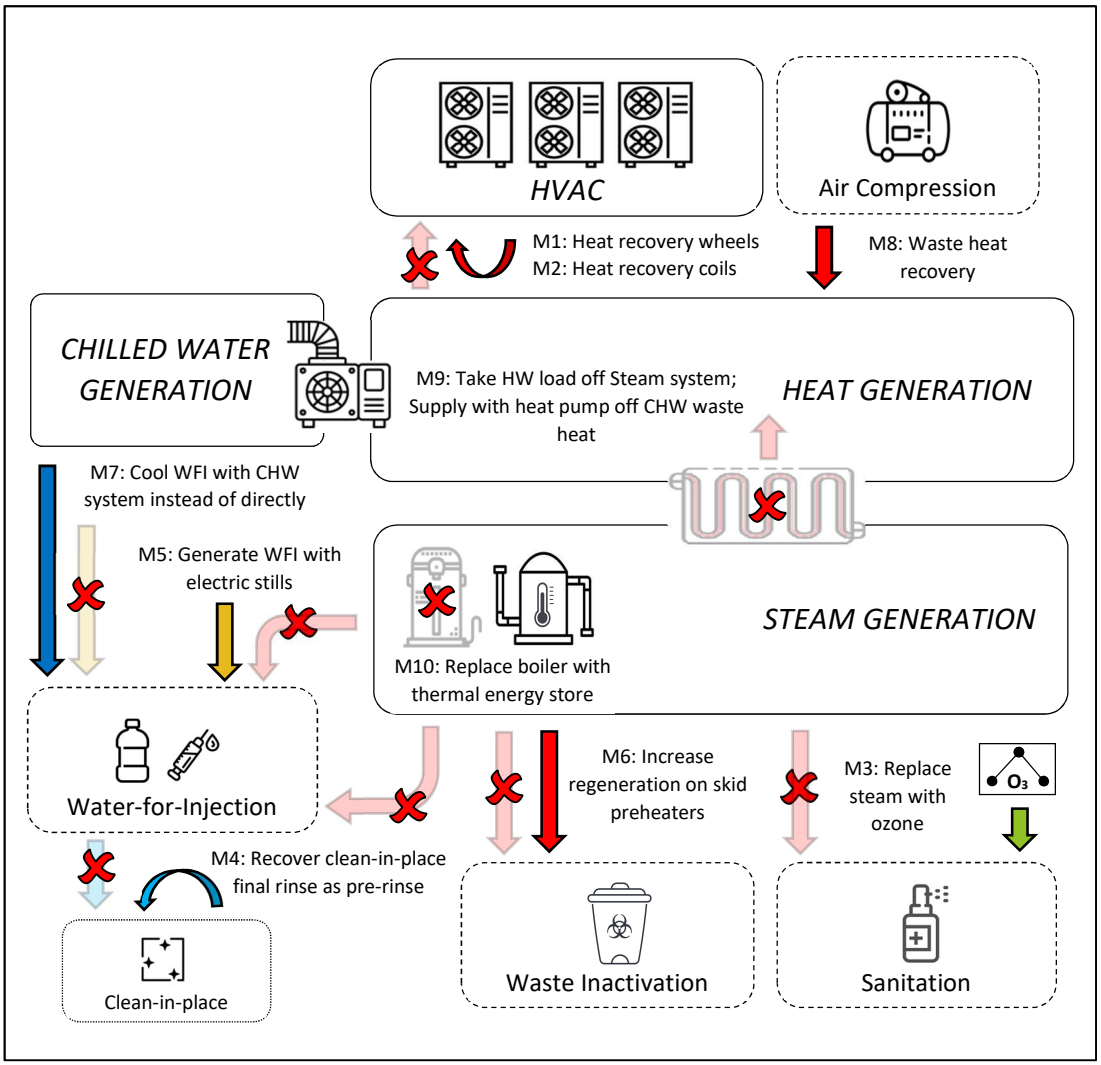


Figure 7.25: Organisation B – Illustration of emissions-reduction measures

The modelling tool approach to resolve these interaction effects is described as follows. Note that each measure only affects a single activity in this case study as there is no transfer of savings between activities, and there is no need to define systems.

- *Measure 1 – Heat recovery wheels*: There are no interaction effects within the HVAC activity as this is the first measure. The energy savings are transferred to the HW system as a load control measure with energy source 'Thermal: HW'; since this is the first measure in the Heat Generation activity, there are no interactions and the energy savings are not adjusted. The full energy savings are then transferred to the Steam Generation activity as a load control measure with energy source 'Thermal: Steam', with adjustment for the efficiency of the heat exchanger.

- *Measure 2 – Heat recovery coils*: There are no interaction effects within the HVAC activity as thermal measures are independent. The energy savings are transferred to the Heat Generation activity as a load control measure with energy source 'Thermal: HW'; there are no interactions within this activity since load control measures are independent. The full energy savings are then transferred to the Steam Generation activity as a load control measure with energy source 'Thermal: Steam', with adjustment for the efficiency of the heat exchanger.
- *Measure 3 – Ozone for sanitation*: There are no interactions within the Steam Generation activity since measures 1 and 2 have been converted to load control measures within this activity, and load control measures are independent.
- *Measure 4 – Water reuse*: There are no interactions within the Steam Generation activity since all previous measures are load control measures within this activity, and load control measures are independent.
- *Measure 5 – Prioritise efficient stills*: There are no interactions within the Steam Generation activity since all previous measures are load control measures within this activity, and load control measures are independent.
- *Measure 6 – Regeneration on heat inactivation skids*: There are no interactions within the Steam Generation activity since all previous measures are load control measures within this activity, and load control measures are independent.
- *Measure 7 – Cooling tower cooling*: There are no interactions within the Chilled Water Generation activity since this is the first measure affecting this activity.
- *Measure 8 – Air compressor heat recovery*: There are no interactions within the Heat Generation activity since all previous measures are load control measures within this activity and they do not interact with thermal measures. The energy savings of the original energy source (Thermal: HW) are transferred to the Steam Generation activity as a load control, with

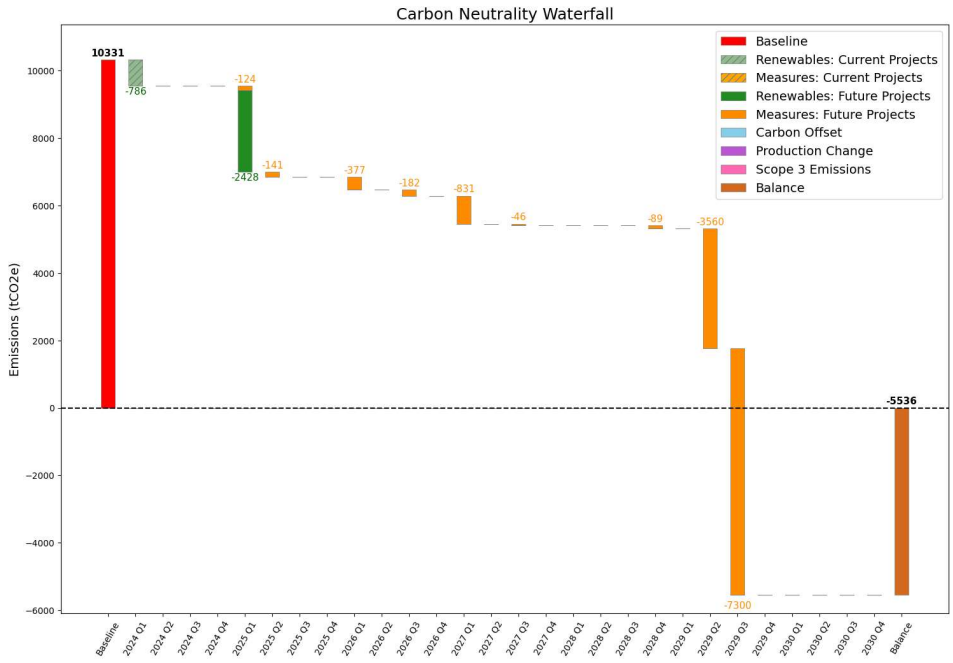
adjustment for the efficiency of the heat exchanger (the corresponding electricity increase is independent of the Steam Generation activity).

- *Measure 9 – HW heat pump*: The energy savings of the original energy source (Thermal: HW) are adjusted by subtracting all load control measures within the Heat Generation activity through the use of the systems ratio, which encompasses measures 1 and 2. The energy savings of the new energy source (Electricity) as well as the implementation cost are adjusted using the new technology ratio. The 'Thermal: HW' energy savings of the original source are then transferred to the Steam Generation activity as a load control measure with adjustment for the efficiency of the heat exchanger (the corresponding electricity increase is independent of the Steam Generation activity).
- *Measure 10 – Thermal energy store for steam*: The energy savings of the original energy source (Thermal: Steam) are adjusted by subtracting all load control measures within the Steam Generation activity through the use of the systems ratio, which encompasses measures 1, 2,3, 4, 5, 6, 7, and 9. The energy savings of the new energy source (Electricity) as well as the implementation cost are adjusted using the new technology ratio.

7.5.2.3 *Results comparison*

The carbon neutrality waterfalls and financial analyses output from the modelling tool for the simulations without and with the interaction effects are shown in Figure 7.26 and Figure 7.27, respectively, with the generated reports shown in Appendix E2. Similarly to Organisation A, the emissions balance is negative when interactions effects are not considered since measures 9 and 10 involve addressing the full hot water and steam loads with new technologies. When interactions with previous measures are considered, the emissions balance decreases to zero. In the financial analysis, the effect of the adjusted implementation costs in 2029 Q1 and Q2 is shown to be substantially lower with the result that savings exceed the costs throughout the carbon neutrality timeline.

No Interactions



Interactions

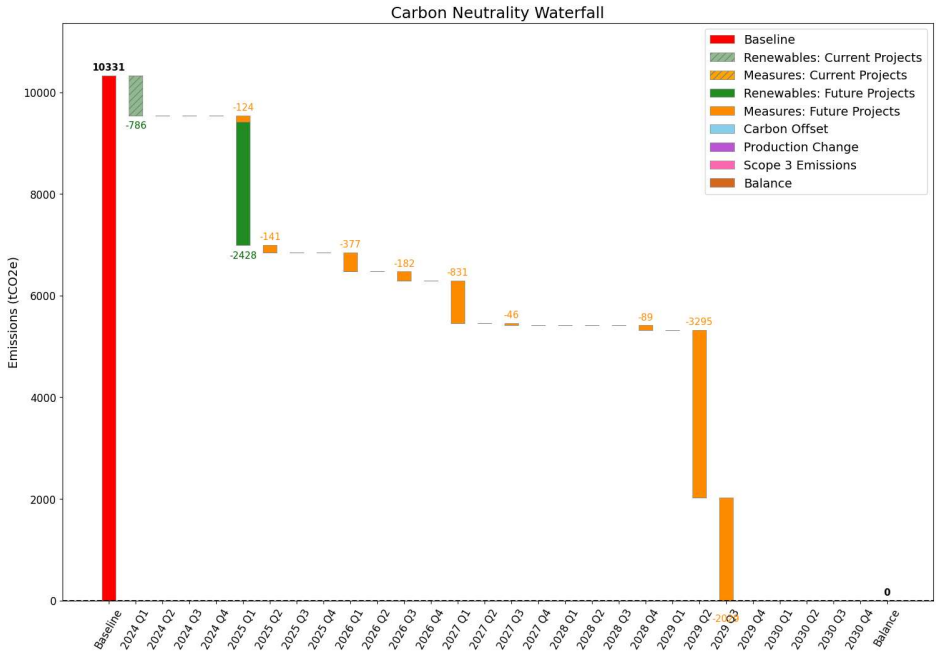


Figure 7.26: Organisation B – Modelling tool outputs – Carbon neutrality waterfall

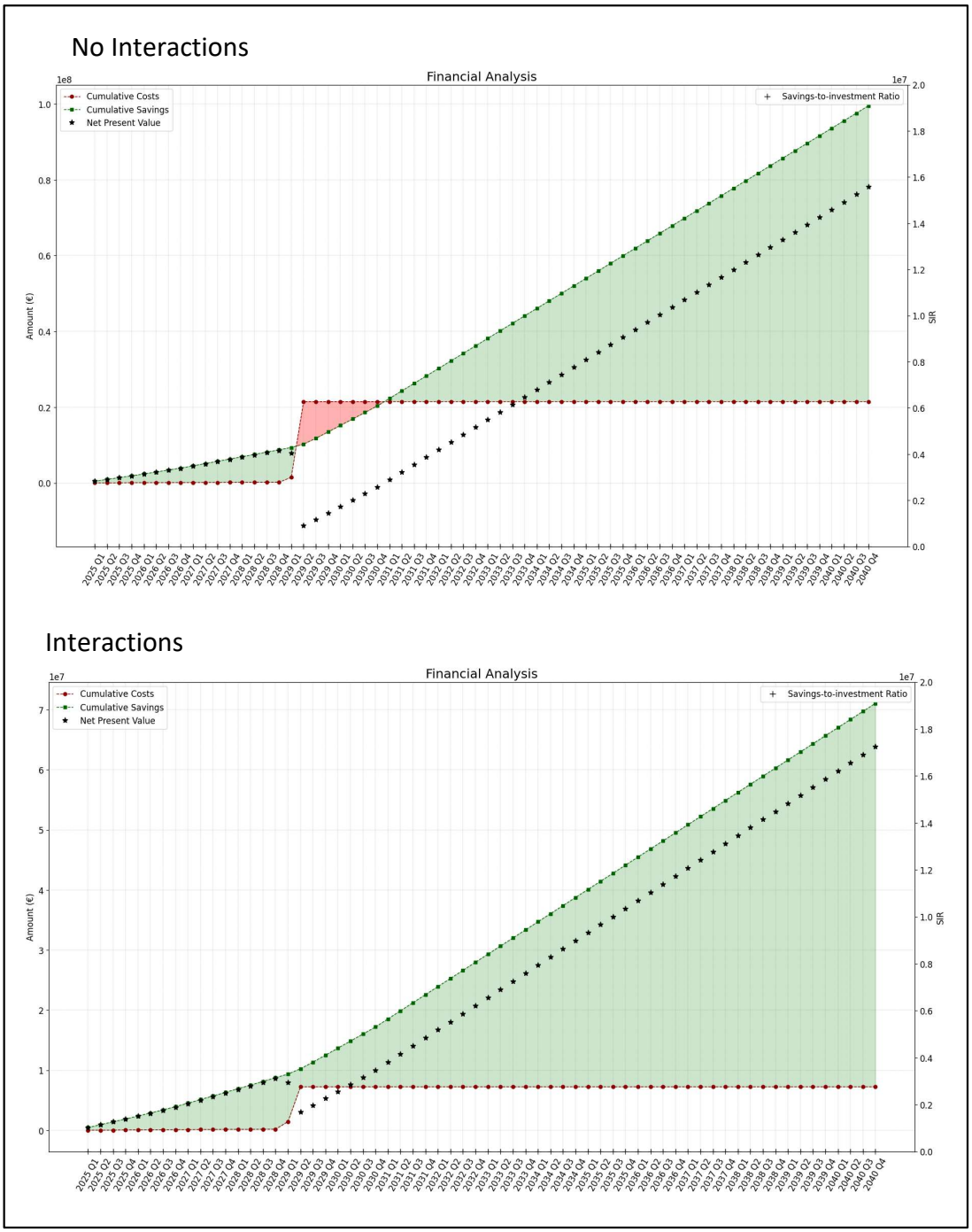


Figure 7.27: Organisation B – Modelling tool outputs – Financial Analysis

7.6 Case study C

7.6.1 Background

Organisation C is a biopharmaceutical manufacturer that employs over 600 staff and has a revenue of approximately €6.6 billion. Organisation C aims to reduce its site energy by 25% by 2025 compared to a 2016 baseline, and reduce their natural gas consumption. Natural gas generates thermal energy in the form of steam which is

converted to HW through multiple heat exchanger skids. The six highest significant energy users are HVAC related and together they comprise over 50% of the total site energy consumption. Thus, the emissions-reduction measures focus on HVAC optimisation and heat recovery.

7.6.2 Modelling tool input

Organisation C has an energy and carbon footprint breakdown as shown in Figure 7.28 for their baseline year. The proposed emissions-reduction measures are described in Table 7.15 with a graphical representation in Figure 7.29. The completed user input sheets are shown in Appendix F1.

