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Use of surplus wind electricity in Ireland to produce compressed renewable gaseous transport fuel through biological power to gas systems

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Abstract

Power to gas (P2G) may be used to store curtailed electricity whilst converting the energy vector to gas. To be economically viable these systems require cheap electricity and a cheap concentrated source of CO₂. Biogas produced from anaerobic digestion typically comprises of 60% methane and 40% CO₂. The P2G system substitutes for the conventional upgrading system by using hydrogen (derived from surplus wind electricity) to react with CO₂ and increases the methane output. The potential CO₂ production from biogas in Ireland associated with typical wet substrates is assessed as more than 4 times greater than that required by the potential level of H₂ from curtailed electricity. Wind energy curtailment in 2020 in Ireland is assessed conservatively at 2175GW_eh/a. Thus P2G is limited by levels of curtailment of electricity rather than biogas systems. It is shown that 1 GW_eh of electricity used to produce H₂ for upgrading biogas in a P2G system can affect a savings of 97 tonnes CO₂. The cost of hydrogen is assessed at €0.96/m³ renewable methane when the price of electricity is €5/kW_eh. This leads to a cost of compressed renewable gas from grass of €1.8/m³. This drops to €1.1/m³ when electricity is purchased at €0.2/kW_eh.

Keywords: Biological Power to Gas; Greenhouse gas emission; Green Gas; Biomethane; Biofuel cost; Seaweed.

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Abbreviations

AD:	Anaerobic Digestion
CAPEX:	Capital expenditure
CNG:	Compressed natural gas
CSTR:	Continuously stirred tank reactor
CRG:	Compressed renewable gas
EPA:	Environmental Protection Agency
E:	GHG (CO _{2eq}) saved
E ₁ :	CO ₂ in biogas used to combine with H ₂ to produce CH ₄
E ₂ :	CO _{2eq} emitted from P2G process (from life cycle assessment of P2G process)
E _d :	CO _{2eq} saved when CH ₄ replaces fossil diesel fuel
E ₄ :	CO _{2eq} emitted from processing of substrate, transport and distribution of biogas from domestic and organic fraction of municipal solid waste (OFMSW)
E ₅ :	CO _{2eq} emitted from collection and processing of substrate, transport and distribution of biogas from agricultural slurries
E ₆ :	CO _{2eq} emitted from collection and processing of substrate, transport and distribution of biogas from slaughter waste
E ₇ :	CO _{2eq} emitted from cultivation and processing of substrate, transport and distribution of biogas from grass
E ₈ :	CO _{2eq} emitted from cultivation and processing of substrate, transport and distribution of biogas from seaweed
E ₉ :	CO _{2eq} emitted when diesel fuel used.
GHG:	Greenhouse gas
GNI:	Gas Networks Ireland
IEA:	International Energy Agency
NGVs:	Natural gas vehicles
OPEX:	Operational expenditure
OFMSW:	Organic fraction of municipal solid waste

P2G: Power to gas
SNSP: System non-synchronous penetration
SHW: Slaughterhouse waste
VS: Volatile solids

1. Introduction

1.1. The need for storage of intermittent renewable electricity

Ireland's target is to achieve 40% renewable energy supply of electricity by 2020 [1], 12% renewable energy supply in heat and 10% renewable energy supply in transport [2]. Within its renewable energy targets, Ireland has set a target of 500MWe of ocean energy capacity by 2020 [3]. In 2012 wind energy and biomass provided 74% and 8% of the renewable electricity of the country, respectively [2].

McGarrigle et al. [4] stated that wind turbines are expected to produce 37% of the electrical energy needs of the island of Ireland in 2020, whereas the existing hydroelectric plants and other forms of renewable electricity generation will generate only 3% of the total electricity. The characteristics of marine renewable electricity are intermittent and fluctuating. In order to provide system security, sometimes wind energy needs to be dispatched down. A total of 196 GWh of energy from wind farms was estimated to be dispatched down in 2013; this is an increase of 86 GWh compared to that of 2012 [5].

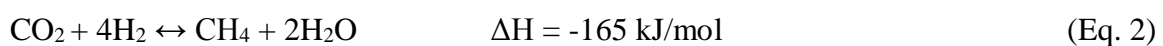
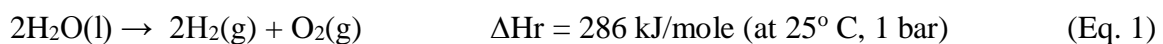
Currently, Ireland's solution for intermittent energy is grid interconnection with Great Britain. Connolly [6] highlighted that Denmark also has a similar approach for grid stability by selling wind power when excess power is available and buying power when it is needed. However, this approach is expensive as the electricity sales are cheaper than electricity purchase. If Ireland considers Great Britain as an energy storage source, this policy will involve the purchase of expensive electricity. If interconnection is also utilized to integrate wind power onto the grid, then Ireland's green power could be used to reduce the CO₂ emissions of Great Britain rather than Ireland [6]. Therefore, new electrical storage systems are required for future energy security in Ireland.

1.2. Biological Power to Gas systems

Power to gas (P2G) is a method to convert electrical power to gaseous fuel in the form of hydrogen or methane. Large amounts of hydrogen addition to natural gas may change the combustion properties of natural gas, reduce the Wobbe Index of the gas, and not integrate sufficiently with the natural gas grid [7]. Many countries have extensive infrastructure systems for methane distribution. Distribution and use of methane is far more readily available than hydrogen based on the current infrastructure.

At present, P2G technologies have high capital cost and relative low efficiency. However, one of its advantages is the diversification of the final products; gas produced may be used for heating, as a gaseous fuel for transport or be converted back to electricity when demand for electricity is high. Murphy and Thamsiroj [8] stated that the final energy demand in the transport and thermal sectors is each approximately 40% of total demand; the demand for electricity is of the order of 20% in Ireland. Therefore, the diversification of energy carrier vectors could meet the demand for green transport and thermal demand.