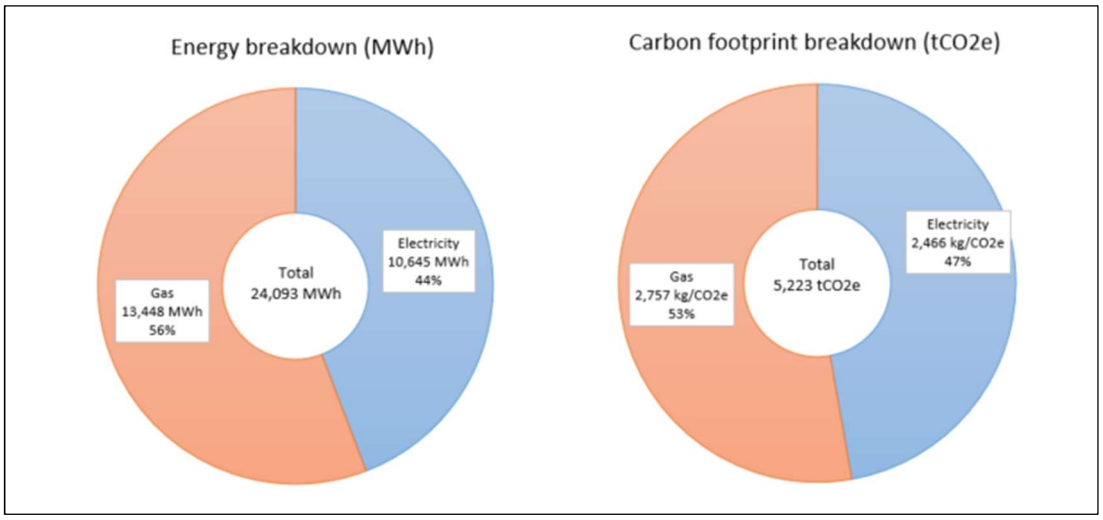


Figure 7.28: Organisation C – Energy and carbon footprint breakdown

Table 7.15: Organisation C – Description of emissions-reduction measures

No.	Description	Category	Activity	System	Notes
1	Revert from full fresh air to return air mixing in AHU units	Load Control	HVAC – Modulating FA - HW	All	Reduces the heating and cooling loads
2	Address inefficiencies in AHU control strategy	Load Control	HVAC – Modulating FA - HW	All	Improvement to control strategy affect the loads

3	Employ setback mode on all appropriate AHUs	Load Control	HVAC – Modulating FA - HW	All	Reduces the heating and cooling loads
4	Restore heat recovery coils on AHUs	Thermal	Heat Generation		Waste heat recovery which reduces the heat generation required from the HW heating coil
5	Recover heat from air compressors	Thermal	Heat Generation		Recovered waste heat for use in current medium-temperature heat applications on the HW system
6	Employ heat pump system for HVAC zone 1	New Technology	HVAC: Modulating FA – HW; HVAC: Packaged	1	Install heat pump for HVAC load in zone 1
7	Employ heat pump system for HVAC zone 2	New Technology	HVAC: Modulating FA – HW; HVAC: Packaged	2	Install heat pump for HVAC load in zone 1
8	Employ high-temperature storage system for steam load	New Technology	Steam Generation	All	Storage system takes up the remaining high-temperature load on this system

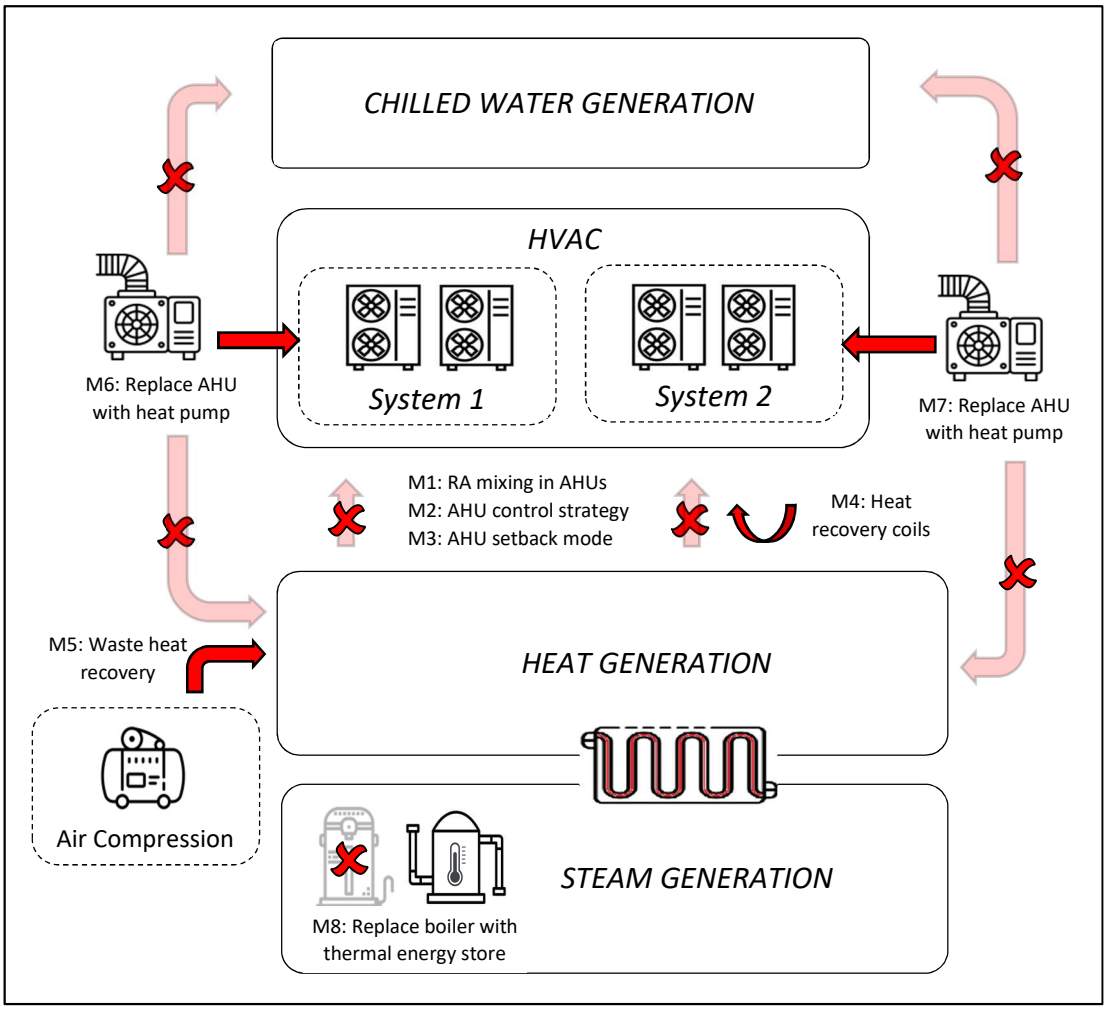


Figure 7.29: Organisation C – Illustration of emissions-reduction measures

The modelling tool approach to resolve these interaction effects is described as follows. Note that each measure only affects a single activity in this case study as there is no transfer of savings between activities. Two systems are defined to account for differing HVAC zones.

- *Measure 1 – Return air mixing*: There are no interaction effects within the HVAC activity as this is the first measure. The energy savings are transferred to the HW system as a load control measure with energy source 'Thermal: HW'; since this is the first measure in the Heat Generation activity, there are no interactions and the energy savings are not adjusted. The full energy savings are then transferred to the Steam Generation activity as a load control measure with energy source 'Thermal: Steam', with adjustment for the efficiency of the heat exchanger.

- *Measure 2 – Control strategy*: There are no interaction effects within the HVAC activity as load control measures are independent. The energy savings are transferred to the Heat Generation activity as a load control measure with energy source 'Thermal: HW'; there are no interactions within this activity since load control measures are independent. The full energy savings are then transferred to the Steam Generation activity as a load control measure with energy source 'Thermal: Steam', with adjustment for the efficiency of the heat exchanger.
- *Measure 3 – HVAC setback mode*: There are no interaction effects within the HVAC activity as load control measures are independent. The energy savings are transferred to the Heat Generation activity as a load control measure with energy source 'Thermal: HW'; there are no interactions within this activity since load control measures are independent. The full energy savings are then transferred to the Steam Generation activity as a load control measure with energy source 'Thermal: Steam', with adjustment for the efficiency of the heat exchanger.
- *Measure 4 – Heat recovery coils*: There are no interaction effects within the HVAC activity as thermal measures are independent. The energy savings are transferred to the Heat Generation activity as a load control measure with energy source 'Thermal: HW'; there are no interactions within this activity since load control measures are independent. The full energy savings are then transferred to the Steam Generation activity as a load control measure with energy source 'Thermal: Steam', with adjustment for the efficiency of the heat exchanger.
- *Measure 5 – Air compressor heat recovery*: There are no interactions within the Heat Generation activity since all previous measures are load control measures within this activity and they do not interact with thermal measures. The energy savings of the original energy source (Thermal: HW) are transferred to the Steam Generation activity as a load control, with adjustment for the efficiency of the heat exchanger (the corresponding electricity increase is independent of the Steam Generation activity).

- *Measure 6 – Heat pump*: In this case the heating and cooling split of the measure is known. The energy savings of the original energy source (Thermal: HW) are adjusted using the systems ratio to apportion the previous load control measures (measures 1-3) within the 'HVAC – Modulating FA – HW' activity to system 1. The energy savings of the new energy source (Electricity) is adjusted using the new technology ratio and then sent to the 'HVAC: Packaged' activity. The energy savings of the original source are then transferred to the Steam Generation and Chilled Water Generation activities as load control measures with adjustment for the efficiency of the heat exchanger. Finally, the implementation cost is adjusted using the new technology ratio.
- *Measure 7 – Heat pump*: In this case the heating and cooling split of the measure is known. The energy savings of the original energy source (Thermal: HW) are adjusted using the systems ratio to apportion the previous load control measures (measures 1-3) within the 'HVAC – Modulating FA – HW' activity to system 2. The energy savings of the new energy source (Electricity) is adjusted using the new technology ratio and then sent to the 'HVAC: Packaged' activity. The energy savings of the original source are then transferred to the Steam Generation and Chilled Water Generation activities as load control measures with adjustment for the efficiency of the heat exchanger. Finally, the implementation cost is adjusted using the new technology ratio.
- *Measure 8 – Thermal energy store*: The energy savings of the original energy source (Thermal: Steam) are adjusted by subtracting all load control measures within the Steam Generation activity through the use of the systems ratio, which encompasses measures 1-7. The energy savings of the new energy source (Electricity) as well as the implementation cost are adjusted using the new technology ratio.

7.6.2.1 *Results comparison*

The carbon neutrality waterfalls and financial analyses output from the modelling tool for the simulations without and with the interaction effects are shown in Figure

7.30 and Figure 7.31, respectively, with the generated reports shown in Appendix F2. It is clear that consideration of the interaction effects impacts both the emissions balance and the financial analysis. In contrast to Organisations A and B, the waterfall does not exhibit a negative balance. This is because Organisation C is focussed on decarbonisation but not to the extent of targeting carbon neutrality, and thus the measures planned for implementation are not expected to mitigate the full carbon footprint. The inclusion of the interaction effects reduces the emissions savings attributed the HVAC heat pumps and the thermal energy store since previous measures have reduced the loads to be addressed by these new technologies. This results in a higher emissions balance, and comparison of the two cases indicates an overestimation of emissions savings of 56% when interaction effects are not considered. In terms of the financial analysis, the financial costs are artificially higher when interaction effects are not considered as the technology is sized for the full load. When interaction effects are considered, this cost is lower and a breakeven point is reached in 2034 Q1. However, the savings are an order of magnitude lower than those of Organisations A and B because the electrification technologies are predominantly powered by more expensive grid electricity and the operational savings are attributed to the high efficiencies of these technologies and the previous measures that reduce the loads. A further factor is the lack of carbon offset savings since there is no commitment to carbon neutrality.

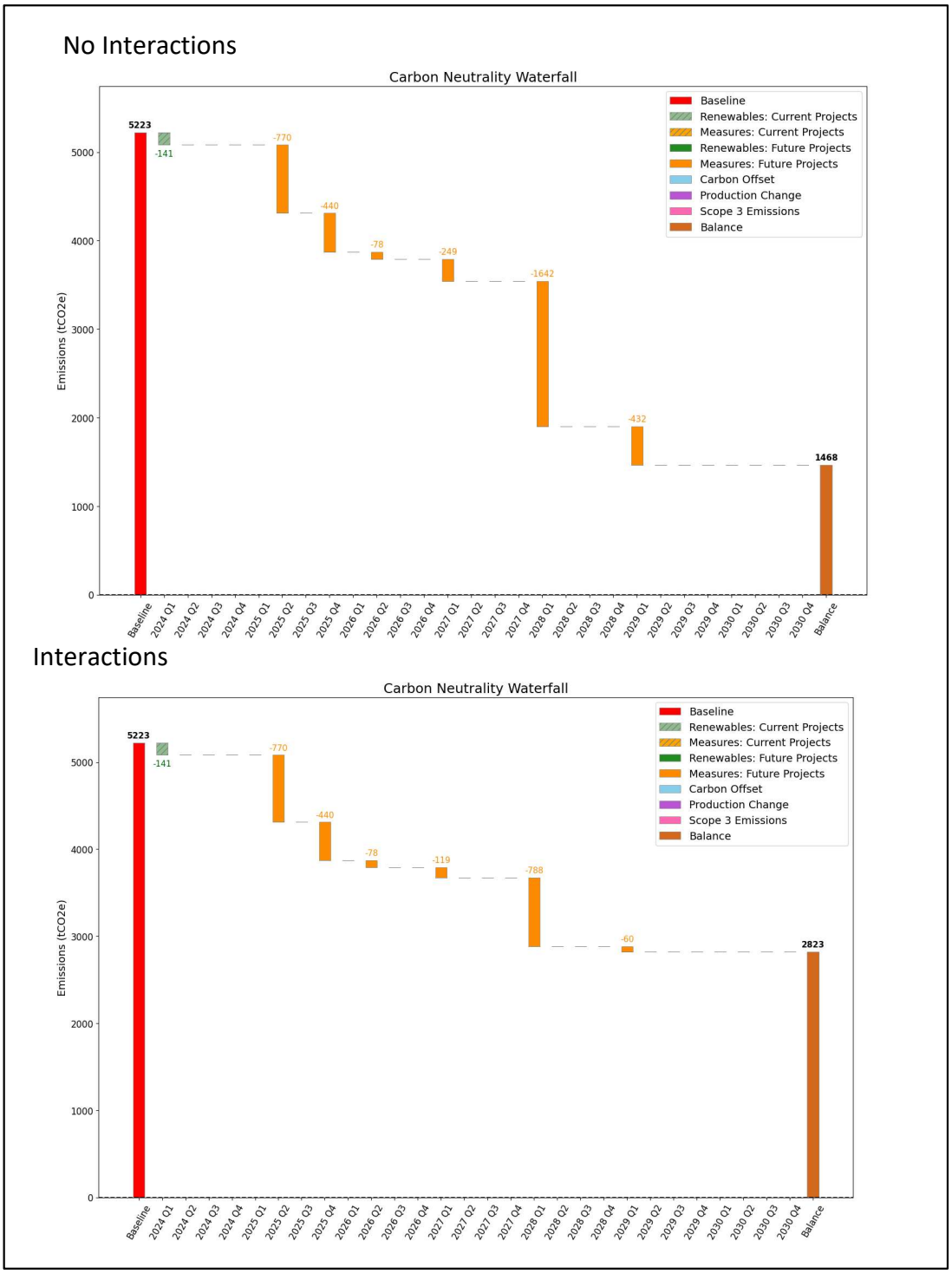


Figure 7.30: Organisation C – Modelling tool outputs – Carbon neutrality waterfall

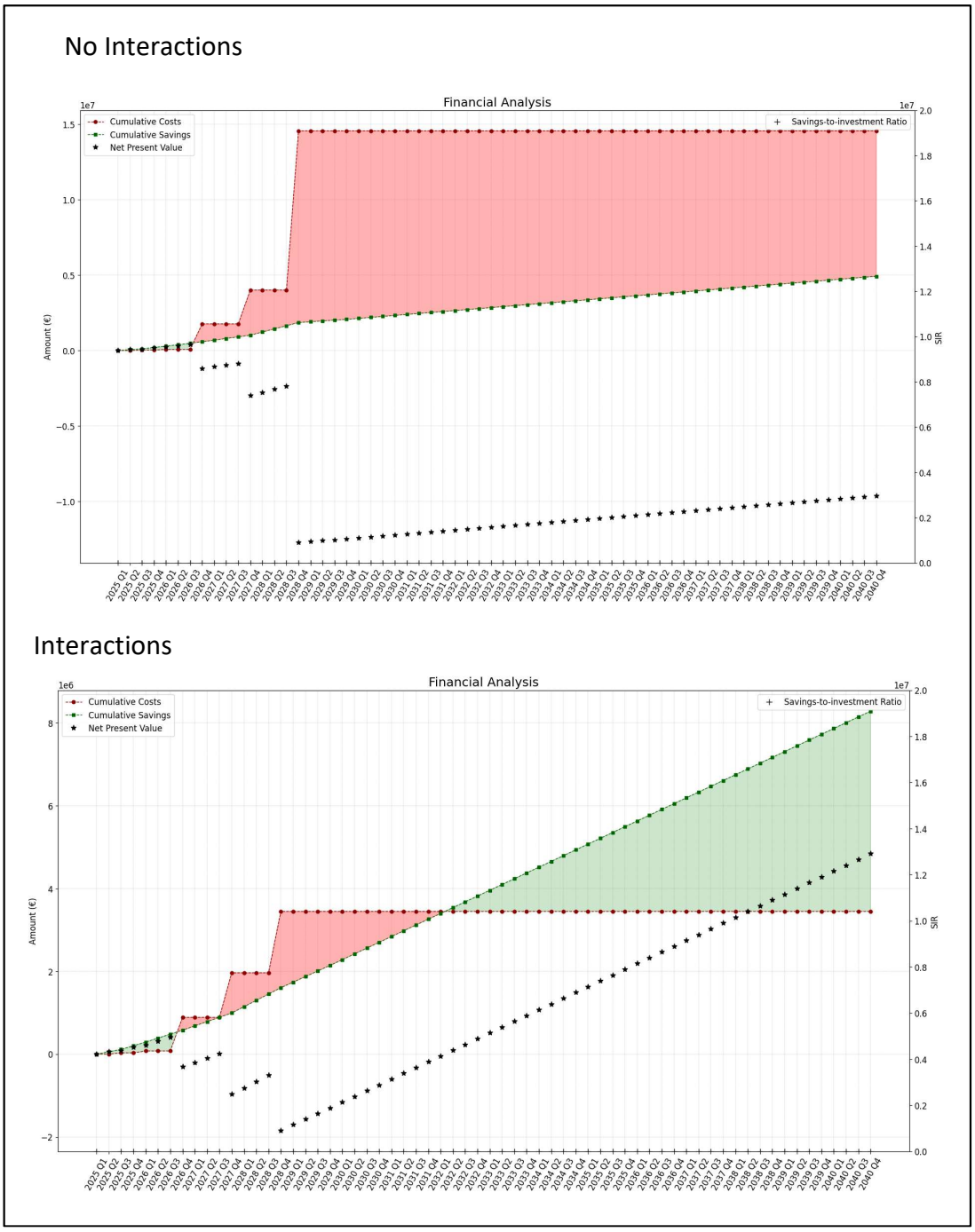


Figure 7.31: Organisation C – Modelling tool outputs – Financial Analysis

7.6.3 Summary of results

The emissions abated, implementation costs, and cumulative financial savings at the 5-, 10-, and 15-year points of the carbon neutrality timeline are compared in Table 7.16 for all case studies modelled with and without consideration of the interaction effects. These results indicate overestimations of 43 - 56% for emissions abatement

and 84 - 322% for implementation costs, and error ranges of -40 - 40% for cumulative financial savings.

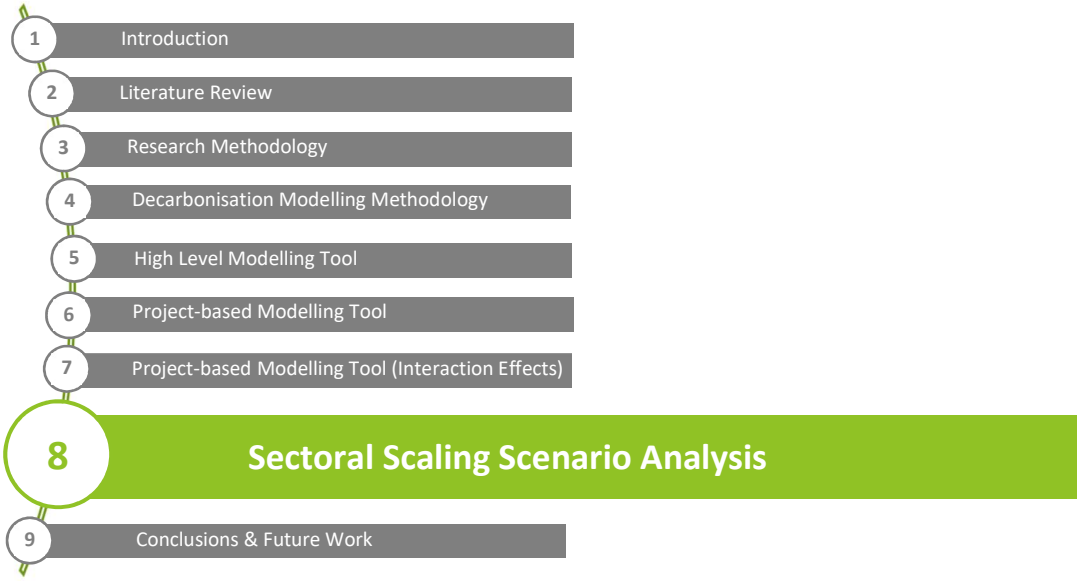
Table 7.16: Organisation A – Comparison of SIR values

	Error (%) Organisation A	Error (%) Organisation B	Error (%) Organisation C
Emissions abated	73%	54%	56%
Implementation cost	84%	197%	322%
Cumulative savings (5 year)	9%	11%	-7%
Cumulative savings (10 year)	18%	35%	-32%
Cumulative savings (15 year)	20%	40%	-40%

7.7 Conclusions

A rule-based method for the consideration of interaction effects was presented and included within the project-based modelling tool to generate applicable carbon neutrality roadmaps and financial analyses for industrial organisations. This method proposes governing rules for each emissions-producing activity based on the category (efficiency, load control, thermal, or new technology) and system of each measure. This additional information is deemed sufficient as there is a balance between the accuracy of the outputs and the user friendliness of the modelling tool. Further attempts to increase the accuracy of the interactions requires additional input from the client which renders the input sheets cumbersome, and may act as a barrier to adoption of the modelling tool. Too little input requires greater assumptions to be made which may cause inaccuracies. Three organisations were used as case studies to determine the impact of these interaction effects. The results show that failure to consider these effects can cause an overestimation of potential emissions reduction of 43-56%, which could jeopardise the achievement of carbon neutrality. The overestimation of the implementation costs and the over- or underestimation of cumulative financial savings can have a substantial effects on financial planning.

This rule-based approach is deemed sufficient for the purposes of the modelling tool as a guide to exploring the sustainability and financial effects of pursuing carbon neutrality. This is a novel approach that addresses the research gap between the unstructured implementation of measures and the employment of a consultant to generate an in-depth site-specific plan.



8.1 Introduction

In an effort to aid non-EII industrial organisations in planning for and subsequently achieving carbon neutrality, a high-level modelling tool and a detailed, project-based modelling tool were developed in this work. The project-based tool is applicable to organisations at the point of commitment to carbon neutrality, and this was applied to three case study organisations as discussed in Chapter 7. While this meets a need in industry and provides valuable information and guidance, further insights can be gained by scaling these results and those of additional case studies to the sectoral level to assess the collective impact of organisational decarbonisation. This aims to provide some insight at the sectoral level and to highlight the importance of developing bottom-up industrial sector models from the organisational level. Consequently, this chapter discusses the scaling of five case studies as a means to quantify the impact of carbon neutrality on Ireland's industrial sector. Section 8.2 provides a background to the industrial sector; section 8.3 presents the approach used to leverage the case studies to generate industrial sector results; section 8.4 presents the case study data; section 8.5 provides a breakdown of the industrial sector into the LIEN categories; section 8.6 details the scaling scenarios; section 8.7 discusses the results; and section 8.8 presents the conclusions.

8.2 Background to Industrial Sector

LIEN is a leading global energy efficiency network comprising 197 active members categorised into five sectors—Pharma/Chem, Food/Drink, Healthcare, Electronics, and Other [183]. Organisations with a minimum annual energy spend of €1 million or those that are certified or targeting ISO 50001 are eligible for LIEN membership. Additional requirements are the development of an energy management action plan, the setting and reviewing of energy targets, and annual reporting of energy performance. It should be noted that the LIEN is a voluntary network that fosters collaboration to support emissions reduction; it is not a commercial entity and thus has no financial interest in the outcomes of this work.

The industrial sector comprises 18% of Ireland's total primary energy requirement (TPER) [148], which equates to the TPER contribution reported by Ireland's Large Industry Energy Network (LIEN). LIEN further reported a total primary energy requirement (TPER) of 30 327 GWh for 2022 (latest available data) with associated emissions of 5.018 Mt CO_2 (8.1%) [183]. However, some LIEN member organisations may be classed as part of the commercial services sector rather than the industrial sector according to Ireland's National Energy Balance [155]. Regardless, for the purposes of this work, the emissions contributions of smaller, non-member industrial organisations can be regarded as negligible, and a carbon neutral LIEN is considered to be a carbon neutral industrial sector. This serves as the rationale for the scenario analysis approach discussed in the following section.

8.3 Approach

Bottom-up industrial sector or sub-sector models reported in the literature are typically based on national energy balance data at the sub-sector level rather than scaling from the organisational level. An example is the study by Fleiter et al. in which a bottom-up industrial sector model was developed using the FORECAST software; the decarbonisation measures of energy efficiency, fuel switching, carbon capture and storage, circular economy and recycling, and material efficiency and substitution down the value chain were applied to each sub-sector [184]. This approach of scaling at the sub-sector level is typically based on proven technologies [185], and this

approach may fail to capture the possible diversity of technologies suitable for individual sites and may not be up-to-date with emerging technologies planned for installation on benchmark sites. In addition, industrial processes may be assessed independently without consideration of process integration. As such, bottom-up sub-sector models provide high level insights as a broad overview of the industrial sector. In contrast, industry sector models scaled from the organisational level may provide more detailed insights and financial analyses based on specific decarbonisation technologies and measures with consideration of process integration. The approach used in this work is the development of a bottom-up industrial sector model scaled from individual case study organisations. The three case study organisations detailed in chapter 7 (Organisations A, B, and C) are targeting carbon neutrality by 2030 using a five-year roadmap. Accordingly, this time frame was chosen as the basis from which to quantify the financial impact of achieving a carbon neutral industrial sector. Two additional case studies (Organisations D and E) with the same timeline became available post modelling work and are included in this section of the work to bring the total to five case studies as a larger base for scaling. The emissions and financial data from the baseline situation and the modelled output of each organisation are leveraged to develop two scaling scenarios based on the grouping of LIEN industrial sector categories according to similarities in the data to the case study organisations (detailed in section 8.6.2). Relevant financial metrics are used to determine the implementation cost and cumulative financial savings ranges of achieving carbon neutrality for each scenario. This approach is illustrated in Figure 8.1, and discussed in further detail in the following sections.

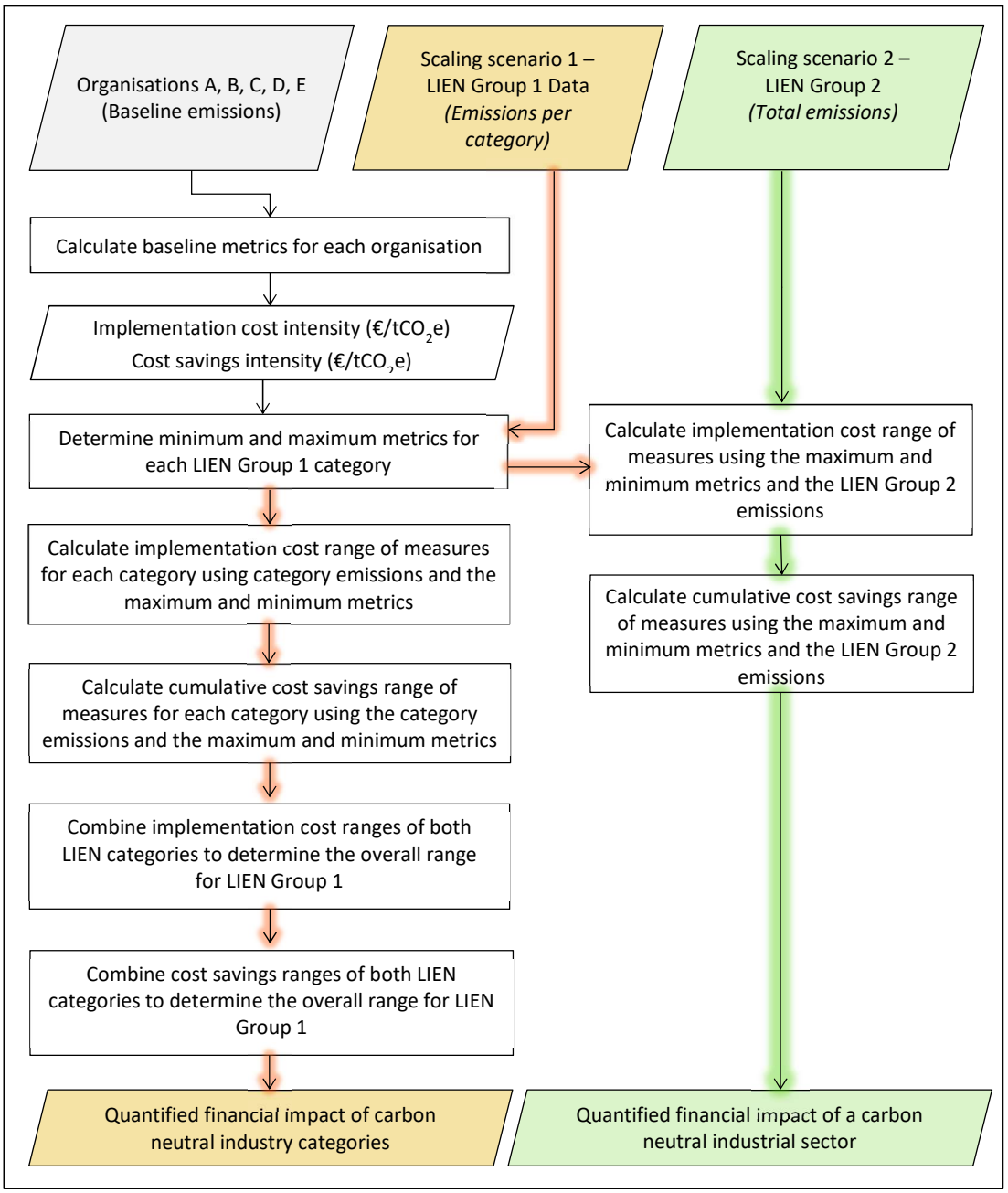


Figure 8.1: Flowchart of case study scaling approach

8.4 Case Study Data

Five case studies are used for scaling—Organisations A, B, and C which are detailed in Chapter 7; and two additional organisations, Organisation D (medical device manufacturer) and Organisation E (pharmaceutical manufacturer). In terms of the LIEN, these case studies comprise three organisations in the Pharma/Chem category and two in the Healthcare category. The baseline energy and emissions data for the five industrial partner case studies are shown in Table 8.1. The annual energy consumption, gas share of energy consumption, renewable electricity share, and

carbon footprint are sourced from reports and data provided by the organisations. In all case studies, the measures planned for implementation include demand reduction and efficiency measures, as well as measures that address the high thermal loads associated with the manufacture of medical devices and pharmaceutical products, which include waste heat recovery and the new technologies in the form of heat pumps and thermal energy stores. The share of energy savings attributed to demand reduction, efficiency, and thermal measures for each organisation is shown in Table 8.1 to explain the model outputs discussed in the following paragraph.

Table 8.1: Case study data – Annual baseline energy and emissions data

Parameter	Org A	Org B	Org C	Org D	Org E
Industry type – Medical device (M) or Pharmaceutical (P)	M	P	P	M	P
Energy consumption (MWh)	146 067	56 053	24 093	53 099	32 300
Gas share of energy consumption (%)	25%	66%	56%	13%	49%
Renewable electricity share (%)	100%	50%	10%	100%	0%
Carbon footprint (tCO_2e)	7 946	10 331	5 223	2 609	8 431
Share of energy savings from demand, efficiency, & thermal measures (%)	70%	38%	56%	50%	30%

The energy consumption of the medical device organisations is higher than that of the pharmaceutical organisations, but definitive conclusions cannot be drawn without context and additional information. Gas consumption can be used as a proxy for thermal loads because the case study organisations are yet to electrify their thermal loads; this proxy can be applied across the industrial sector since the case

study organisations are decarbonisation leaders and are indicative of the level of adoption of electrification. Thus, the gas share of energy consumption values indicate that the pharmaceutical organisations have higher thermal-electrical load ratios. This is attributed in part to more stringent temperature, humidity, and HVAC controls [186]; and the requirement for onsite sterilisation in contrast to medical device manufacturing facilities where steam-based sterilisation may occur at post-production facilities rather than on site [186].

The outputs from the project-based modelling tool (with interactions) are shown in Table 8.2 for the five case studies. The cumulative implementation costs of emissions-reduction measures and the cumulative financial savings (excluding carbon offset savings) at the carbon neutrality target year of the five-year plan are indicated. On observation, it is clear that Organisations A and B exhibit similar emissions abatements; however, the latter has a considerably higher implementation cost. This is predominantly attributed to the higher proportion of new technology measures in Organisation B, which have a higher cost per MWh saved. Although direct comparisons can be made given the emissions similarities between these two organisations, two additional metrics are defined for comparison between all organisations—implementation cost intensity and cost savings intensity; these refer to the cumulative costs and financial savings, respectively, per cumulative emissions savings. Analysis of the input sheets of each organisation indicates that the implementation cost intensity is dependent on the organisation's electrical RES. For electrification measures, the emissions savings comprise savings attributed to the decrease in gas consumption as well as possible negative savings (additional emissions) attributed to the increase in electrical load. This means that an organisation using 100% renewable electricity has higher emissions savings and thus a lower implementation cost intensity than an organisation with no renewable electricity for the same measure. Consequently, the implementation cost intensity should decrease with increasing electrical RES. The implementation cost intensity is also dependent on the proportion of emissions-savings measures that reduce demand, improve efficiency, and recover heat; these measures typically have a lower cost intensities than new technology measures where the investment costs can be

substantial. Consequently, the implementation cost intensity should increase with decreasing proportion of these measures. Organisation A has the lowest implementation cost intensity since it operates with 100% renewable electricity and has the highest proportion of demand, efficiency, and thermal measures. Conversely, Organisation E has the highest implementation cost intensity since it operates with no renewable electricity and has the lowest proportion of demand, efficiency, and thermal measures. Organisations B, C, and D have varying electrical RES and proportions of demand, efficiency, and thermal measures, which cause the implementation cost intensities to fall within the minimum and maximum value range of Organisations A and E. The cost savings intensity is dependent on the share of renewable electricity; the proportions of fuel savings; the proportion of emissions-savings measures that reduce demand, improve efficiency, and recover heat; and variations in fuel costs, particularly the high variations in renewable electricity attributed to the PPA terms negotiated by each organisation. There are a number of factors responsible for the large difference in cost saving intensity of Organisations A and B. Organisation B is on a higher gas tariff than Organisation A and its overall electricity cost is almost double; this means a higher cost savings for the same energy reduction. In Organisation B, the share of efficiency projects is low and the majority of savings are from new technology measures which have emissions savings from gas reduction with an associated increase in emissions since it only operates with 50% RES; this means that that the overall emissions savings are low compared to an organisation operating with 100% RES like Organisation A. The increased cost savings and lower emissions savings of Organisation B yield a higher cost savings intensity, which is compounded by using the values at the five-year point of the roadmap.

Table 8.2: Case study data – Modelling tool output

Parameter	A	B	C	D	E
Industry type	M	P	P	M	P
Implementation cost (€)	€ 2 747 746	€ 6 280 287	€ 3 446 713	€ 665 000	€ 5 376 714
Emissions abated (tCO_2e)	7946	7117	2 259	868	2 512
Implementation cost intensity (€/tCO_2e)	346	1036	1 526	1285	2230
Financial savings (€)	€ 4 218 449	€ 13 681 000	€ 2 131 632	€ 941 923	€ 1 257 255
Cost savings intensity (€/tCO_2e)	€ 531	€ 1 922	€ 944	€ 1 085	€ 500

These cost and savings intensities can be used as scaling metrics to quantify the financial impact of a carbon neutral industrial sector. The scaling scenarios are defined based on the applicability of the case studies to the LIEN industrial sector organisational groups discussed in the following section.

8.5 LIEN Sector Analysis

The LIEN energy efficiency network comprising decarbonisation leader organisations is used as the basis for scaling. A breakdown of LIEN organisations and their TPER contributions by sector are shown in Figure 8.2. Further details specific to each sector are provided in the following sub-sections, along with an evaluation of their applicability for scaling using the case studies.

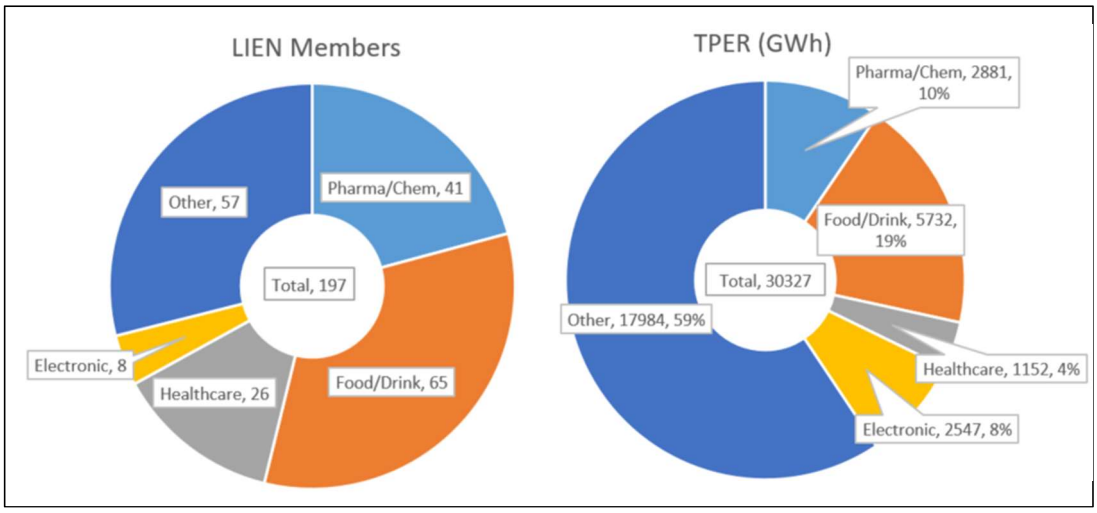


Figure 8.2: LIEN sector breakdown (2022): (a) Membership; (b) TPER contribution

8.5.1 Pharma/Chem

The Pharma/Chem category comprises organisations responsible for manufacturing active pharmaceutical ingredients, finished dosage forms, vaccines, and various chemicals. Typical pharmaceutical and chemical industrial processes include chemical synthesis, fermentation, bioprocesses, blending, granulation, compression, coating, encapsulation, separation, drying, sterilisation, purification, and reactions [187] [188]. These processes often require high grade heat in the form of utility steam, chemical-free steam, and clean steam [189]. In addition, all manufacturers require a highly regulated manufacturing environment with strict controls to guarantee product safety and efficacy. Further, pharmaceutical and chemical manufacturing produces waste materials including volatile organic compounds and active pharmaceutical ingredients which pose a hazard to site and worker safety; this results in high ventilation requirements. As such, all manufacturing facilities within this category are expected to have high HVAC loads in the region of 50 – 80% [190] to ensure safety through strict temperature and humidity control, local exhaust ventilation systems, full fresh air ventilation zones, HEPA filtration systems, and negative pressure zones. Some common opportunities for increased energy efficiency within this category are thermal oxidation heat recovery, switch to greener solvents, investment in solvent recovery systems, and a switch from batch processing to continuous processing. Organisations in the Pharma/Chem category contribute 9.5% of the LIEN network's TPER [183]. Organisations B, C and E are included within

this category and are thus representative of the type and level of energy-related activities and the technologies employed.