A study conducted by the International Energy Agency (IEA) Bioenergy Task 37 [2] concluded that P2G would be an optimal route to produce renewable transport fuel from surplus electricity. In order to produce methane, electricity is first converted to hydrogen through electrolysis as shown in Eq. 1. CO₂ is then combined with hydrogen to produce methane by the Sabatier reaction as shown in Eq. 2 [9]. The efficiency of electrolysis process is based on the technologies. The efficiency of alkaline electrolyses and polymer electrolyte membrane electrolyzers vary from 55- 84% [10, 11]. Additionally, the efficiency of solid oxide electrolyzers is the range of 90-95% [12]. Therefore, this paper assumed 75% is efficiency of electrolyser as in Ahern et al. [12].



There are two methods to produce methane: chemical and biological methanation. The principles of the two methods are based on Eq. 2. Chemical methanation requires that the input CO₂ is free from impurities (such as siloxanes); however, biological methanation requires less stringent quality and may use the CO₂ in raw biogas derived from anaerobic digestion to produce methane [13]. As such this acts as an upgrading process of biogas to biomethane.

The biological methanation process is an anaerobic process in which carbon dioxide and hydrogen are used by a group of microorganisms (hydrogenotrophic methanogenic archaea) to produce methane. This process happens at much lower temperatures than for chemical methanation: the mesophilic and thermophilic processes are usually conducted under 20-40°C and 45-60 °C, respectively [7]. "In-situ" and "ex-situ" biogas upgrading are two methods for biological methanation. When H₂ is introduced into the main anaerobic reactor this is known as the "in-situ" method [14, 15]; the methane content can be increased from ca. 50% to 75% [16]. When the biogas and the H₂ react in a separate reactor (filled with hydrogenotrophic methanogenic archaea), a high methane content (up to 98%) can be achieved; this is known as an "ex-situ" process [17].

1.3. Biogas production and biogas upgrading methods

Biogas consisting of CH₄ (40-75%) and CO₂ (25-60%) can be produced from a broad range of feedstocks including organic fraction of municipal solid waste (OFMSW) [18-20], agriculture slurries [21], grass [22-24] or seaweed [25]. In order to be fed into the existing natural gas network or to be utilised as biofuel, biogas needs to be upgraded to remove contaminants and CO₂ [26]. Absorption (water scrubbing, organic solvent scrubbing, chemical) and adsorption (pressure swing adsorption) are two traditional methods for upgrading biogas. However, those processes have high costs and the sustainability may be

affected by the discharge of small amounts of methane in the upgrading step [27]. Biological methanation can potentially provide an alternative method for the upgrading of biogas produced from a digester. The methane content after the “in-situ” methanation process is 75%, therefore gas upgrading (to remove CO₂) and gas cleaning (to remove impurities such as water and H₂S) is required. The methane content after the “ex-situ” process can reach 98%, consequently only gas cleaning is required. Thus, renewable gas (biomethane) from an “ex-situ” biological methanation process will be assessed in this paper. A schematic of the process is shown in Figure 1.

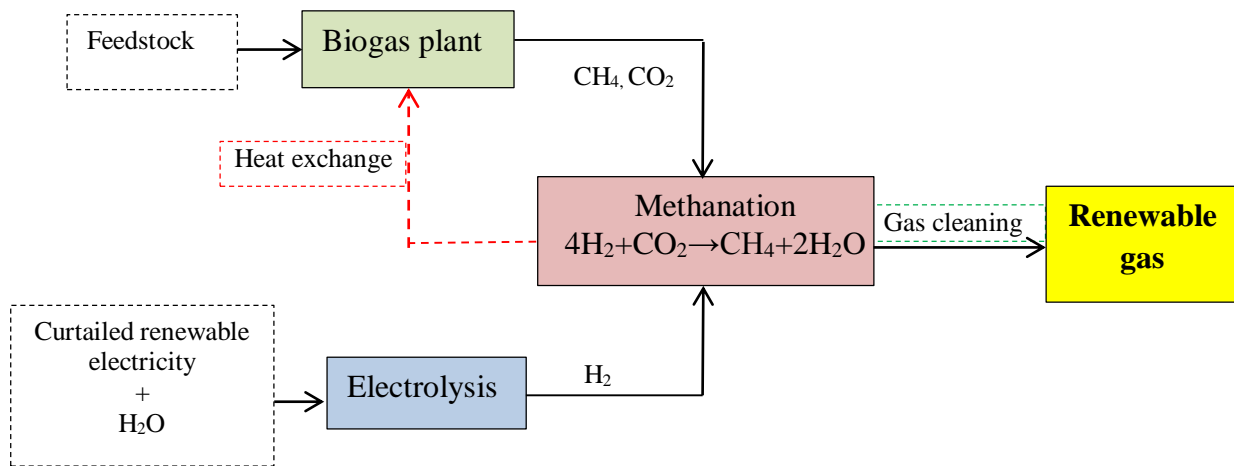


Figure 1: Design of biological P2G system as a biogas upgrading process

1.4. Potential gaseous fuel market in Ireland

Compressed natural gas (CNG) is a gaseous transport fuel stored under high pressure (ca. 250 bar). Approximately 18 million natural gas vehicles (NGVs) are used worldwide, with 1.9 million NGVs located in Europe. Owing to a lack of service stations to serve NGVs or policy to promote their use, there is no NGV industry in Ireland. However, Gas Networks Ireland (GNI), the owner and operator of the gas network in Ireland, are actively promoting the use of CNG fuel for transport. A target of 5% has been set for the commercial transport market (16,000 vans), 10% for buses (1,130 buses) and 10% for trucks (2,720 trucks) in Ireland to

operate on CNG by 2020 [28, 29]. It is envisaged that this target will create a gas demand for NGVs of ca. 305 Mm³/year equating to 11.6 PJ of energy [30].

1.5. Rationale and Objectives of the Research

The aim of this paper is to expand upon research assessing the combination of curtailed renewable electricity and CO₂ sourced from anaerobic digestion as a method of upgrading biogas using biological P2G systems and providing a source of renewable transport fuel. Previous studies have explored the reduction of greenhouse gas (GHG) emissions when biomethane (upgraded biogas) is used to replace fossil diesel fuel [31-36]. However, assessing the GHG reduction associated with biological P2G systems combined with biomethane production from a digester as a substitute for diesel transport fuel has not been assessed.

The cost of renewable gas originating for P2G systems has been reviewed [13] and examined [16]. However, these studies considered the methanation process as a separate entity, and did not consider the upgrading of biogas in anaerobic digestion using a biological P2G process. Ahern et al. [12] undertook an initial examination on financial sustainability of P2G such as the cost of hydrogen; the cost of carbon capture; revenue from sale of renewable gas as a transport fuel; and financial viability. However, the costs of renewable gas from different digestion feedstocks have not been assessed. This paper seeks to fill these gaps by:

- Examining the quantity of CO₂ associated with potential levels of biogas in Ireland;
- Determining the limiting factor for power to gas: curtailed electricity or CO₂ from biogas;
- Determining the potential gaseous transport fuel resource associated with biological power to gas systems in Ireland;
- Calculating the GHG savings associated with renewable gas;

- Calculating the combined cost of renewable gas and biomethane produced from biological power to gas systems for a range of feedstocks.

2. Methodology

2.1. Wind energy curtailment

Wind energy needs to be curtailed due to: (i) system stability requirements (synchronous inertia, dynamic and transient stability); (ii) operating reserve requirements, including negative reserve; (iii) voltage control requirements; (iv) morning load rise requirements and (v) system non-synchronous penetration (SNSP) limit (SNSP limit is constraint on non-synchronous penetration, in which SNSP is calculated as $SNSP = (\text{wind generation} + \text{high voltage direct current imports}) / (\text{system demand} + \text{high voltage direct current exports})$) [4].

The total wind energy curtailment used in this study is based on the work of McGarrigle et. al [4] where it was suggested that 7-14% of electricity from wind could be curtailed in Ireland by 2020. This was based on SNSP limits of 70% and 60%, respectively. The total H₂ produced was modelled based on the energy curtailment as input to the electrolysis process [4].

2.2. Environmental benefits

The environmental benefits considered in this paper are the GHG emissions (CO_{2eq}) saved when CO₂ from biogas is combined with H₂ to produce methane. The short term CO₂ in the biogas, which would have been released in the upgrading process will be reused to produce methane and thus displace fossil diesel.

2.2.1. CO_{2eq} saved from biogas upgrading process

The CO_{2eq} saved from the biogas upgrading process was calculated by Eq. (3):

$$E = E_1 - E_2 \tag{3}$$

Where:

E: GHG (CO_{2eq}) saved

E₁: CO₂ in biogas used to combine with H₂ to produce CH₄

E₂: CO_{2eq} emitted from P2G process (from life cycle assessment of P2G process).

The CO_{2eq} from electricity production from wind was included as a part of P2G process.

2.2.2. CO_{2eq} saved from replacement of fossil diesel fuel

The projected 2020 transport fuel demands for heavy vehicles in Ireland are dominated by diesel fuel [37]. Therefore, this paper focused on analysing the replacement of diesel by renewable gas (the biomethane produced from the combination of the biogas plant and biological P2G process). Five digestion feedstocks for biomethane production were considered – grass, pig slurry, slaughter house waste (SHW), seaweed and OFMSW. Lifecycle assessment results from literature were collected in order to determine GHG emissions in replacing diesel with renewable gas. The "Well to Wheel" life cycle assessment includes emissions associated with fuel production, processing, transportation, distribution and consumption. The EU Renewable Energy Directive of 2009 [38] states that biofuel emissions are calculated as zero due to balancing the amount of carbon released with an equivalent amount sequestered, therefore such emissions were not considered. The total CO_{2eq} saved when the total CH₄ produced is used to replace diesel fuel was calculated by using Eq. (4):

$$E_d = E_9 - E_4 - E_5 - E_6 - E_7 - E_8 + E \quad (4)$$

Where:

E_d: CO_{2eq} saved when CH₄ replaces fossil diesel fuel;

E₄: CO_{2eq} emitted from processing of substrate, transport and distribution of biogas from domestic and organic fraction of municipal solid waste (OFMSW);

E₅: CO_{2eq} emitted from collection and processing of substrate, transport and distribution of biogas from agricultural slurries;

E₆: CO_{2eq} emitted from collection and processing of substrate, transport and distribution of biogas from slaughter waste;

E₇: CO_{2eq} emitted from cultivation and processing of substrate, transport and distribution of biogas from grass;

E₈: CO_{2eq} emitted from cultivation and processing of substrate, transport and distribution of biogas from seaweed;

E₉: CO_{2eq} emitted when diesel fuel used.

The CO₂ emission from well to wheel of diesel fuel was calculated through Eq. (5):

$$E_9 = \text{MJ fuel used} \times \text{gCO}_{2\text{eq}}/\text{MJ} \quad (5)$$

E: The CO_{2eq} saved from the biogas upgrading process (Eq. 3)

2.3. Economic benefits

The economic benefits were analysed in three areas:

- Total money saved through CO_{2eq} reduction when renewable gaseous fuel replaces diesel fossil fuel;
- Total money saved through reduction in wind energy curtailment;
- Comparison of the costs of biomethane produced from conventional upgrading and in a biological methanation system (renewable gas).