8.5.2 Food/Drink

The Food/Drink category includes organisations responsible for the manufacture and processing of beverages, dairy, meat, poultry, seafood, grains, confectionery, fruit & vegetables, pet food, condiments, and frozen foods [191]. Typical processes include pasteurisation, homogenisation, canning, extrusion, freeze-drying, fermentation, sterilisation, and drying [191]. Although organisations in this category have varied manufacturing processes and regulatory requirements, they typically have high thermal loads (74% of total load) which can be categorised as approximately 23% low grade heat, 59% medium/low grade heat, and 18% medium grade heat [149]. Based on Madeddu et al.'s electrification technology options for industry [150], this heat profile facilitates the adoption of heat pumps to address 82% of the thermal load, with the remaining load addressed by electric boilers. Although the case studies are not directly applicable to this category, the high thermal loads and new technology options align with those of the modelled organisations. Food/Drink is the largest dedicated LIEN category and comprises 18.9% of the network's TPER [183].

8.5.3 Healthcare

The Healthcare category comprises organisations responsible for the manufacturing of medical devices. Typical processes include injection moulding, metal heat treatment, machining, extrusion, cutting, sintering, 3D printing, and sterilisation [192], some of which are high-heat processes which indicate high thermal loads. Organisations in the Healthcare category contribute 3.8% of the LIEN network's TPER [183]. Organisations A and D are included within this category and are thus representative of the type and level of energy-related activities and the technologies employed.

8.5.4 Electronics

The Electronics category comprises organisations responsible for the manufacture of consumer devices, and this category contributes 8.4% of the LIEN network's TPER

[183]. The loads are predominantly electrical (approximately 80%) rather than thermal [148], and thus electronics organisations are not well-represented by the case studies.

8.5.5 Other

This is the largest category in terms of the number of members and the LIEN network TPER contribution (59%). It comprises a broad range of industries such as banks, retail, data centres, cement manufacturing, and refineries. As such, the industrial processes and technologies employed are expected to vary considerably with high electrical loads in data centres and high thermal loads in refineries.

8.5.6 Summary

The categories of Healthcare and Pharma/Chem together comprise 13.3% of the LIEN network's TPER, and are deemed applicable for scaling as their load profiles and electrification new technology options align with those of the case study organisations which all fall within these categories. Of the LIEN categories that are not represented by the case studies, Food/Drink is likely to have the most similar decarbonisation measures owing to its high thermal load and suitability for similar electrification technologies. The Electronics category is not well represented, but only comprises a small share of the TPER. The loads and suitable decarbonisation measures for organisations within the Other category are unknown at the organisational level, and the applicability of the case studies to this category is difficult to determine. Specific scaling scenarios are developed based on the case study applicability to the LIEN categories, and these scenarios are discussed further in the following section.

8.6 Scaling metrics and scenarios

The implementation cost and savings cost intensities provide an indication of the financial impact of the decarbonisation of similar organisations. These metrics must be scaled to the industrial sector based on similarities at the organisational level or at the category level.

8.6.1 Scaling at the organisational level

The energy consumption and emissions data of individual LIEN organisations are proprietary information and are thus unavailable for organisations outside of the case studies. However, there are a number of organisational parameters that are publically available in most cases and could be used to generate an industry sector model. This is based on matching individual organisations to a single case study, thereby creating groups of organisations aligned with each of the five case studies. The total carbon footprint per group would be calculated using the number of organisations in the group and the average organisational emissions for the LIEN category. Then, the implementation cost and cost savings for each group would be scaled using the total carbon footprint and the implementation cost and cost savings intensities of the relevant case study. Finally, the costs and saving per group would be summed to determine the financial impact of decarbonising the industrial sector. The following organisational parameters are considered for scaling at the organisational level:

- Facility size – For organisations manufacturing similar products, the facility size may provide an indication of the site's energy consumption. However, even within each category of the case studies (Pharma/Chem and Healthcare), the facility size is highly dependent on the product type and the portions of the site dedicated to storage, logistics, and R&D, as well as the regulatory requirements which determine the areas required for waste treatment plants and clean rooms. Thus, facility size is not considered a good indicator of energy consumption.
- Staff size – The staff size varies considerably between different categories as well as between organisations within the same category. Staff size is based on a number of factors such as the energy intensity of the manufacturing processes, the level of automation of the production lines, the level of staff-intensive activities such as product assembly, and the number of additional staff employed in aligned activities such as R&D. Thus, employee number is not considered a good indicator of energy consumption.

- Revenue – For organisations manufacturing similar products, the revenue may provide an indication of the site's energy consumption. However, even within a single LIEN category, revenue is highly diverse as a result of product demand, competition, market share, regulations and compliance, and consumer behaviour in the case of certain medical devices with direct customer sales. Thus, revenue is not considered a good indicator of energy consumption.

In the absence of a reliable organisational parameter with which to scale individual organisations, scaling on a LIEN category basis is explored in the following section.

8.6.2 Scaling on category basis

The total emissions attributed to each LIEN category are known, and these can be used to determine the investment cost required for decarbonisation. These emissions need to be matched for scaling according to the most applicable case study or a combination of case studies. As highlighted in section 8.4, the implementation cost is dependent on the renewable electricity share which is known for each LIEN category, as well as the proportion of demand reduction, efficiency, and thermal measures which is site-specific data resulting from detailed energy audits and is thus not available for the LIEN categories. However, the fuel breakdown is available at the category level; the gas share of an organisation's total energy consumption may affect the implementation costs since a high reliance on gas likely indicates high thermal loads. Consequently, linear and multiple linear regression analysis was conducted to explore the prediction capability of the implementation cost intensity using the electricity RES and the gas share as the independent variables. RES has a high correlation to emissions (r^2 of 0.79) and gas share has a lower correlation (r^2 of 0.19), and together they yield a good prediction (adjusted R^2 =0.89). While it appears that the implementation cost could be reliably predicted, the case study sample size does not meet the lower bound rule-of-thumb of ten data points required per predictor variable for regression analysis [193]. As such, this exercise serves to highlight that these parameters affect the cost of industrial decarbonisation. Consequently, the implementation costs are calculated as a range using the cost intensities for all case studies rather than a distinct value predicted from the

regression analysis. This is considered acceptable given that the intention is to provide an indication of the scale of investment. As such, the following two scaling scenarios are envisioned for the organisations in the LIEN categories.

- Scenario 1: Individual LIEN Groups (Pharma/Chem and Healthcare) – Organisations in these categories are identified as most closely aligning with the case study organisations. Each category is evaluated separately by scaling the values for each applicable case study organisation using the total category emissions to generate a range of cost and savings. Then, the results are combined for the full scenario as 'LIEN 1'.
- Scenario 2: LIEN All – This scenario expands scenario 1 to include all LIEN organisations which is reflective of the full industrial sector. The organisations in the additional categories are likely to have different load and heat profiles, and may require specific technologies for decarbonisation. This category is expected to have a lower level of accuracy owing to these differences. Consequently, the emissions intensities of all five organisations are used to generate a range of cost and savings values.

8.7 Results & Discussion

The inputs and results for scenarios 1 and 2 are shown in Table 8.3. The analysis indicates a total investment in the range of € 620 million – € 1.84 billion to achieve carbon neutrality in the Pharma/Chem and Healthcare categories combined, which comprise 13% of Ireland's TPER. The analysis further indicates an investment cost range of € 2 – 10 billion to achieve a carbon neutral industrial sector. This broad range is attributed to the sensitivity of the model to electrical RES and gas share of energy consumption; accordingly, sensitivity analysis is discussed in section 8.7.1. However, the lower end of this range is in line with the required €3 billion investment in key technologies to decarbonise the industrial sector estimated in CAP 2023 and reiterated in CAP 2024 [21]. The cumulative financial savings and the ROI at the carbon neutrality target year are shown for comparison, and indicate that investment in carbon neutrality may yield financial benefits at the five-year point, although savings are expected to increase substantially following the carbon neutrality target year owing to carbon offset savings.

Table 8.3: Scenario 1: LIEN scenario analysis

	Scenario 1			Scenario 2:
	Pharma /Chem	Healthcare	LIEN 1	All LIEN members
Total emissions (tCO_2e)	729 584	275 730	1 005 315	5 018 000
Calculated cumulative implementation cost (€)	€ 0.52-1.63 billion	€ 95-211 million	€ 0.62-1.84 billion	€ 2.0-10.0 billion
Calculated cumulative financial cost savings at end of year 5(€)	€ 354-966 million	€ 146-299 million	€ 0.66-1.1 billion	€ 2.67-3.24 billion
ROI at year 5	-0.78-0.86	0.42-0.54	-0.64-0.81	-0.75-0.62

8.7.1 Sensitivity analysis

In this work, observation and regression analysis show that the electrical RES and the gas share both affect the cost intensity of an organisation; this may indicate that a sensitivity analysis should be conducted on these variables. However, the observations were determined by evaluating each organisation as a singe data point. The relationships between each of these variables to the cost and savings intensities within a case study are complex and non-monotonic since there are non-linear interdependencies between input variables. The total implementation cost of all measures is determined by scoped projects identified from an in-depth energy audit; these measures are specific to the organisation based on its significant energy uses and fuel breakdown. Changing parameters to test the model sensitivity of a specific organisation alters the entire decarbonisation roadmap to the point where the roadmap is not reflective of a likely situation; in reality, new measures would be defined and costed to suit the new fuel supply. For instance, increasing the RES of a particular organisation to test the sensitivity may change the measures prioritised for emissions reduction—an organisation with low electrical RES may have a large number of electrical efficiency or demand reduction projects which may no longer be deemed relevant at high RES. Conversely, reducing the RES of an organisation operating with 100% renewable electricity may negate the planned investment in electrification technologies. For these reasons, a sensitivity analysis is not conducted

in this work. However, it is noted that the electrical RES and gas share affect the types of measures planned for implementation. The most effective way of including these effects is to conduct further case studies to increase the number of data points and strengthen the regression analysis to make reliable cost predictions.

8.7.2 State supports

There are several state supports available directly at the organisational level for industrial decarbonisation strategies; these are shown in Table 8.4 with the decarbonisation areas that they address. The Department of Enterprise, Trade and Employment facilitates a Green Transition fund with an allocation of €55 million over the five-year period 2022-2026 [194]. In June 2024, the department announced the provision of €300 million available until 2030 for industrial decarbonisation; this is facilitated through the Environment Aid Scheme [195]. The Department of Environment, Climate and Communications provided €81 million in business support from 2019-2023, facilitated through the SEAI, and an amount of €56 million has been allocated for 2024 [195]. The increasing amounts available and the development of new funds indicate the government's acknowledgement of the scale of the challenge of industrial decarbonisation. However, the total support value of € 411 million leaves a deficit of at least € 1.6 billion (80%) to be borne by organisations, based on the predicted minimum requirement of € 2 billion to decarbonise the industrial sector.

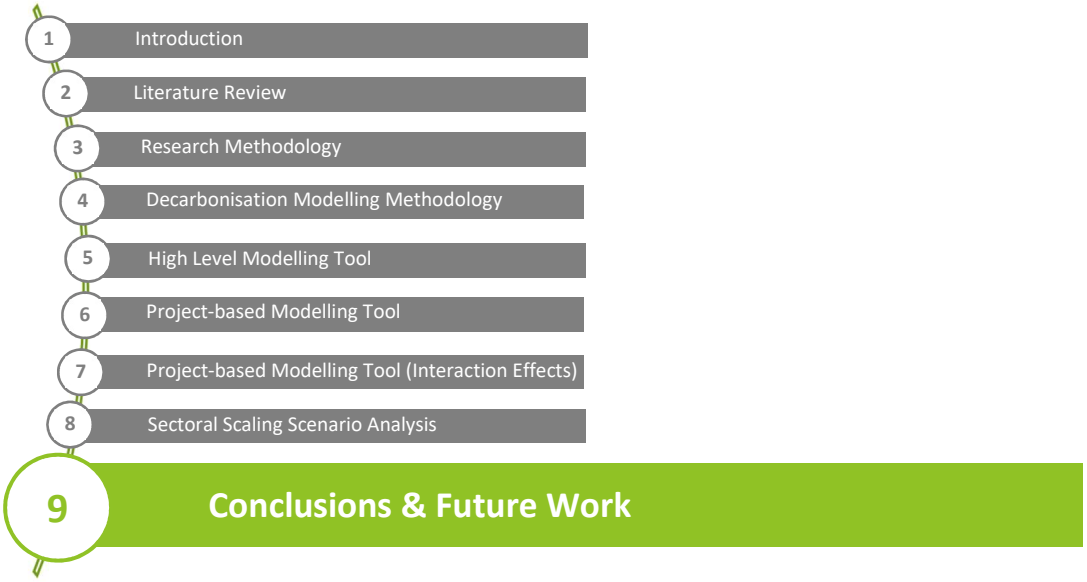
Table 8.4: Financial state supports for industrial decarbonisation

Support scheme	Energy Efficiency	Electrification	Biomass	Biomethane	Fund Value € million	Governing Body
Green Transition Fund	✓	✓	✓	✓	€ 55	Department of Enterprise, Trade and Employment
Environment Aid Scheme	✓	✓	✓	✓	€ 300	
SEAI Community Grant (non-domestic)	✓	✓	✓	✓	€ 23.5	Department of Environment, Climate and Communications
SEAI Support Scheme for Energy Audits	✓				€ 3.2	
SEAI Support Scheme for Renewable Heat		✓	✓		€ 4.6	
SEAI Excellence in Energy Efficiency Design		✓	✓		€ 4.6	
SEAI Non-domestic Microgeneration		✓			€ 17	
SEAI Non-domestic Retrofit	✓				€ 2	
SEAI Advisory Support					€ 0.9	
Total support value					*€ 411*	

8.8 Conclusions

Five case studies were leveraged to scale the financial impact of achieving carbon neutrality from the organisational to the sectoral level. The metrics of implementation cost intensity and cost savings intensity were used as a basis for the scaling. The LIEN industrial categories were analysed to define two scaling scenarios based on similarities in energy-related activities and potential new technology solutions to the case study organisations. The calculated total investment cost range of € 2 – 10 billion required across the industrial sector to achieve carbon neutrality is affirmed by the proposed investment value in CAP 24. It should be noted the CAP 24 value was calculated using top-down modelling; the investment range determined from the case study predictions in this work highlights the importance of developing bottom-up models for the industrial sector in conjunction with top-down models to gain a more representative model. The corresponding ROI range at the five-year marks indicates that the investment in these emissions-reduction projects and predominantly electrification technologies is not only environmentally and politically

beneficial, but may also be financially advantageous, particularly after the carbon neutrality point. However, it should be noted that the financial analysis in this study is based on individual measures from a limited number of case studies confined to two industry categories. There is no consideration of renewable energy share increases in utility energy or in the quantity of renewable energy sourced by the organisation. In addition, organisations are at various stages of decarbonisation where some may have high scope for energy and emissions reduction through more economical energy efficiency, demand reduction, and heat recovery projects, while other organisations may have implemented many of these already. As such, the model deployment and scaling scenarios presented provide a broad indication of the level of investment required to decarbonise the industrial sector, as well as the associated financial savings. This bottom-up approach could benefit from an increased number and broader range of case studies. However, there is currently limited access to data at the organisational level since the LIEN is a voluntary body with private submissions by member organisations. The only available data in the public domain is the annual Energy in Ireland report and National Energy Balance which indicate fuel breakdowns and loads at the industry sub-sector level, where the sub-sectors do not align with the LIEN categories. Future work could involve collaborating directly with the SEAI to gain access to additional data to generate a more accurate and reliable bottom-up industry sector model. The increased confidence of the predictions will enable the model to be used to inform policy applicable to Ireland's industrial sector. This is valuable since current state supports only cover a maximum of 20% of the predicted investment required to achieve a carbon neutral industrial sector.



9.1 Summary of Research

There is increasing regulatory, financial, and social motivation for industrial decarbonisation at the organisational level. Organisations may have robust energy, environmental, and quality management systems which play an important role in reducing energy consumption, environmental impact, and waste, respectively. While these three management systems have distinct focus areas, synergies between these systems can systematically enhance these reductions to support broader decarbonisation objectives and improve the overall organisational performance. Synergies include data-driven decision-making based on the monitoring of key performance indicators to optimise resources; process optimisation and efficiency to reduce waste and thereby energy consumption; and supply chain management to ensure sustainable supplier selection and energy-efficient procurement. However, the key connection between these management systems is that their governing standards are underscored by structured, continuous-improvement processes utilising the Plan-Do-Check-Act cycle, where actions plans are specified in the Plan step to improve energy performance. However, these standards are frameworks that form the foundation on which industrial organisations develop their own procedures and processes, and they do not provide explicit technical guidance relevant to action plan development and decarbonisation planning. Accordingly, the overarching aim of this thesis is to advance existing technical support available to non-EII Irish

organisations targeting carbon neutrality. This subject area was highlighted as an industry need through collaboration with industry partners who have carbon neutrality commitments and are facing challenges with regard to developing pathways to carbon neutrality and evaluating scenarios to determine the best options for implementation. The scientific challenge of this industry need was confirmed through a thematic literature review which found that deep decarbonisation is an emerging research field with a high potential for further investigation and advancement. Accordingly, the following research questions were defined to assess the current academic, public, and commercial offerings in terms of carbon neutrality methodologies and modelling tools:

RQ1 *– What methodologies exist to support industrial organisations in achieving carbon neutrality?*

RQ2 *– What existing mathematical and commercial modelling resources are applicable to individual organisations, and what level of detail do they contain?*

RQ3 *– How do existing modelling resources consider the interactions between emissions-reduction measures?*

A thorough thematic literature review was conducted in chapter 2 in respect of these research questions, and this lead to the determination of four specific research objectives to cement the research scope and to provide a foundation from which to assess the success of the research outcomes. A six-step, mixed-methods research methodology was proposed in chapter 3 to structure the research and align it with the defined research objectives; this includes a scrum software design methodology to provide a known, accepted structure for the development of the modelling toolkit.

9.2 Research Conclusions According to Objectives

Four specific research objectives were defined in response to these research questions to support the overarching aim of this work. Conclusions and contributions with respect to each objective are presented in the following sub-sections.

RO1 *– Development of a methodology to aid non-EII industrial organisations in achieving carbon neutrality*

A nested methodology was developed for applicability at different stages of the carbon neutrality journey for non-EII organisations across different industrial sectors with varying budgets and energy management strategies. The top tier comprises a high-level methodology for early-stage planning and the bottom tier comprises a detailed methodology for detailed planning. The high-level methodology offers guidance for organisations in the initial or exploratory stages of carbon neutrality, and uses readily available site data. It incorporates a high-level modelling tool that generates a carbon neutrality roadmap and financial analysis. The aim of this is to provide sufficient motivation for organisations to invest in gathering more detailed site-specific data which is required to follow the detailed methodology. This detailed methodology is a hybrid DMAIC-SIPOC continuous improvement approach in which the define step involves calculating the carbon footprint; the measure step ensures that accurate and appropriate measuring and monitoring systems are in place; the analyse step involves detailed studies to generate potential emissions-reduction projects and renewable energy strategies; the improve step contains a detailed modelling tool that generates an organisation-specific carbon neutrality waterfall and financial analysis; and the control step involves monitoring progress towards emissions reduction along the carbon neutrality timeline with the implementation of the identified measures, and adjustment of the carbon neutrality roadmap where necessary. The proposed methodology addresses the research gap of an open-access, detailed, cross-sectoral methodology with reference to a modelling tool.

RO2.1 *– Development of a high-level modelling tool to aid non-EII industrial organisations in early-stage carbon neutrality planning*

A high-level modelling tool was developed for non-EII organisations in the initial stages of exploring carbon neutrality, with the aim of combatting green stagnation. The modelling tool uses readily available site-level data to generate a five-year carbon neutrality roadmap and a 15-year financial analysis. This is based on measures prioritised in the order of demand reduction, energy efficiency, heat pump adoption to address hot water loads, electric boiler

adoption to address steam loads, renewable electricity, and finally carbon offsetting of the remaining emissions. The case study applied indicated an accuracy of 25%. Although this is not considered highly accurate and the results are expected to vary considerably across organisations, the models generated provide a broad indication of the scale of investment required to target carbon neutrality. This is deemed sufficient since the intention is to motivate organisations to invest in more in-depth studies to gather data for more detailed carbon neutrality modelling. The development of this modelling tool successfully addresses the issue of green stagnation by progressing the carbon neutrality journey without the need for investment in costly exploratory studies needed for more detailed planning.

RO2.2 *– Development of a detailed, project-based modelling tool to aid non-EII industrial organisations in carbon neutrality planning*

A detailed, project-based modelling tool was developed to generate an organisation-specific carbon neutrality roadmap and financial analysis. This is based on site data gathered from energy audits, heat studies and renewable energy studies in accordance with the detailed methodology. The key user input is the list of current and future emissions-reduction measures, with additional inputs in the form of targets and scenarios, baseline site data, production forecasting, planned carbon offsetting, scope 3 emissions reductions, and costing. Verification of the modelling tool using industry representative data confirmed the accuracy of the modelling tool against the mathematical model. This modelling tool bridges the research and development gap between modelling tools aimed at the country or regional level, and commercial proprietary carbon-management software that are aimed at industrial organisations but do not appear to offer detailed and structured roadmaps to carbon neutrality but rather focus on carbon accounting and offering general independent decarbonisation options. However, validation of the modelling tool by means of an industry partner case study indicated that the interaction effects between emissions-reduction measures should be considered to improve the applicability of the tool.

***RO3** – Method for the resolution of interaction effects between emissions-reduction measures in a modelling tool to aid non-EII industrial organisations in planning carbon neutrality*

A methodology was developed to resolve the interaction effects between emissions-reduction measures using a heuristic approach. This was based on investigation into typical industrial processes within emissions-producing activities. A set of rules was developed for each activity and included in the modelling tool. Three case studies were leveraged to assess this rule-based method, and substantial differences were found on comparison with the models generated without consideration of interaction effects. Emissions abatement was overestimated by 43 – 56% in the models without interactions; this level of inaccuracy may jeopardise the achievement of carbon neutrality; similarly, the financial errors in the case studies are significant indicating that ignoring these interaction affects can greatly affect financial planning. It was concluded that the modelling tool including the interaction effects ruled-based system lead to improved models that were more reflective of actual scenarios. This method and its inclusion in the project-based modelling tool addresses the issue of overestimation of emissions reductions in carbon neutrality planning.

As part of this research objective, these case studies along with an additional two case studies were deployed to develop a bottom-up financial model of the industrial sector to analyse the impact of achieving industrial carbon neutrality. The metrics of implementation cost intensity and cost savings intensity were used as the basis for scaling within two scenarios of LIEN industrial categories; these categories were defined considering similarities in energy-related activities and potential new technology solutions. The results indicated a required investment of €2 - €10 billion at the organisational level to achieve carbon neutrality of the industrial sector, and the lower end of this range is in line with the investment costs proposed in CAP 24. This validates the potential for the modelling tool to be used as a decision support system to guide industrial policy. In addition, the gap between the current financial state supports and the investment required to achieve a carbon neutral sector

highlights the importance of developing bottom-up industrial sector models. In particular, the integration of bottom-up and top-down models provides a comprehensive understanding of Ireland's industrial sector; this knowledge allows for informed decision-making with regards to sectoral financial investment and infrastructure requirements such as electrical grid upgrades. Thus, bottom-up models scaled from the organisational level are a key contribution to meet multiple industrial sector planning needs.

The research objectives were met, and consequently the overarching aim of providing technical support to non-EII Irish organisations targeting carbon neutrality was achieved. The carbon neutrality roadmaps generated through the proposed methodology and modelling toolkit can be embedded into the action plans of organisations' integrated management systems. In addition to the research outputs discussed in the body of this thesis, a systematic mapping study was conducted to analyse research trends in total site heat integration. While this is not pertinent to the work presented, it provides a potential basis for future work regarding the optimisation of heat streams to reduce emissions. The research gaps, contributions, and corresponding journal outputs are shown in Table 8.1. However, these contributions should be interpreted with regard to the limitations and threats to validity of the work.

Table 9.1: Research contributions

Research gap	Contribution	Research Output
Analysis of research trends in total site heat integration	Overview of total site heat integration and mapping of the literature	Journal Article 1: *'Total Site Heat Integration in Carbon Neutral Industrial Manufacturing – A Systematic Mapping Study'*
Open-access, detailed, cross-sectoral methodology with reference to a modelling tool	Methodology to aid non-EII industrial organisations in achieving carbon neutrality	Journal Article 2: *'Methodology for Carbon Neutrality in Industrial Manufacturing'*

Open-access modelling tool aimed at the organisational level with consideration of demand and supply side measures	High-level modelling tool applicable to early stage carbon neutrality planning	
	Detailed project-based modelling tool applicable to organisations at the point of detailed carbon neutrality planning	Journal Article 3: *Development of a Modelling Tool to Aid the Transition to Carbon Neutral Industrial Manufacturing*
Heuristic, bottom-up, universal method of considering interaction effects based on industrial processes	Methodology to resolve the interaction effects between emissions-reduction measures using a heuristic approach, and inclusion of these effects in the model	Journal Article 4 – submitted: *'Methodology for the Resolution of Interaction Effects Between Emissions-reduction Measures in Carbon Neutrality Modelling'*
	Quantification of the potential financial impact of achieving a carbon neutral industrial sector	

9.3 Research limitations & threats to validity

This work is subject to general limitations relating to the intention and boundaries of the work, and threats to validity in the form of factors that affect its accuracy.

9.3.1 General limitations

This following general limitations apply to this work.

- *Geographical constraints* – The modelling toolkit was developed for application in Ireland as the emissions factors inherent to the modelling tool represent the Irish grid and utility supplies. However, this can be adapted for alternative geographic regions.
- *Rebound affects* – Energy efficiency measures may be subject to rebound effects in which the resulting energy reductions achieved are less than

predicted as a result of behavioural changes [149]. These rebound affects are partially mitigated within the methodology by framing the carbon neutrality roadmap as a continuous improvement process. The predicted emissions balance is adjusted after implementation of each measure, allowing the roadmap to be adjusted to include additional measures if necessary.

- *Inclusion of scope 3 emissions* – This emissions category is the biggest contributor to GHG emissions; although the tool allows for scope 3 emissions reduction projects to be entered as emissions reductions, it does not directly calculate these emissions from source data. Scope 3 emissions-reduction measures may affect scope 2 emissions. These interactions are not considered in the modelling tool as they are not covered by the GHG Protocol for typical emissions-producing activities from which the interaction rule-based method was developed.
- *Optimal sequence of projects* – The projects modelling tool generates the carbon neutrality roadmap and financial analysis based on measures input in for implementation in specific time periods defined by the user. This may not represent the optimal sequence of projects to maximise emissions reduction and financial gain.
- *Carbon offsetting* – The modelling tool generates a model based on user input, and thus assists in planning carbon neutrality within the boundaries of user-defined projects and renewable energy uptake, and does not influence the level of remaining emissions to be offset. It also does not offer recommendations with regard to verified offset projects to mitigate the risk that user-sourced projects may be on paper only owing to poorly verified offset projects.
- *World events* – Unpredictable events beyond the organisational boundary can have a considerable effect on the predicted financial savings, such as the natural gas price increases associated with the war on Ukraine.
- *Non-energy benefits* – The implementation of energy efficiency measures may yield non-energy benefits. The methodology and modelling toolkit inherently include some of these non-energy benefits in the form of

emissions reduction and financial benefits as the focus of this work, as well as renewable energy. However, additional benefits in the form of increased productivity and benefits relating to broader sustainability such as waste reduction and improved working environment are not considered.

9.3.2 Threats to validity

This following threats to validity apply to this work.

- *Data input errors* – The accuracy of the generated outputs of the modelling tools relies on the accuracy of the user input. Misrepresentation of the organisation's energy and emissions data through accidental errors or misunderstanding of the input required can lead to the generation of inaccurate models.
- *Algorithmic errors* – Errors in the Python code can cause incorrect output to be used as a basis for decision-making. However, the project-based modelling tool was verified against the mathematical model using representative dummy data and all modelling tools were subject to regular code reviews in an attempt to mitigate errors.
- *Complex interactions* – Interactions between emissions-reduction measures implemented on site are complex, and there are likely to be numerous smaller systems subject to interactions that are not captured within the rule-based system.
- *Case study sample size and bias* – Three case studies models were deployed for scenario analysis to determine the financial impact of achieving a carbon neutral industrial sector. This sample size was constrained by the data available through industry partner organisations, and all case studies were in similar industrial sectors which introduced sample bias. While the calculated cost aligned with the figure proposed in CAP 24, additional multi-sectoral case studies would increase the accuracy of the prediction.

These limitations and threats to validity serve as a basis for the development of future research.

9.4 Proposed further research

Two parallel streams of future work with regards to the modelling toolkit are envisioned—the first is the progression of the current modelling tools, and the second is the development of a new tool with a different focus. Additional future work is envisioned to enhance the accuracy of the sectoral scaling scenario analysis based on industrial case studies to develop a bottom-up model of Ireland's industrial sector. This future work is illustrated in Figure 8.1 and discussed in in the following sub-sections.

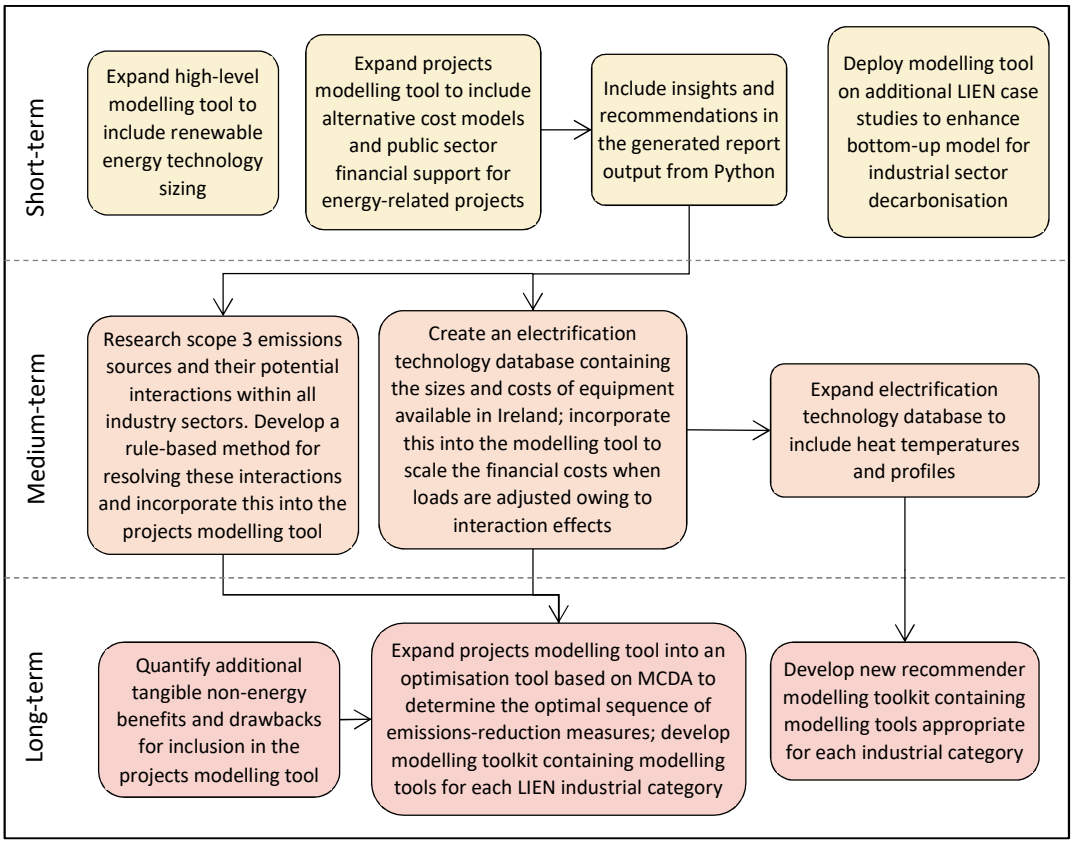


Figure 9.1: Proposed future research

9.4.1 Progression of existing modelling tools

Each of the modelling tools within the toolkit can be progressed to improve the functionality without changing the intention of the tool.

9.4.1.1 *High-level modelling tool*

Limited progression is proposed for the high-level modelling tool as additional complexity compromises its role as a simple tool for early stage planning. However,

additional information regarding renewable electricity could be generated to aid decision making in terms of pursuing carbon neutrality. The physical extent of the renewable energy technology could be quantified in terms of space required for the installation of solar PV, and the number of wind turbines and corresponding space required in the case of wind energy. This provides a means to assess if the renewable energy strategy selected is viable.

9.4.1.2 *Project-based modelling tool*

Consideration of non-energy benefits and drawbacks beyond those inherently included in the project-based modelling tool would allow a more comprehensive evaluation of the true investment value of proposed emissions-reduction measures. This allows for more informed decision-making. Tangible non-energy benefits are more easily quantifiable and are planned for future inclusion in the modelling tool. The effect of intangible, broad sustainability benefits on investment value is an interesting and relevant area for future investigation. However, the qualitative nature of these benefits means that significant exploration is required to assess the quantifiability of these benefits prior to inclusion in the model. This can be viewed as a distinct but aligned research direction with the potential for future collaboration; however, it is not recognised as a priority for future work at this stage.

The project-based modelling tool includes a rule-based system for interactions based on typical emissions-producing activities representative of high-level industrial processes. However, these rules can be expanded for each industry category to consider interactions in greater depth by investigating typical processes used in each industry. Consequently, a project-based modelling tool can be developed for each industry category. Then, the following improvements can be made to these modelling tools:

- A basic financial approach is used in the modelling tools whereby the full investment cost in projects is paid at the point of implementation. However, this may not reflect the financial strategy of the specific organisation, especially in the case of investment in costly electrification technologies. Alternative cost models can be explored to include different financial

instruments such as loans, bonds, leasing, and energy performance contracting.

- The modelling tool includes an input for business grants which are deducted from the implementation cost. A register of relevant and current public sector programmes can be included within the modelling tool as a means to automatically reduce the implementation costs where appropriate.
- The rule-based interaction method can be expanded to include scope 3 emissions to future proof against the inclusion of all scope 3 emissions for carbon neutrality. This involves extensive research into typical sources of scope 3 emissions, which may differ for each industrial sector, and how they may impact scope 1 and 2 emissions activities.
- A database of electrification technologies (heat pumps, electric boilers, thermal energy stores) available in Ireland can be developed through supplier quotes. This can be used to match the investment cost of technologies in cases where the load has decreased with the consideration of interaction effects. This is an improvement on the current pro-rata costing method in the interaction model since the cost will be matched to a specific equipment size with an appropriate load range.
- The generated report output from Python can be improved to offer insights and recommendations based on the carbon neutrality roadmap and financial analysis.

A further development is the possible incorporation of multi-criteria decision analysis (MCDA) to determine the optimal order of the defined measures. With the current modelling tool, the measures are input by the user and the modelling tool generates a model for each set of user inputs. For comparison of different sets of inputs (e.g. order of measures, inclusion/exclusion of measures), a new user input sheet must be generated manually. MCDA allows for a single user input sheet, from which multiple models can be generated and compared against user-defined criteria (e.g. cost, savings, carbon neutrality target period, emissions reduction). The optimised model can be identified and output from this process. This modelling tool can be viewed as a natural progression from a simulation model to an optimisation model to aid

organisations in making the best decisions with the information that they have gathered.

9.4.2 Next generation modelling tool – Recommender Tool

Future work could include the development of a new tool that acts as an in-depth recommender system for emissions-reduction measures. This differs from the optimisation modelling tool in that it would not require a register of emissions-reduction measures. Instead, it would operate on a similar principle to the high level modelling where there is a defined sequence of approaches, e.g. demand reduction, energy efficiency, electrification, renewable electricity, and offsetting of the emissions balance. However, the recommender tool would explore each category in more depth. In particular, extensive research would be need to be conducted into typical electrification technologies and equipment to address thermal loads. This could be used to build up a database from which to match technologies to the site heat stream temperatures and profiles. In addition, the graphical process integration approach of pinch analysis could be investigated as a method of maximising heat exchange between heat streams based on the thermal data provided. This recommender modelling tool could be adapted to each LIEN industry category to more accurately recommend appropriate technologies.