In order to compare the cost of biogas with conventional upgrading and upgrading via biological methanation, the methodology and data from the study of Browne et al. [39] was used in this paper. The operational costs of the biogas plant do not change according to scale and are summarised in Table 1.

Table 1: Assumptions for calculating biomethane costs (adapted from Browne et al. [39])

	Grass	Pig Slurry	SHW	OFMSW
CH ₄ content in biogas	55%	65%	55%	60%
CO ₂ content in biogas	45%	35%	45%	40%
m ³ biomethane yield/tonne feedstock	59.4	14.4	41	66
Technology used	CSTR [*]	CSTR	CSTR	Batch process
Maintenance and overhead	€5/t	€5/t	€10/t	€25/t
Digestate disposal				€4/t
Electrical demand of biogas plant	10 kW _e h/t	10 kW _e h/t	10 kW _e h/t	6 kW _e h/t
Cost of feedstock	€17/t			
Storage pit	€30/t			
Gate fee			€20/t	€70/t
Compression and distribution cost	€0.149/m ³	€0.149/m ³	€0.135/m ³	€0.149/m ³
Interest rate	6%/a			
Life time	15 years			
Cost of electricity	€0.15/kW _e h			
Gas grid connection	€300,000			
CNG service station	€500,000			

*. CSTR: Continuously stirred tank reactor

3. Results and discussion

3.1. The sources of CO₂ from biogas

Ahern and co-workers [12] assessed potential feedstocks (agricultural slurries, SHW, grass and OFMSW) for renewable gas in Ireland as 7.4 Mtonnes/a. These feedstocks can produce 430 Mm³ CO₂/a (58 m³ CO₂/tonne feedstock) as a by-product of anaerobic digestion as illustrated in Table 2. This represents a significant available resource of concentrated CO₂ in Ireland.

Table 2: Quantifying the CO₂ resource from anaerobic digestion of selected substrates in Ireland (adapted from [12])

	Agricultural Slurries	Slaughter Waste	OFMSW	Grass	Total
Feedstock (Mt/a)	2.79	0.21	0.22	4.16	7.38
CH ₄ from Anaerobic Digestion (AD) (Mm ³ /a)	49.76	18.08	14.98	447.59	530.41
Practical resource from AD (PJ/a)	1.88	0.68	0.57	16.07	19.20
% CO ₂ in biogas	45	45	35	45	-
CO ₂ from AD (Mm ³ /a)	41	15	8	366	430

The gas volume in this paper is expressed under standard temperature (0 °C) and pressure (1 atm).

For the purposes of this study, the following section will analyse in detail the potential CO₂ content in biogas from seaweed for the benefit of the reader.

Burton et al. suggested a total area of 700 ha for seaweed cultivation in Ireland by 2020 [40]. It is assumed forty tonnes of seaweed (on a wet weight basis) may be produced per hectare per annum. *Laminaria* species in Cork was found to comprise of 10.34% volatile solids (VS) [41]. The methane yield from *Laminaria* species was assessed at 238 L CH₄/kg VS [42]. Thus the methane yield may be calculated as 24.6 m³ CH₄/tonne feedstock with the ratio of CH₄ to CO₂ in the biogas at 55%:45%. Using these figures, the potential biogas and analysis

of the P2G system from the seaweed feedstock is summarised in Table 3. It should be noted that the seaweed productivity used is a conservative value based on the current available technology; a much higher value may be achieved if advanced cultivation technologies are applied [43]. For examples, a high productivity may be achieved by using multilayer textile substrates for seaweed cultivation (<http://www.atsea-project.eu/>).

Table 3: Potential biogas and P2G production from seaweed (*Laminaria* species) in Ireland

Component	Data	Quantity	Unit
Potential area		700	ha
Seaweed cultivated per year	40tonnes wet weight/ha	$700*40 = 28,000$	tonnes/a
Total VS	10.34% VS	$28,000*10.34\% = 2,895$	tonnes/a
CH ₄ yield from biogas	238 L CH ₄ /kg VS	$2,895 \text{ tonnes} * 238 \text{ m}^3/\text{tVS} = 689,058$	m ³ /a
Energy content of CH ₄	Energy value of CH ₄ : 37.8 MJ/m ³	$689,058 * 37.8 = 0.026$	PJ/a
CO ₂ from anaerobic digestion	45% CO ₂ from biogas	$689,058 * 45\% / 55\% = 563,774$	m ³ /a
CH ₄ produced from P2G	1 CO ₂ \approx 1 CH ₄	563,774	m ³ /a
CH ₄ produced from biogas and P2G from seaweed		1,252,832	m ³ /a
H ₂ required	H ₂ required at 4 times the volume of CO ₂ eq.(2)	$563,774 * 4 = 2,255,098$	m ³ /a
Electricity required to make H ₂ for P2G system	H ₂ energy value of: 12MJ/m ³ . Electrolysis conversion efficiency: 75%	$2,255,098 \text{ m}^3/\text{a} * 12 \text{ MJ}/\text{m}^3 / (0.75) * 28 / 10^6 = 10$	GWh/a

The numbers in this study may not sum exactly due to rounding.

Overall, the potential capacity of CO₂ from biogas in Ireland in the year 2020 would be 430.6 Mm³/a predominantly originating from agricultural slurries, slaughter waste, OFMSW and grass (Table 2); with just 0.6 Mm³/a from seaweed (Table 3). If the total CO₂ capacity is used for upgrading in a biological P2G process, ca. 7,654 GWh/a of electricity could be used in P2G systems (shown in Table 4). However, McGarrigle et al. [4] concluded that the installed capacity of wind turbines in Ireland by 2020 will be between 5,911 MW and 6,890 MW. If the curtailment rate is 14% and the capacity factor is 30%, the total wind energy that will be curtailed in 2020 is in the range of 2,175 – 2,535 GWh/a. In order to simplify this calculation, this paper only analyses the benefits based on 2,175 GWh/a of curtailed wind energy in 2020. If the curtailed electricity was used to produce H₂ through an electrolysis process, the H₂ amount would be sufficient to combine with 28.4% of CO₂ from biogas of potential indigenous feedstock. Thus P2G is limited by levels of curtailment of electricity rather than biogas systems.