9.4.3 Enhanced bottom-up model for industrial sector decarbonisation

The sectoral scaling scenario analysis based on case studies could be improved to enhance the confidence level of the prediction. This could be achieved through direct collaboration with the SEAI which would provide access to organisational level data across the LIEN. The modelling tool could be applied to organisations within each LIEN industrial category, where the 'Others' category could be further split into sub-categories. This should provide more accurate scaling scenarios based on specific industrial processes and heat profiles to create an enhanced bottom-up model that more reliably predicts the financial impact of industrial sector decarbonisation.

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Appendix A1 – High Level Modelling Tool – User Input Sheets

Baselines

Parameter	Value
Facility annual operating hours	8760
Annual energy spend (€)	€600,000
Year of most recent carbon footprint	2023
Carbon footprint (tCO2e)	10000
Baseline electricity consumption (MWh)	16300
Baseline gas consumption (MWh)	27581
Baseline oil consumption (kl)	0
Renewable energy source	Solar PV
Thermal output (MWh)	25
Steam proportion of thermal load (%)	50%
Steam boiler fuel	Gas
Steam boiler efficiency (gas)	86%
Hot water proportion of thermal load (%)	50%
Hot water boiler fuel	Gas
Hot water boiler efficiency (gas)	86%

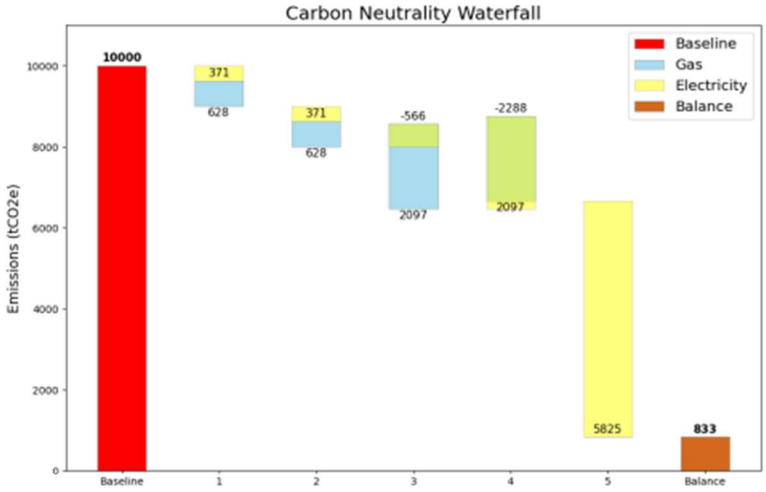
Costs

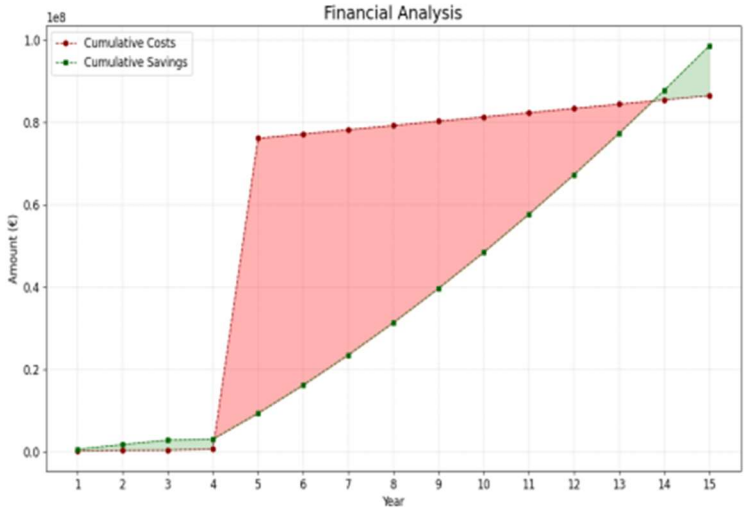
Parameter	Value
Discount rate	4%
Utility electricity cost (€/MWh)	220
Utility gas cost (€/MWh)	59
Utility oil cost (€/kl)	1270
Carbon offset risk option	Low Risk

Appendix A2 – High Level Modelling Tool – Generated Report

Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 03, September, 2024 for the Case Study Organisation .





Appendix B1 – Project-based Modelling Tool – User Input Sheets – Verification

Targets & Scenarios

Parameter	Value
Carbon neutrality plan start year	2025
Carbon neutrality target year	2030
Is carbon neutrality prescribed?	No
Should the proposed future renewable share from the utility provider be included?	Yes

Baselines

Parameter	Value
Year of most recent carbon footprint	2023
Carbon footprint (tCO2e)	5500
Discount rate	4%
Footprint electricity consumption (MWh)	11000
Footprint gas consumption (MWh)	12000
Footprint oil consumption (kl)	8
Any additional fuel to be considered?	Yes
Footprint Additional Fuel consumption (unit)	500
Footprint Additional Fuel emissions factor (tCO2e/unit)	0.100
Electricity market-based emissions factor	Not Applicable
Steam output (MWh) from gas boilers	10000
Steam output (MWh) from oil boilers	0
Steam output (MWh) from electrode boilers	0
Steam boiler efficiency (gas)	90%
Steam boiler efficiency (oil)	100%
Steam boiler efficiency (electrode)	100%
HW output (MWh) from gas boilers	0
HW output (MWh) from oil boilers	0
HW output (MWh) from electrode boilers	5000
HW output (MWh) from heat pumps	0
HW output (MWh) from steam heat exchange	0
HW boiler efficiency (gas)	90%
HW boiler efficiency (oil)	100%
HW boiler efficiency (electrode)	100%
HW heat pump efficiency	100%
Steam-HW heat exchange efficiency	100%
Onsite electrical generation by gas (MWh)	Not Applicable
Efficiency of gas-fuelled generators	100%
Onsite electrical generation by oil (MWh)	Not Applicable
Efficiency of oil-fuelled generators	100%
Is the energy consumption expected to increase owing to production increase or facility expansion over the carbon neutrality timline?	Yes
Are any carbon offset programmes expected to be implemented within the carbon neutrality timeline?	Yes

Production Forecasting

Year of inclusion	Quarter	Increase
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
2025	4	
2026	1	
2026	2	
2026	3	
2026	4	
2027	1	
2027	2	
2027	3	
2027	4	
2028	1	15.0%
⋮		
2040	2	
2040	3	
2040	4	

Carbon Offsetting

Year of inclusion	Quarter	Offset (tCO2e)
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
2025	4	
2026	1	
2026	2	
2026	3	
2026	4	
2027	1	500.00
2027	2	
2027	3	
2027	4	
2028	1	
2028	2	
2028	3	
2028	4	
2029	1	700.00
⋮		
2040	2	
2040	3	
2040	4	

Renewable Share

Year of inclusion	Quarter	Electricity	Gas	Oil	Additional Fuel
2023	4	0.0%	0.0%	0.0%	
2024	1	0.0%	0.0%	0.0%	
2024	2	0.0%	0.0%	0.0%	
2024	3	0.0%	0.0%	0.0%	
2024	4	0.0%	0.0%	0.0%	
2025	1	20.0%	0.0%	0.0%	
⋮					
2040	3	50.0%	0.0%	0.0%	
2040	4	50.0%	0.0%	0.0%	

Costs

Parameter	Value
1. Electricity from utility provider	
Input option	Simple
Utility electricity cost (€/MWh)	136.0000
Utility electricity annual increase (%)	2.0%
2. Electricity from renewables sources	
Input option	Simple
Renewable electricity cost (€/MWh)	350.000
Renewable electricity annual increase (%)	0.0%
3. Gas from utility provider	
Input option	Simple
Utility gas cost (€/MWh)	44.0000
Utilityl gas cost annual increase (%)	0.0%
4. Gas from renewable sources	
Input option	Simple
Renewable gas cost (€/MWh)	0
Renewable gas cost annual increase (%)	0.0%
5.Oil from utility provider	
Input option	Simple
Utility oil cost (€/kl)	1000
Utility oil cost annual increase (%)	0.0%
6. Oil from renewable sources	
Input option	Simple
Renewable oil cost (€/kl)	0.0
Renewable oil cost annual increase (%)	0.0%
7. Additional Fuel from utility provider	
Input option	Simple
Utility Additional Fuel cost (€/unit)	50
Utility Additional Fuel annual increase (%)	0.0%
8. Additional Fuel from renewable sources	
Input option	Simple
Renewable Additional Fuel cost (€/unit)	0
Renewable Additional Fuel annual increase (%)	0.0%
9. Carbon Offset	
Input option	Simple
Carbon offset cost (€/tonne CO2)	0
Carbon offset annual increase (%)	0.0%

Advanced Costs

Year of inclusion	Quarter	Electricity (Utility)	Electricity (Renewable)	Gas (Utility)	Gas (Renewable)	Oil (Utility)	Oil (Renewable)	Additional Fuel (Utility)	Additional Fuel (Renewable)	Carbon Offset
2024	3									
2024	4									
2025	1									
2025	2									
2025	3									
2040	1									
2040	2									
2040	3									
2040	4									

Current Projects

Project no.	Project name	Year of implementation	Quarter	No. fuel types affected	Savings fuel type 1	Savings quantity 1	Savings fuel type 2	Savings quantity 2	Savings fuel type 3	Savings quantity 3
1	Project 1	2024	1	1	Additional Fuel (Unit)	200	Not Applicable		Not Applicable	

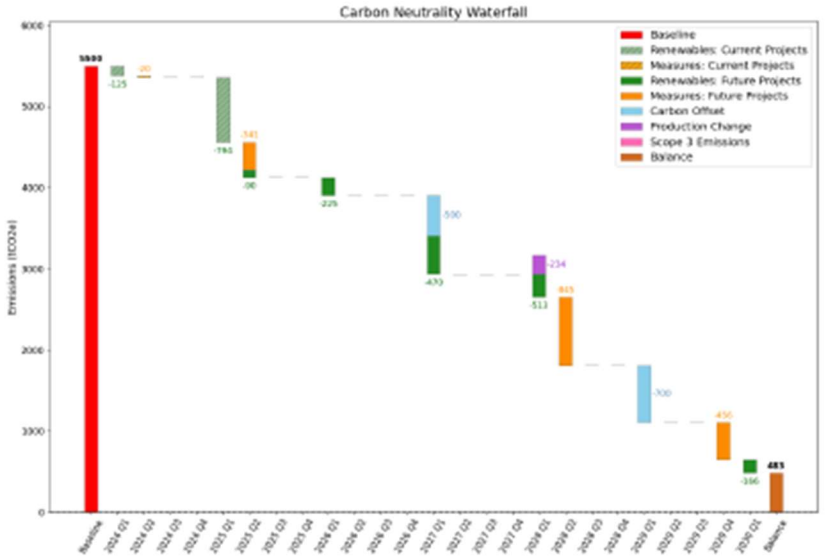
Future Projects

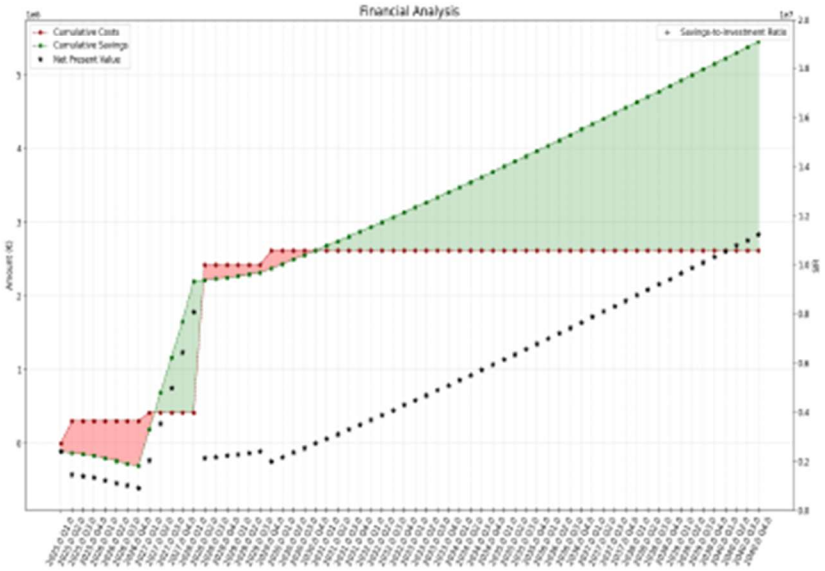
Project no.	Project name	Include	Year of implementation	Quarter	No. fuel types affected	Savings fuel type 1	Savings quantity 1	Savings fuel type 2	Savings quantity 2	Savings fuel type 3	Savings quantity 3	Implementation cost (€)	Business Grant (€)
1	Project 2	Yes	2025	1	1	Thermal: HW (MWh)	2,000	Not Applicable		Not Applicable		€300,000	€0
2	Project 3	Yes	2026	4	1	Electricity (MWh)	6,000	Not Applicable		Not Applicable		€120,000	€0
3	Project 4	No	2026	4	1	Electricity (MWh)	2,500	Not Applicable		Not Applicable		€85,000	€0
4	Project 4	Yes	2028	1	2	Thermal: Steam (MWh)	5,000	Thermal: HW (MWh)	-5,000	Not Applicable		€2,000,000	€0
5	Project 5	Yes	2029	3	2	Gas (MWh)	3,000	Not Applicable		Not Applicable		€200,000	€0

12 Appendix B2 – Project-based Modelling Tool – Generated Report – Verification

Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 09, September, 2024 for the Verification Organisation .





Appendix C1 – Project-based Modelling Tool – User Input Sheets – Validation

Targets & Scenarios

Parameter	Value
Carbon neutrality plan start year	2025
Carbon neutrality target year	2030
Is carbon neutrality prescribed?	Yes
Should the proposed future renewable share from the utility provider be included?	No

Baselines

Parameter	Value
Year of most recent carbon footprint	2023
Carbon footprint (tCO2e)	7946
Discount rate	4%
Footprint electricity consumption (MWh)	122622
Footprint gas consumption (MWh)	39036
Footprint oil consumption (kl)	8
Any additional fuel to be considered?	No
Footprint Additional Fuel consumption (unit)	0
Footprint Additional Fuel emissions factor (tCO2e/unit)	0.000
Electricity market-based emissions factor	Not Applicable
Steam output (MWh) from gas boilers	21059
Steam output (MWh) from oil boilers	0
Steam output (MWh) from electrode boilers	0
Steam boiler efficiency (gas)	90%
Steam boiler efficiency (oil)	Not Applicable
Steam boiler efficiency (electrode)	Not Applicable
HW output (MWh) from gas boilers	16139
HW output (MWh) from oil boilers	0
HW output (MWh) from electrode boilers	0
HW output (MWh) from heat pumps	0
HW output (MWh) from steam heat exchange	0
HW boiler efficiency (gas)	90%
HW boiler efficiency (oil)	Not Applicable
HW boiler efficiency (electrode)	Not Applicable
HW heat pump efficiency	Not Applicable
Steam-HW heat exchange efficiency	Not Applicable
Onsite electrical generation by gas (MWh)	Not Applicable
Efficiency of gas-fuelled generators	Not Applicable
Onsite electrical generation by oil (MWh)	Not Applicable
Efficiency of oil-fuelled generators	Not Applicable
Is the energy consumption expected to increase owing to production increase or facility expansion over the carbon neutrality timline?	No
Are any carbon offset programmes expected to be implemented within the carbon neutrality timeline?	No

Production Forecasting

Year of inclusion	Quarter	Increase
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Carbon Offsetting

Year of inclusion	Quarter	Offset (tCO2e)
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
2025	4	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Renewable Share

Year of inclusion	Quarter	Electricity	Gas	Oil	Additional Fuel
2023	4	100.0%	0.0%	0.0%	
2024	1	100.0%	0.0%	0.0%	
2024	2	100.0%	0.0%	0.0%	
2024	3	100.0%	0.0%	0.0%	
2024	4	100.0%	0.0%	0.0%	
⋮					
2040	1	100.0%	0.0%	0.0%	
2040	2	100.0%	0.0%	0.0%	
2040	3	100.0%	0.0%	0.0%	
2040	4	100.0%	0.0%	0.0%	

Costs

Parameter	Value
1. Electricity from utility provider	
Input option	Simple
Utility electricity cost (€/MWh)	220.0000
Utility electricity annual increase (%)	0.0%
2. Electricity from renewables sources	
Input option	Simple
Renewable electricity cost (€/MWh)	77.800
Renewable electricity annual increase (%)	0.0%
3. Gas from utility provider	
Input option	Simple
Utility gas cost (€/MWh)	36.7000
Utilityl gas cost annual increase (%)	0.0%
4. Gas from renewable sources	
Input option	Simple
Renewable gas cost (€/MWh)	0
Renewable gas cost annual increase (%)	0.0%
5.Oil from utility provider	
Input option	Simple
Utility oil cost (€/kl)	0
Utility oil cost annual increase (%)	0.0%
6. Oil from renewable sources	
Input option	Simple
Renewable oil cost (€/kl)	0.0
Renewable oil cost annual increase (%)	0.0%
7. Additional Fuel from utility provider	
Input option	Simple
Utility Additional Fuel cost (€/unit)	0
Utility Additional Fuel annual increase (%)	0.0%
8. Additional Fuel from renewable sources	
Input option	Simple
Renewable Additional Fuel cost (€/unit)	0
Renewable Additional Fuel annual increase (%)	0.0%
9. Carbon Offset	
Input option	Advanced
Carbon offset cost (€/tonne CO2)	
Carbon offset annual increase (%)	

Advanced Costs

Year of inclusion	Quarter	Electricity (Utility)	Electricity (Renewable)	Gas (Utility)	Gas (Renewable)	Oil (Utility)	Oil (Renewable)	Additional Fuel (Utility)	Additional Fuel (Renewable)	Carbon Offset
2024	3									0
2024	4									0
2025	1									0
2025	2									0
2025	3									0
2025	4									0
⋮										
2040	1									68
2040	2									68
2040	3									68
2040	4									68

Current Projects

Project no.	Project name	Year of implementation	Quarter	No. fuel types affected	Savings fuel type 1	Savings quantity 1	Savings fuel type 2	Savings quantity 2	Savings fuel type 3	Savings quantity 3
1					Not Applicable		Not Applicable		Not Applicable	
2					Not Applicable		Not Applicable		Not Applicable	
3					Not Applicable		Not Applicable		Not Applicable	
4					Not Applicable		Not Applicable		Not Applicable	
5					Not Applicable		Not Applicable		Not Applicable	

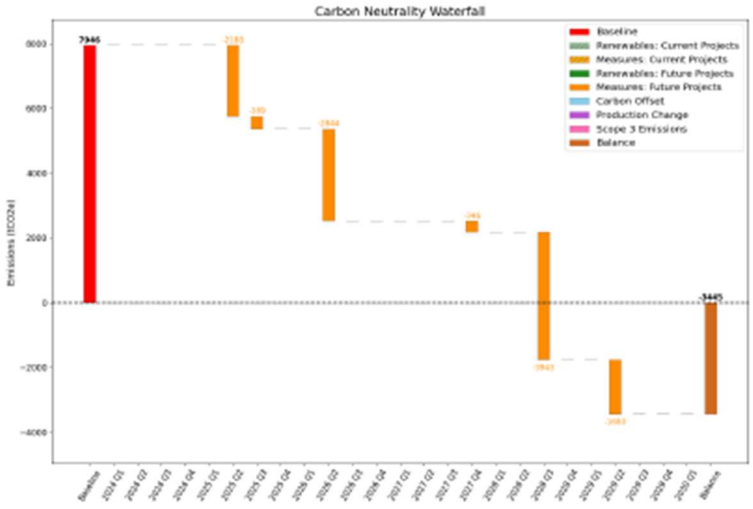
Future Projects

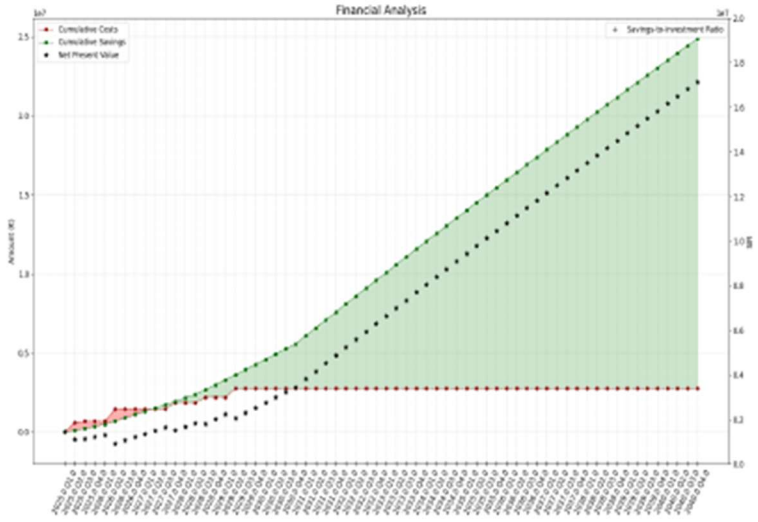
Project no.	Project name	Include	Year of implementation	Quarter	No. fuel types affected	Savings fuel type 1	Savings quantity 1	Savings fuel type 2	Savings quantity 2	Savings fuel type 3	Savings quantity 3	Implementation cost (€)	Business Grant (€)
1	Compressor heat recovery	Yes	2025	1	1	Thermal: HW (MWh)	10,142	Not Applicable		Not Applicable		€584,320	€0
2	RTO heat recovery	Yes	2025	2	1	Thermal: HW (MWh)	1,804	Not Applicable		Not Applicable		€83,798	€0
3	LPHW heating on return leg to DI tank	Yes	2026	1	2	Thermal: Steam (MWh)	13,180	Electricity (MWh)	-2,843	Not Applicable		€766,700	€0
4	Feedwater preheating (heat pump)	Yes	2027	3	2	Thermal: Steam (MWh)	1,604	Electricity (MWh)	-388	Not Applicable		€407,000	€0
5	LPHW heat pump	Yes	2028	2	2	Thermal: HW (MWh)	18,273	Electricity (MWh)	-5,316	Not Applicable		€1,316,700	€0
6	HT heat pump	Yes	2029	1	2	Thermal: Steam (MWh)	7,787	Electricity (MWh)	-3451	Not Applicable		€1,892,000	€0

Appendix C2 – Project-based Modelling Tool – Generated Report – Validation

Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 11, September, 2024 for Organisation A.





Appendix D1 – Project-based Modelling Tool (Interactions) – User Input Sheets – Case Study Organisation A

Targets & Scenarios

Parameter	Value
Carbon neutrality plan start year	2025
Carbon neutrality target year	2030
Is carbon neutrality prescribed?	Yes
Should the proposed future renewable share from the utility provider be included?	No

Baselines

Parameter	Value
Year of most recent carbon footprint	2023
Carbon footprint (tCO2e)	7946
Discount rate	4%
Footprint electricity consumption (MWh)	122622
Footprint gas consumption (MWh)	39036
Footprint oil consumption (kl)	8
Any additional fuel to be considered?	No
Footprint Additional Fuel consumption (unit)	0
Footprint Additional Fuel emissions factor (tCO2e/unit)	0.000
Electricity market-based emissions factor	Not Applicable
STEAM GENERATION	
Steam output (MWh) from gas boilers	21059
Steam output (MWh) from oil boilers	0
Steam output (MWh) from electric boilers	0
Steam boiler efficiency (gas)	95%
Steam boiler efficiency (oil)	100%
Steam boiler efficiency (electrode)	100%
HEAT GENERATION	
HW output (MWh) from gas boilers	16139
HW output (MWh) from oil boilers	0
HW output (MWh) from electrode boilers	0
HW output (MWh) from heat pumps	0
HW output (MWh) from steam heat exchange	0
HW boiler efficiency (gas)	95%
HW boiler efficiency (oil)	
HW boiler efficiency (electrode)	
HW heat pump efficiency	
Steam-HW heat exchange efficiency	
ONSITE GENERATION	
Onsite electrical generation by gas (MWh)	Not Applicable
Efficiency of gas-fuelled generators	100%
Onsite electrical generation by oil (MWh)	Not Applicable
Efficiency of oil-fuelled generators	100%
LIGHTING	
Electricity input (MWh)	
PRODUCTION LINE EQUIPMENT	
Electricity input (MWh)	
TRANSPORT	
Oil input (MWh)	
Electricity input (MWh)	
AIR COMPRESSION	
Oil input (MWh)	
Gas input (MWh)	
Electricity input (MWh)	
CHILLED WATER GENERATION	
Electricity input (MWh)	
Gas input (MWh)	
Diesel input (MWh)	
Chiller COP	
HVAC	
Electricity input (MWh)	
HW input (MWh)	
Is the energy consumption expected to increase owing to production increase or facility expansion over the carbon neutrality timline?	No
Are any carbon offset programmes expected to be implemented within the carbon neutrality timeline?	No

Production Forecasting

Year of inclusion	Quarter	Increase
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Carbon Offsetting

Year of inclusion	Quarter	Offset (tCO2e)
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
2025	4	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Renewable Share

Year of inclusion	Quarter	Electricity	Gas	Oil	Additional Fuel
2023	4	100.0%	0.0%	0.0%	
2024	1	100.0%	0.0%	0.0%	
2024	2	100.0%	0.0%	0.0%	
2024	3	100.0%	0.0%	0.0%	
2024	4	100.0%	0.0%	0.0%	
⋮					
2040	1	100.0%	0.0%	0.0%	
2040	2	100.0%	0.0%	0.0%	
2040	3	100.0%	0.0%	0.0%	
2040	4	100.0%	0.0%	0.0%	

Costs

Parameter	Value
1. Electricity from utility provider	
Input option	Simple
Utility electricity cost (€/MWh)	220.0000
Utility electricity annual increase (%)	0.0%
2. Electricity from renewables sources	
Input option	Simple
Renewable electricity cost (€/MWh)	77.800
Renewable electricity annual increase (%)	0.0%
3. Gas from utility provider	
Input option	Simple
Utility gas cost (€/MWh)	36.7000
Utilityl gas cost annual increase (%)	0.0%
4. Gas from renewable sources	
Input option	Simple
Renewable gas cost (€/MWh)	0
Renewable gas cost annual increase (%)	0.0%
5.Oil from utility provider	
Input option	Simple
Utility oil cost (€/kl)	0
Utility oil cost annual increase (%)	0.0%
6. Oil from renewable sources	
Input option	Simple
Renewable oil cost (€/kl)	0.0
Renewable oil cost annual increase (%)	0.0%
7. Additional Fuel from utility provider	
Input option	Simple
Utility Additional Fuel cost (€/unit)	0
Utility Additional Fuel annual increase (%)	0.0%
8. Additional Fuel from renewable sources	
Input option	Simple
Renewable Additional Fuel cost (€/unit)	0
Renewable Additional Fuel annual increase (%)	0.0%
9. Carbon Offset	
Input option	Advanced
Carbon offset cost (€/tonne CO2)	
Carbon offset annual increase (%)	

Advanced Costs

Year of inclusion	Quarter	Electricity (Utility)	Electricity (Renewable)	Gas (Utility)	Gas (Renewable)	Oil (Utility)	Oil (Renewable)	Additional Fuel (Utility)	Additional Fuel (Renewable)	Carbon Offset
2024	3									0
2024	4									0
2025	1									0
2025	2									0
2025	3									0
2025	4									0
2040	1									68
2040	2									68
2040	3									68
2040	4									68

Current Projects

Project no.	Project name	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings energy source type 1	Activity 1 Savings quantity 1	Activity 1 Savings energy source type 2	Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings energy source type 1	Activity 2 Savings quantity 1	Activity 2 Savings energy source type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)

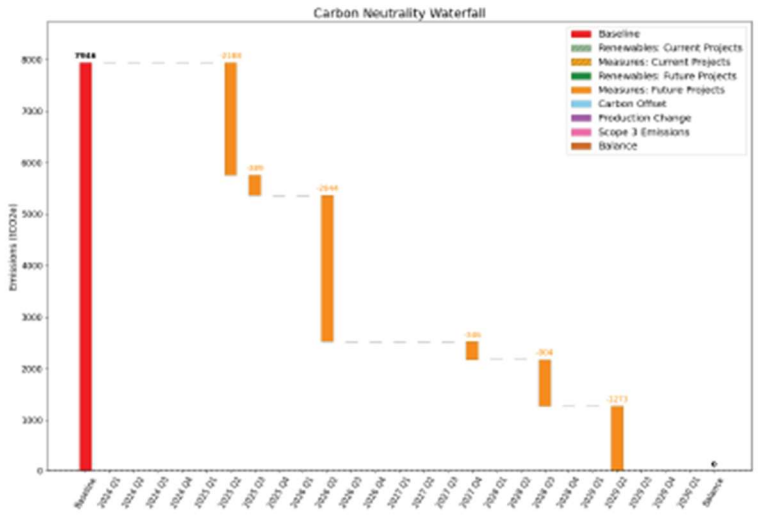
Future Projects

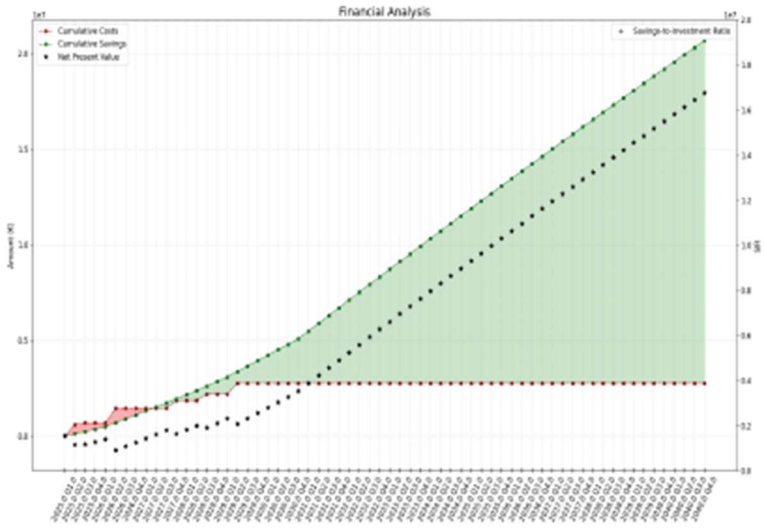
Project no.	Project name	Include	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings energy source type 1	Activity 1 Savings quantity 1	Activity 1 Savings energy source type 2	Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings energy source type 1	Activity 2 Savings quantity 1	Activity 2 Savings energy source type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)
1	Compressor heat recovery	Yes	Yes	2025	1	Thermal	Heat Generation	All	Thermal: HW (MWh)	10,142	Not Applicable			Not Applicable			Not Applicable		€584,320	€0
2	RTO heat recovery	Yes	Yes	2025	2	Thermal	Heat Generation	All	Thermal: HW (MWh)	1,804	Not Applicable			Not Applicable			Not Applicable		€83,798	€0
3	LPHW heating on return leg to DI tank	Yes	Yes	2026	1	Load Control	Steam Generation	All	Thermal: Steam (MWh)	13,180	Electricity (MWh)	-2,843		Not Applicable			Not Applicable		€766,700	€0
4	Feedwater preheating (heat pump)	Yes	Yes	2027	3	Load Control	Steam Generation	All	Thermal: Steam (MWh)	1,604	Electricity (MWh)	-388		Not Applicable			Not Applicable		€407,000	€0
5	LPHW heat pump	Yes	Yes	2028	2	New Technology	Heat Generation	All	Thermal: HW (MWh)	18,273	Electricity (MWh)	-5316		Not Applicable			Not Applicable		€1,316,700	€0
6	HT heat pump	Yes	Yes	2029	1	New Technology	Steam Generation	All	Thermal: Steam (MWh)	7,787	Electricity (MWh)	-3451		Not Applicable			Not Applicable		€1,892,000	€0

Appendix D2 – Project-based Modelling Tool (Interactions) – Generated Report – Case Study Organisation A

Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 11, September, 2024 for Organisation A (Interaction Effects).





14 Appendix E1 – Project-based Modelling Tool (Interactions) – User Input Sheets – Case Study Organisation B

Targets & Scenarios

Parameter	Value
Carbon neutrality plan start year	2025
Carbon neutrality target year	2030
Is carbon neutrality prescribed?	Yes
Should the proposed future renewable share from the utility provider be included?	No

Baselines

Parameter	Value
Year of most recent carbon footprint	2023
Carbon footprint (tCO2e)	10331
Discount rate	4%
Footprint electricity consumption (MWh)	19310
Footprint gas consumption (MWh)	36743
Footprint oil consumption (kl)	
Any additional fuel to be considered?	No
Footprint Additional Fuel consumption (unit)	0
Footprint Additional Fuel emissions factor (tCO2e/unit)	0.000
Electricity market-based emissions factor	Not Applicable
STEAM GENERATION	
Steam output (MWh) from gas boilers	24621
Steam output (MWh) from oil boilers	0
Steam output (MWh) from electrode boilers	0
Steam boiler efficiency (gas)	90%
Steam boiler efficiency (oil)	100%
Steam boiler efficiency (electrode)	100%
HEAT GENERATION	
HW output (MWh) from gas boilers	0
HW output (MWh) from oil boilers	0
HW output (MWh) from electrode boilers	0
HW output (MWh) from heat pumps	0
HW output (MWh) from steam heat exchange	17738
HW boiler efficiency (gas)	67%
HW boiler efficiency (oil)	100%
HW boiler efficiency (electrode)	100%
HW heat pump efficiency	100%
Steam-HW heat exchange efficiency	95%
ONSITE GENERATION	
Onsite electrical generation by gas (MWh)	Not Applicable
Efficiency of gas-fuelled generators	100%
Onsite electrical generation by oil (MWh)	Not Applicable
Efficiency of oil-fuelled generators	100%
LIGHTING	
Electricity input (MWh)	
PRODUCTION LINE EQUIPMENT	
Electricity input (MWh)	
TRANSPORT	
Oil input (MWh)	
Electricity input (MWh)	
AIR COMPRESSION	
Oil input (MWh)	
Gas input (MWh)	
Electricity input (MWh)	
CHILLED WATER GENERATION	
Electricity input (MWh)	7265.00
Electric chiller COP	4.00
Gas input (MWh)	
Gas chiller COP	
Oil input (MWh)	
Oil chiller COP	
HVAC	
Electricity input (MWh)	
HW input (MWh)	12569.00
Is the energy consumption expected to increase owing to production increase or facility expansion over the carbon neutrality timline?	No
Are any carbon offset programmes expected to be implemented within the carbon neutrality timeline?	No

Production Forecasting

Year of inclusion	Quarter	Increase
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Carbon Offsetting

Year of inclusion	Quarter	Offset (tCO2e)
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
2025	4	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Renewable Share

Year of inclusion	Quarter	Electricity	Gas	Oil	Additional Fuel
2023	4	40.0%	0.0%	0.0%	
2024	1	50.0%	0.0%	0.0%	
2024	2	50.0%	0.0%	0.0%	
2024	3	50.0%	0.0%	0.0%	
2024	4	50.0%	0.0%	0.0%	
2025	1	100.0%	0.0%	0.0%	
⋮					
2040	3	100.0%	0.0%	0.0%	
2040	4	100.0%	0.0%	0.0%	

Costs

Parameter	Value
1. Electricity from utility provider	
Input option	Simple
Utility electricity cost (€/MWh)	220.0000
Utility electricity annual increase (%)	0.0%
2. Electricity from renewables sources	
Input option	Simple
Renewable electricity cost (€/MWh)	65.000
Renewable electricity annual increase (%)	0.0%
3. Gas from utility provider	
Input option	Simple
Utility gas cost (€/MWh)	55.0000
Utilityl gas cost annual increase (%)	0.0%
4. Gas from renewable sources	
Input option	Simple
Renewable gas cost (€/MWh)	0
Renewable gas cost annual increase (%)	0.0%
5.Oil from utility provider	
Input option	Simple
Utility oil cost (€/kl)	0
Utility oil cost annual increase (%)	0.0%
6. Oil from renewable sources	
Input option	Simple
Renewable oil cost (€/kl)	0.0
Renewable oil cost annual increase (%)	0.0%
7. Additional Fuel from utility provider	
Input option	Simple
Utility Additional Fuel cost (€/unit)	0
Utility Additional Fuel annual increase (%)	0.0%
8. Additional Fuel from renewable sources	
Input option	Simple
Renewable Additional Fuel cost (€/unit)	0
Renewable Additional Fuel annual increase (%)	0.0%
9. Carbon Offset	
Input option	Advanced
Carbon offset cost (€/tonne CO2)	
Carbon offset annual increase (%)	

Advanced Costs

Year of inclusion	Quarter	Electricity (Utility)	Electricity (Renewable)	Gas (Utility)	Gas (Renewable)	Oil (Utility)	Oil (Renewable)	Additional Fuel (Utility)	Additional Fuel (Renewable)	Carbon Offset
2024	3									0
2024	4									0
2025	1									0
2025	2									0
2025	3									0
2025	4									0
2040	1									68
2040	2									68
2040	3									68
2040	4									68