Table 4: Potential storage capacity by methanation of CO₂ from biogas.

Components	Quantity	Unit
CO ₂ from AD	430.6	Mm ³ /a
H ₂ requirement	403.6*4 = 1722	Mm ³ /a
Energy value of H ₂	1722Mm ³ /12MJ/m ³ = 20,664	TJ/a
Electricity required to produce H ₂	20,664TJ*0.2778/0.75 = 7,654	GWh/a

Note: - Energy value of H₂: 12MJ/m³, 1GWh = 3.6 TJ

- Efficiency from power to H₂: 75%
- H₂ volume is 4 times that of CO₂ according to Eq. 2
- 1TJ = 0.2778GWh
- The numbers may not sum exactly due to rounding

3.2 Environment benefits

3.2.1 Greenhouse gas savings when CO₂ from biogas is utilised

The combination of CO₂ from biogas with H₂ creates additional value from CO₂ by utilising that CO₂ to produce biomethane in a biological methanation process. If wind energy curtailment in 2020 in Ireland (2,175 GWh/a) is used to produce hydrogen for a biological methanation process, then 211,450 tonnes CO_{2eq} (outlined in Box 1) would be saved annually. This means that for 1GWh of surplus wind energy used to produce hydrogen for upgrading biogas, approximately 97 tonnes CO₂ can be fixed from biogas in a P2G system.

Box 1: CO_{2eq} saved when CO₂ in biogas is utilized to produce CH₄

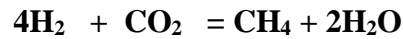
Assumptions:

- Efficiency from Power to H₂: 75%;

Calculations:

E₁- CO_{2eq} saved to produce CH₄ by biogas upgrading:

Sabatier equation:



2,175 GWh/a.

Wind electricity curtailed in 2020:

7.83 PJ

H₂ produced from curtailed electricity: = (7.83 PJ/12 MJ/m³)*75%= 489 Mm³/a

CO₂ required (H₂ : CO₂ ≈ 4:1): = 489 Mm³/4= 122 Mm³/a

= (122 Mm³*1.96 kg/m³)/1000=239,120 tonnes/a

CH₄ produced from combination of CO₂ and H₂ process¹ (1 CO₂ ≈ 1 CH₄) 122 Mm³/a

E₂ – Total CO_{2eq} emitted from P2G process when producing CH₄: = 122 Mm³* 37.8 MJ/m³ * 6 g CO₂/MJ =27,670 tonnes CO_{2eq}/a

Total CO_{2eq} saved (E) through utilisation of CO₂ from anaerobic digestion in P2G and CH₄ used as biofuel for transport²: = 239,120 tonnes/a - 27,670 tonnes/a
= 211,450 tonnes CO₂/a

Notes:

- E was calculated as Eq.(3)
- Density of CO₂: 1.96 kg/m³
- Energy value of H₂: 12 MJ/m³;
- Energy value of CH₄: 37.8 MJ/m³;
- Density of methane: 0.714 kg/m³
- CO_{2eq} emitted from producing CH₄ by catalyst P2G process: 6 gCO₂/MJ [44]. The CO_{2eq} emitted from producing CH₄ by biological P2G is not available in literature. Thus, the GHG data of catalyst P2G is applied in this study.
- The numbers may not sum exactly due to rounding.

¹ excluding CH₄ from biogas process.

² The CO₂ from the biogas plant will be released to the environment by conventional upgrading, therefore when it is utilised in combination with H₂, it is considered as CO₂ saved.

3.2.2. CO_{2eq} savings when fossil diesel fuel is replaced by CNG .

The total CO₂ from the feedstock needed to combine with H₂ produced from surplus wind energy is 122 Mm³/a. The data from Table 2 shows that one feedstock source alone will not meet the demand of CO₂ for biological P2G. Therefore, it is assumed that the CO₂ will be sourced from biogas from SHW, OFMSW, agricultural slurries (Table 2) and seaweed (Table 3). The remainder (57.4 Mm³/a) will be sourced from biogas from grass feedstock.

The efficiency of biomethane fuel at present is about 18-29% less than that of diesel fuel on a km/MJ basis [32, 45]. In this paper, 20% lower efficiency of gaseous fuel than that of diesel fuel is used to calculate the total replaced diesel. It is expected that future vehicle efficiencies will improve. The calculation of GHG emissions (gCO_{2eq}/MJ) for conventional biogas production includes biomethane loss and biogas upgrading. However, the biological P2G process helps avoid biomethane slippage in upgrading systems as biogas upgrading is replaced by ex-situ biomethanation. Thus, the calculations of GHG emissions from biogas in this paper do not include biomethane loss and GHG emissions from traditional biogas upgrading.

The Biograce GHG calculation tool (<http://www.biograce.net/home>) is used for demonstrating compliance with the sustainability criteria under Directives 98/70/EC and 2009/28/EC of the European Parliament and of the Council. In this tool, CO_{2eq} from biogas upgrading including methane leakages by pressurized water scrubbing is 11.87 g/MJ. The CO_{2eq} emitted from cultivation, processing, transport and distribution of biogas from OFMSW is 26.7 g/MJ and from wet manure is 26.1 g/MJ. Therefore, subtracting the upgrading emissions, calculation of GHG emissions from OFMSW and agricultural slurry derived biomethane were taken as 14.83 and 14.23 gCO_{2eq}/MJ, respectively, in this paper.