Current Projects

Project no.	Project name	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings energy source type 1	Activity 1 Savings quantity 1	Activity 1 Savings energy source type 2	Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings energy source type 1	Activity 2 Savings quantity 1	Activity 2 Savings energy source type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)

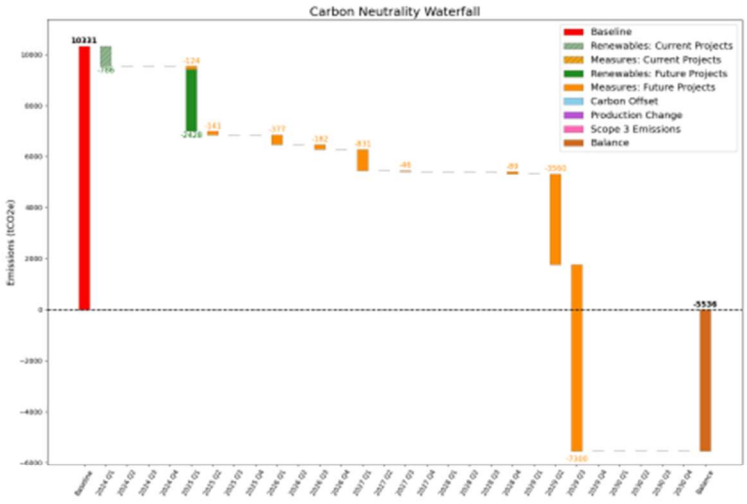
Future Projects

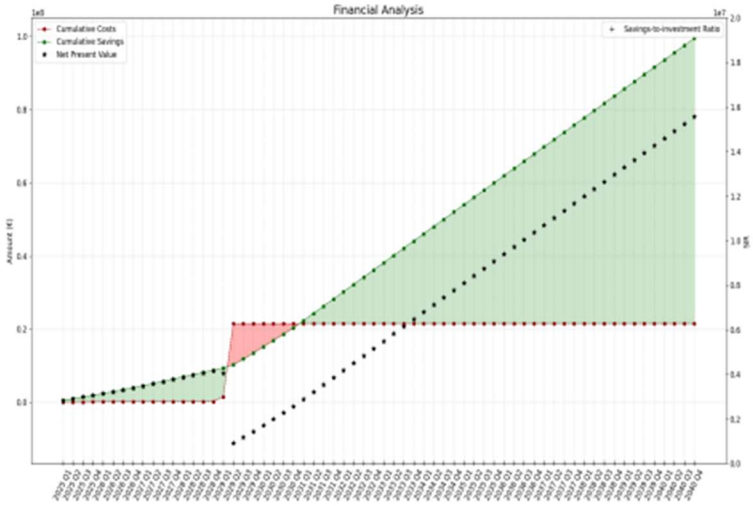
Project no.	Project name	Include	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings energy source type 1	Activity 1 Savings quantity 1	Activity 1 Savings energy source type 2	Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings energy source type 1	Activity 2 Savings quantity 1	Activity 2 Savings energy source type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)
1	EED 3 Heat recovery wheels	Yes	Yes	2024	4	Thermal	HVAC: AHU VAV- HW	All	Thermal: HW (MWh)	626	Not Applicable			Not Applicable			Not Applicable		€0	€0
2	EED 32 Heat recovery coils	Yes	Yes	2025	1	Thermal	HVAC: AHU VAV- HW	All	Thermal: HW (MWh)	711	Not Applicable			Not Applicable			Not Applicable		€20,000	€0
3	EED 16 Ozone	Yes	Yes	2025	4	Load Control	Steam Generation	All	Thermal: Steam (MWh)	1,898	Electricity (MWh)	61		Not Applicable			Not Applicable		€50,000	€0
4	EED 12 CIP pre-rinse	Yes	Yes	2026	2	Load Control	Steam Generation	All	Thermal: Steam (MWh)	917	Electricity (MWh)	186		Not Applicable			Not Applicable		€20,000	€0
5	EED 4 Still efficiency	Yes	Yes	2026	4	Load Control	Steam Generation	All	Thermal: HW (MWh)	4,184	Electricity (MWh)	-536		Not Applicable			Not Applicable		€20,000	€0
6	EED 18 Regen on preheater	Yes	Yes	2027	2	Thermal	Steam Generation	All	Thermal: Steam (MWh)	232	Not Applicable			Not Applicable			Not Applicable		€20,000	€0
7	EED 3 Cooling tower to chill WFI	Yes	Yes	2027	4	Load Control	Chilled Water Generation	All	CHW	284									€20,000	€0
8	EED 20 Air comp heat recovery	Yes	Yes	2028	3	Thermal	Heat Generation	All	Thermal: HW (MWh)	450	Electricity (MWh)	0.33		Not Applicable			Not Applicable		€26,000	€0
9	EED 10 Heat pump on chillers	Yes	Yes	2029	1	New Technology	Heat Generation	All	Thermal: HW (MWh)	17,923	Electricity (MWh)	-2555		Not Applicable			Not Applicable		€1,300,000	€0
10	EED 17 Thermal energy store	Yes	Yes	2029	2	New Technology	Steam Generation	All	Thermal: Steam (MWh)	36,748	Electricity (MWh)	-6709		Not Applicable			Not Applicable		€20,000,000	€0

15 Appendix E2 – Project-based Modelling Tool (Interactions) – Generated Reports – Case Study Organisation B

Carbon Neutrality Roadmap & Financial Impact

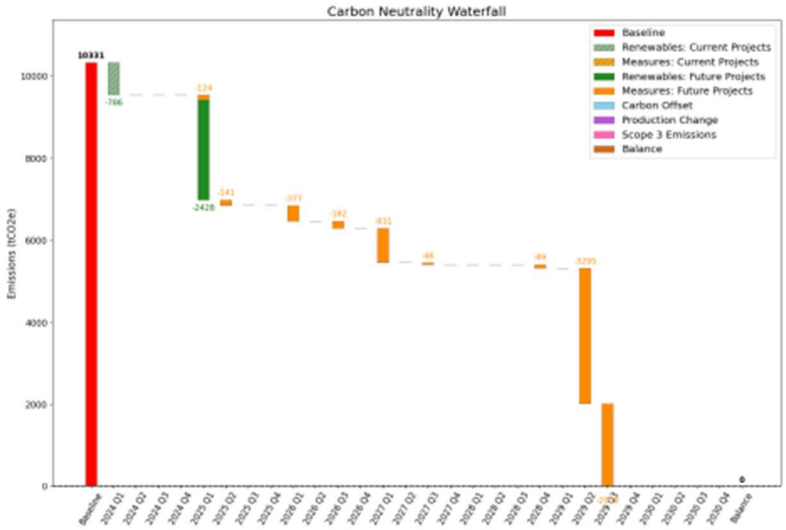
This report shows the carbon neutrality raodmap and financial analysis generated on 12, September, 2024 for Organisation B.

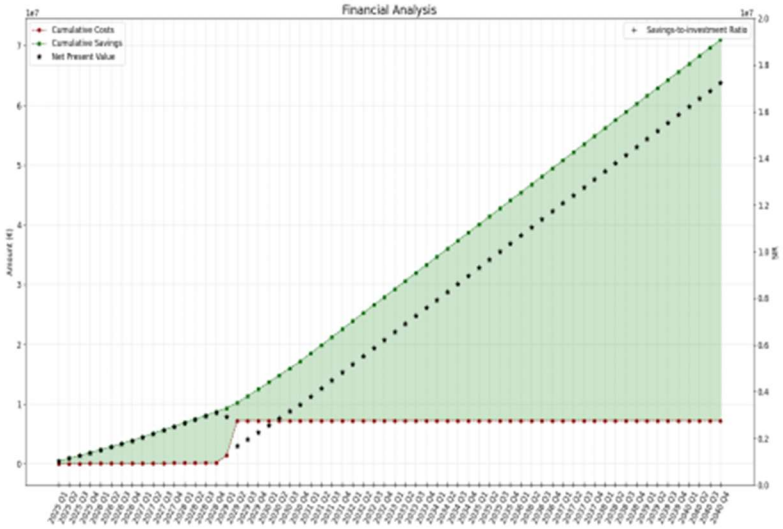




Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 12, September, 2024 for Organisation B (Interaction Effects).





Appendix F1 – Project-based Modelling Tool (Interactions) – User Input Sheets – Case Study Organisation C

Targets & Scenarios

Parameter	Value
Carbon neutrality plan start year	2025
Carbon neutrality target year	2030
Is carbon neutrality prescribed?	No
Should the proposed future renewable share from the utility provider be included?	No

Baselines

Parameter	Value
Year of most recent carbon footprint	2023
Carbon footprint (tCO2e)	5223
Discount rate	4%
Footprint electricity consumption (MWh)	10645
Footprint gas consumption (MWh)	13448
Footprint oil consumption (kl)	
Any additional fuel to be considered?	No
Footprint Additional Fuel consumption (unit)	0
Footprint Additional Fuel emissions factor (tCO2e/unit)	0.000
Electricity market-based emissions factor	Not Applicable
STEAM GENERATION	
Steam output (MWh) from gas boilers	10799
Steam output (MWh) from oil boilers	
Steam output (MWh) from electrode boilers	
Steam boiler efficiency (gas)	80%
Steam boiler efficiency (oil)	
Steam boiler efficiency (electrode)	
HEAT GENERATION	
HW output (MWh) from gas boilers	
HW output (MWh) from oil boilers	
HW output (MWh) from electrode boilers	
HW output (MWh) from heat pumps	
HW output (MWh) from steam heat exchange	10350
HW boiler efficiency (gas)	
HW boiler efficiency (oil)	
HW boiler efficiency (electrode)	
HW heat pump efficiency	
Steam-HW heat exchange efficiency	96%
Onsite electrical generation by gas (MWh)	
Efficiency of gas-fuelled generators	
Onsite electrical generation by oil (MWh)	
Efficiency of oil-fuelled generators	
LIGHTING	
Electricity input (MWh)	
PRODUCTION LINE EQUIPMENT	
Electricity input (MWh)	
TRANSPORT	
Oil input (MWh)	
Electricity input (MWh)	
AIR COMPRESSION	
Oil input (MWh)	
Gas input (MWh)	
Electricity input (MWh)	
CHILLED WATER GENERATION	
Electricity input (MWh)	
Electric chiller COP	
Gas input (MWh)	
Gas chiller COP	
Oil input (MWh)	
Oil chiller COP	
HVAC	
Electricity input (MWh)	
HW input (MWh)	9629.00
Is the energy consumption expected to increase owing to production increase or facility expansion over the carbon neutrality timline?	No
Are any carbon offset programmes expected to be implemented within the carbon neutrality timeline?	No

Production Forecasting

Year of inclusion	Quarter	Increase
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Carbon Offsetting

Year of inclusion	Quarter	Offset (tCO2e)
2023	4	
2024	1	
2024	2	
2024	3	
2024	4	
2025	1	
2025	2	
2025	3	
2025	4	
⋮		
2040	1	
2040	2	
2040	3	
2040	4	

Renewable Share

Year of inclusion	Quarter	Electricity	Gas	Oil	Additional Fuel
2023	4	10.0%	0.0%	0.0%	
2024	1	10.0%	0.0%	0.0%	
2024	2	10.0%	0.0%	0.0%	
2024	3	10.0%	0.0%	0.0%	
⋮					
2040	3	10.0%	0.0%	0.0%	
2040	4	10.0%	0.0%	0.0%	

Costs

Parameter	Value
1. Electricity from utility provider	
Input option	Simple
Utility electricity cost (€/MWh)	151
Utility electricity annual increase (%)	0.0%
2. Electricity from renewables sources	
Input option	Simple
Renewable electricity cost (€/MWh)	0.000
Renewable electricity annual increase (%)	0.0%
3. Gas from utility provider	
Input option	Simple
Utility gas cost (€/MWh)	44.0000
Utilityl gas cost annual increase (%)	0.0%
4. Gas from renewable sources	
Input option	Simple
Renewable gas cost (€/MWh)	0
Renewable gas cost annual increase (%)	0.0%
5.Oil from utility provider	
Input option	Simple
Utility oil cost (€/kl)	0
Utility oil cost annual increase (%)	0.0%
6. Oil from renewable sources	
Input option	Simple
Renewable oil cost (€/kl)	0.0
Renewable oil cost annual increase (%)	0.0%
7. Additional Fuel from utility provider	
Input option	Simple
Utility Additional Fuel cost (€/unit)	0
Utility Additional Fuel annual increase (%)	0.0%
8. Additional Fuel from renewable sources	
Input option	Simple
Renewable Additional Fuel cost (€/unit)	0
Renewable Additional Fuel annual increase (%)	0.0%
9. Carbon Offset	
Input option	Simple
Carbon offset cost (€/tonne CO2)	
Carbon offset annual increase (%)	

Advanced Costs

Year of inclusion	Quarter	Electricity (Utility)	Electricity (Renewable)	Gas (Utility)	Gas (Renewable)	Oil (Utility)	Oil (Renewable)	Additional Fuel (Utility)	Additional Fuel (Renewable)	Carbon Offset
2024	3									0.000
2024	4									0.000
2025	1									0.000
2025	2									0.000
⋮										
2040	3									0.000
2040	4									0.000

Current Projects

Project no.	Project name	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings energy source type 1	Activity 1 Savings quantity 1	Activity 1 Savings energy source type 2	Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings energy source type 1	Activity 2 Savings quantity 1	Activity 2 Savings energy source type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)

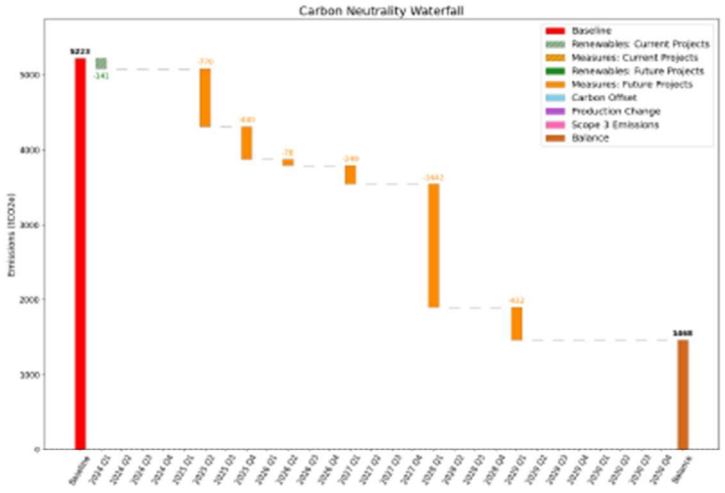
Future Projects

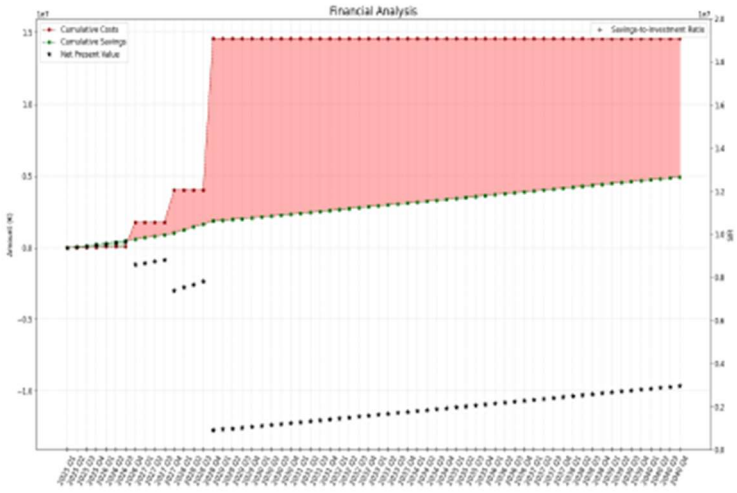
Project no.	Project name	Include	Consider interactions	Year of implementation	Quarter	Category	Activity 1 (Load Removal)	Activity 1 System No.	Activity 1 Savings energy source type 1	Activity 1 Savings quantity 1	Activity 1 Savings energy source type 2	Activity 1 Savings quantity 2	Activity 2 System No.	Activity 2 (Load Addition)	Activity 2 Savings energy source type 1	Activity 2 Savings quantity 1	Activity 2 Savings energy source type 2	Activity 2 Savings quantity 2	Implementation cost (€)	Business Grant (€)
1	EED 32 RA mixing	Yes	Yes	2025	1	Load Control	HVAC: AHU Modulating FA - HW	All	Thermal: HW (MWh)	2,206	Not Applicable			Not Applicable			Not Applicable		€0	€0
2	EED 47 Control	Yes	Yes	2025	1	Load Control	HVAC: AHU Modulating FA - HW	All	Thermal: HW (MWh)	521	Electricity (MWh)	70		Not Applicable			Not Applicable		€0	€0
3	EED 2 AHU setback mode	Yes	Yes	2025	1	Load Control	HVAC: AHU Modulating FA - HW	All	Thermal: HW (MWh)	1,069	Not Applicable			Not Applicable			Not Applicable		€0	€0
4	EED 5 Heat recovery coils AHU	Yes	Yes	2025	3	Thermal	Heat Generation	All	Thermal: HW (MWh)	2,216	Not Applicable			Not Applicable			Not Applicable		€30,000	€0
5	Air comp heat recovery	Yes	Yes	2026	1	Thermal	Heat Generation	All	Thermal: HW (MWh)	395	Electricity (MWh)	1.09		Not Applicable			Not Applicable		€45,025	€0
6	EED 14 HP zone 1	Yes	Yes	2026	4	New Technology	HVAC: AHU Modulating FA - HW	1	Thermal: HW (MWh)	1,672	Not Applicable		1	HVAC: Packaged	Electricity (MWh)	-364	Not Applicable		€1,689,810	€0
7	EED 13 HP zone 2	Yes	Yes	2027	4	New Technology	HVAC: AHU Modulating FA - HW	2	Thermal: HW (MWh)	9,888	Not Applicable		2	HVAC: Packaged	Electricity (MWh)	-1423	Not Applicable		€2,245,997	€0
8	EED 48 Energy store	Yes	Yes	2028	4	New Technology	Steam Generation	All	Thermal: Steam (MWh)	13,448	Electricity (MWh)	-9892		Not Applicable			Not Applicable		€10,563,864	€0

16 Appendix F2 – Project-based Modelling Tool (Interactions) – Generated Reports – Case Study Organisation C

Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 12, September, 2024 for Organisation C.





Carbon Neutrality Roadmap & Financial Impact

This report shows the carbon neutrality raodmap and financial analysis generated on 12, September, 2024 for Organisation C (Interaction Effects).