The GHG emissions data of biogas from SHW is quite limited; only one study by Singh and Murphy [46] was found in the literature. However, the authors did not include emissions from

transport and distribution as these processes will take place whether biomethane is produced or not. A figure of 31.42 kgCO_{2eq}/tonne was reported, equating to 10 gCO_{2eq}/MJ (using a biogas yield of 119.6m³/tonne and energy content of biogas as 26MJ/m³), which would be emitted if slaughterhouse waste is utilized for biogas production. Korres et al. [32] suggested that the GHG emission savings of grass biomethane as compared to diesel fuel (88.8 gCO_{2eq}/MJ) was 54.2% allowing for wind energy used in electricity production supplying parasitic demand, improved heating, improved vehicle efficiency and ignoring carbon sequestration in pasture land. This meant that the GHG emissions from grass biomethane was 40.7gCO_{2eq}/MJ. Removal of CO_{2eq} from biogas losses (10.82 gCO_{2eq}/MJ) and from biogas upgrading (12.64 gCO_{2eq}/MJ) [32], the total CO_{2eq} from grass biomethane used in this paper was 17.24 gCO_{2eq}/MJ.

GHG emissions from seaweed biomethane was reported as 176 kgCO_{2eq}/tonnes dry seaweed [44], which equates to 35 gCO_{2eq}/MJ (at 133 m³ methane yield/tonne dry seaweed and energy content of methane at 37.8 MJ/m³); biomethane losses or biogas upgrading were not considered [47]. Therefore, 35 gCO_{2eq}/MJ was used to calculate CO_{2eq} reduction from cultivation, processing, transport and distribution of biogas from seaweed.

The GHG emission results of each feedstock type are shown in Table 5.

Table 5: Greenhouse gas emission from biogas of different feedstocks when biological P2G is used to upgrade biogas.

Feedstock	Greenhouse Gas emission (gCO_{2eq}/MJ)
Slaughterhouse waste	10
OFMSW	14.83
Agricultural Slurries	14.23
Seaweed	35
Grass	17.24

Box 2 presents the results of the net GHG emissions saved when biomethane from digestion of feedstocks displaces fossil diesel fuel. The total methane produced from biological P2G is ca. 271 Mm³/a. Gas Networks Ireland have a target to fuel 10% of buses, 10% of trucks and 5% of commercial vans in 2020 (305 Mm³/a). Methane produced from biological P2G is sufficient to satisfy 89% of this target. If biomethane is used as a gaseous fuel to replace diesel fossil fuel then 865,767 tonnes CO_{2eq} will be saved annually. This means the total CO_{2eq} reduction of biomethane compared with diesel fuel is 117%, which satisfies the requirement of the EU Renewable Energy Directive.

Box 2: CO₂ saved when fossil diesel fuel is replaced by biomethane and renewable methane

	CH ₄ from combination of CO ₂ and H ₂ (Box 1):	122 Mm ³ /a
	CH ₄ from anaerobic digestion (assume 55% CH ₄ : 45% CO ₂):	= (122 Mm ³ /a * 55%)/45% = 149 Mm ³ /a
	Total CH ₄ produced:	271 Mm ³ /a = (271 Mm ³ /a * 37.8 MJ/m ³)/10 ⁹ = 10.24 PJ/a
E ₄	Energy content of biogas from OFMSW CO _{2eq} emitted from cultivation, processing, transport and distribution of biogas from OFMSW:	0.57 PJ/a = 0.57 PJ/a * 14.83 gCO _{2eq} /MJ = 8,453 t/a
E ₅	Energy content of biogas from agricultural slurries CO _{2eq} emitted from cultivation, processing, transport and distribution of biogas from agricultural slurries:	1.88 PJ/a = 1.88 PJ/a * 14.23 gCO _{2eq} /MJ = 26,752 t/a
E ₆	Energy content of biogas from slaughter waste CO _{2eq} emitted from production of biogas from slaughterhouse waste:	0.68 PJ/a = 0.68 PJ/a * 10 gCO _{2eq} /MJ = 6,800 t/a
E ₇	Energy content of biogas from grass CO _{2eq} emitted from cultivation, processing, transport and distribution of biogas of from grass	2 PJ/a = 2 PJ/a * 17.24 gCO _{2eq} /MJ = 34,480 t/a
E ₈	Energy content of biogas from seaweed CO _{2eq} emitted from cultivation, processing, transport and distribution of biogas of from biogas of seaweed:	0.026 PJ/a = 0.026 PJ/a * 35 gCO _{2eq} /MJ = 910 t/a
	Total diesel will be replaced:	= 10.3 PJ/a * 80% = 8.24 PJ/a 260 ML/a
E ₉	CO ₂ emitted from diesel fuel (from well to wheel gCO ₂ /MJ):	= 8.24 PJ/a * 88.8 gCO _{2eq} /MJ = 731,712 tonnes/a
E_d	CO₂ saved when biomethane and renewable methane replace diesel fuel:	865,765 tonnes/a
<i>Notes:</i>		
- E _d = E ₉ - E ₄ - E ₅ - E ₆ - E ₇ - E ₈ + E Eq. (4)		
- E _d = 731,712 - 8,453 - 26,572 - 6,800 - 34,480 - 910 + 211,450 (E from Box 1)		
- Energy value of Automotive Diesel Fuel: 36.8MJ/L;		
- The GHG emission of diesel fuel is 88.8 gCO _{2eq} /MJ [48]		
- Energy value of CH ₄ : 37.8 MJ/m ₃ ;		

3.3 Economic benefits

3.3.1 Carbon tax

As of May 28th 2014, the Irish Environmental Protection Agency (EPA) stated that Ireland would not meet its EU 2020 targets for GHG emission reduction. Even under the best case scenario (which assumes full implementation of Government policies and measures) the emission in 2020 will be 5-12% below the 2005 levels and would not meet the 20% reduction target [49]. The sources of GHG emissions in Ireland are mainly from the non-emission trading sectors, in which agriculture accounts for 30.5%, energy emits 21.8% and transport 18.9% [50]. Ireland must rapidly decarbonise energy and transport to get further mitigation in GHG. According to Murphy et al. [51], energy demand of transport in 2020 will be 188 PJ/a. If CH₄ from biological P2G in this study is used as a renewable transport fuel (10.3 PJ/a), it would meet 5.5% of energy demand in the transport sector. A carbon tax of €20 per tonne of CO₂ emitted for transport fuels was stated in the Irish Governmental Budget of 2012 [50]. If the renewable methane produced from wind energy curtailment and CO₂ from anaerobic digestion replaces fossil diesel fuel around €17 million euros would be saved per year in carbon fines.

3.3.2 Money saved through utilization of wind curtailment

As mentioned in section 3.2.2, of the order of 2175GWh/a of wind energy will be curtailed in Ireland by 2020. Wind energy developers would not be paid for this. However, if this is used for P2G a monetary value for wind energy of 5c€/kWh could be achieved [12], generating around €109 million annually.

3.3.3 The costs of renewable gas

The costs of renewable gas include the cost of hydrogen, the cost of methane from the biogas plant and the cost of biomethane from methanation. It is assumed that the gas is compressed to ca. 250 bar for use as a transport fuel and this cost is included for in the compression and distribution costs in Table 1.

- **Biomethane cost:** The costs of renewable gas include for capital expenditure (CAPEX) and operational expenditure (OPEX). This process is a combination of the biogas plant and the biological methanation system, and as such the CAPEX and OPEX for the two processes must be assessed.

According to Götz et al.[13], the size of biological methanation should not be greater than 5MW (gross energy). If the capacity is higher than 5 MW, catalytic methanation is suggested as being more economical. Therefore, a 5MW biological methanation plant is used to calculate the capacity of biogas plant in this study. The 5MW biological methanation plant is equivalent to a 1.75 MWe digester if electricity efficiency is 35%. If an assumption is made of a 5MW system with a capacity factor of 50%, this will produce 21,900 MWh/a, which equals with 2,190,000m³ methane per year (at 1 m³CH₄ ≈ 0.01MWh). For an ex-situ process, with biomethane at 98% methane content, this is equivalent to 2,234,694 m³ biomethane. It may be assumed that half of the biomethane is derived from the original biogas, therefore approximately 1,117,347 m³CH₄/a is from biogas. Taking the methane yield of each feedstock in Table 2 and 24.6 m³CH₄/t for seaweed (section 3.1), we can find that the quantity required for each feedstock type for a 5 MW biological methanation is different: 19,000 tonnes/a of grass; 77,000 tonnes/a of slurry; 27,000 tonnes/a of SHW; 19,000 tonnes/a of OFMSW and 46,000 tonnes/a of seaweed.

Browne et al. [39] assessed the costs of biogas facilities for food waste, SHW and combined grass and slurry at a scale of 50,000 tonnes/a. These costs will be used as a basis for the following analysis but will be adjusted for scale.

- **Biogas plant CAPEX:** Biogas plant capital costs are effected by economies of scale; the relationship of maize silage feedstock and investment cost of biogas plant [39] is shown in Eq. (6):

$$y = 558.89 * x^{-0.159} \quad (6)$$

In which, y is investment cost (€/t feedstock) and x is tonnes of feedstock per annum.

Based on this equation, different quantities of feedstocks will have different investment costs. Applying the feedstock quantities calculated previously for grass, slurry, SHW, OFMSW and seaweed (19000 t/a, 77000 t/a, 27000 t/a, 19000 t/a and 46000 t/a, respectively), Table 6 determines the investment costs as would apply for these quantities of maize silage feedstock. Table 6 also illustrates the percentage cost difference as compared to a 50000 t/a maize silage plant.

Table 6: Percentage difference in investment cost of different scale of maize silage biogas plant

Tonne of maize silage	Investment cost (€/t/a feedstock)	% cost difference comparing to 50 000 tonnes
19000	116	16
27000	110	10
46000	101	1
77000	93	-7
50000	100	0

The capital cost of grass, OFMSW, SHW and slurry biogas plants have been reported in previous literature as 140 €/t/a, 280 €/t/a, 140€/t/a and 110 €/t/a (shown in Table 7). It is assumed that the calculated percentage cost difference (reported in Table 6) can similarly be applied for grass, slurry, SWH and OFMSW biogas plants to adjust for a 5MW scale biological methanation system. This is outlined in Table 7.

The capital cost of a seaweed biogas plant at 50,000 tonnes scale is not available in the literature, therefore it will be calculated in this paper. To the authors knowledge, there is no commercial biogas plant with a feedstock of 100% seaweed. The Solrød biogas plant in Denmark uses seaweed as one part of feedstock, however this only accounts for approximately 3% [52]. Due to the characteristics of cast seaweed with high salt content, low C/N ratio, heavy metals and high sulphur content [53], seaweed biogas plants may need to have pre-treatment processes and H₂S removal prior to digestion. The capital cost of a seaweed biogas plant in this study is assumed to be 20% higher than a maize silage biogas plant. At 46,000 tonnes per year, maize silage has an investment cost of €101/t/a, thus the capital cost of seaweed plant is taken as €134/t/a. Seasonal variation greatly affects seaweed biomethane potential. Herrmann et al. [54] suggested that seaweed should be harvested in summer and stored via ensiling process for maximising biogas production. In this study, the investment cost of storage pit for seaweed is assumed the same as for grass (€30/t/a) [39]. The capital costs of different feedstocks at 5MW biological methanation plant are presented in Table 7. For example the investment cost of a seaweed digester is €7.54M (Table 2 Annex).

Table 7: Capital costs of biogas plants with different feedstocks at 5MW biological methanation plant

Feedstocks	% cost difference comparing to 50,000 tonnes biogas plant	Capital cost of different biogas plants at 50,000 tonnes scale (€/t/a)	Capital cost at 5MW scale (€/t/a)
Grass	16	140	162
OFMSW	16	280	325
SHW	10	140	154
Seaweed	1		164
Slurry	-7	110	102

- Biomethanation capital cost:** The challenge when microorganisms are used as a biocatalyst is the poor solubility characteristic of H₂. Continuously stirred tank reactors, trickle-bed reactors and membrane reactors have been applied to improve this issue. Among the three technologies the trickle-bed reactor was shown to have a high methane conversion of 98%. The investment cost for a 5MW ex-situ biomethanation plant is suggested as €3,000,000 [55].

- Biomethane OPEX:** The waste heat from a biological methanation facility for a 5 MW plant according to Götz et al. [13] was 420 kW, thus the thermal demand of a biogas facility in this case could be satisfied by the waste heat from biological methanation (Figure 1). The operational data is not greatly effected by scaling, therefore data from Browne et al. (Table 2) is used [39]. Seaweed was not included in the study by Browne et al. [39], thus this study will illustrate the biomethanation cost with seaweed feedstock.

Due to the characteristics of certain seaweeds, especially beach cast mixes, the anaerobic digestion process may suffer due to high levels of ammonia, volatile fatty acids and/or hydrogen sulphide [56]. It is suggested that the maintenance cost of a seaweed biogas facility

will be higher than that of a grass biogas facility; a value of €15/t is assumed. The technology used to convert seaweed to biogas is modelled as a CSTR with an electrical demand of biogas plant is 10 kW_e/h/t [57]. The digestate produced from digestion of cast seaweeds (as opposed to cultivated seaweeds) may have high heavy metal content, in particular cadmium [58] as well as salt [59], and so may not be readily applicable as fertiliser. The biodegradability index of seaweed is suggested at ca. 54% [60], thus the seaweed digestate in this study is taken as 43,516 tonnes. The cost of seaweed in Ireland is taken at €40/t wet weight or €267/t dry weight [40] if it is harvested mechanically (total solids content 15%). However, other studies suggest seaweed costs in the future associated with large scale cultivation at ca. €50/t dry weight [61]. This is the assumed cost in this study for seaweed. The lifetime of biogas plant as well as the interest rate are the same for all feedstocks (Table 2). The operation cost of the biomethanation facility is assumed at 3% of the investment cost. Biomethane production costs for each type of feedstock are based on the assumptions in Table 2 in the Annex. The costs of biomethane are shown in Table 8.

Table 8: Cost of renewable gas production (excluding hydrogen production costs)

	Grass	Slurry	SHW	OFMSW	Seaweed	Unit
Biomethane yield from biogas plants	1,128,600	1,108,800	1,107,000	1,254,000	1,131,600	m ³ /a
Biomethane yield from combination of CO ₂ from biogas and H ₂ from wind energy	923,400	597,046	905,727	836,000	925,855	m ³ /a
Total biomethane yield (from biogas and from methanation)	2,052,000	1,705,846	2,012,727	2,090,000	2,057,455	m ³ /a
Annual cost of renewable gas production	1,478,167	2,152,228	918,478	660,987	2,790,565	€
Cost of renewable gas production	0.7	1.3	0.5	0.3	1.4	€/m ³

- Hydrogen production costs:** The cost of H₂ production is mostly based on the cost of electricity which is even higher than the capital costs. According to Benjaminsson et al. [16] the production cost of hydrogen by electrolysis (including maintenance costs, electricity grid cost, electricity cost and capital cost) from three manufacturers (Proton-Onsite, NEL and ErreDue) are in the range €0.09 – 0.1/kWh. Of these costs, €0.047 - 0.055/kWh and €0.02 – 0.028/kWh are from electricity and capital costs, respectively. Gonzalez et al. [62] examined the cost of hydrogen from surplus wind energy in Ireland and concluded that hydrogen cost (excluding capital cost) would be $3.53 * C_e$ €/GJ, where C_e is the surplus electricity value in c€/kWh. The study of Ahern et al. [12] recommended the bidding price of electricity for P2G is 0.05 €/kWh therefore C_e in this study is assumed as 5 c€/kWh. Thus, the production cost of H₂/m³ of methane in 2020 in Ireland is assessed as €0.96/m³ renewable methane as shown in Box 3.

Box 3: Hydrogen production cost

Cost of hydrogen (excluding capital cost) per GJ = $3.53 * C_e$ [62]

$$= 3.53 * 5 = 17.65 \text{ €/GJ}$$

Cost of hydrogen (excluding capital cost) per kWh = $17.65\text{€/GJ} / 278\text{kWh} = 0.06 \text{ €}$

In which C_e is surplus electricity value in c€/kWh = 5 c€/kWh

1GJ = 278 kWh

The annualised capital cost of hydrogen plant of NEL manufacture: 0.02 €/kWh [16]

Hydrogen production cost (including capital cost): = $0.02 + 0.06 = 0.08 \text{ €/kWh}$

Sabatier equation: $4\text{H}_2 + \text{CO}_2 = \text{CH}_4 + 2\text{H}_2\text{O}$

To produce one cubic meter of methane, requires four cubic meters of H₂

1 m³ H₂ contains 3 kWh

Cost of H₂/m³ biomethane= $0.08 \times 4\text{m}^3\text{H}_2/\text{m}^3\text{CH}_4 \times 3 \text{ kWh}/\text{m}^3\text{H}_2 = 0.96 \text{ €/m}^3$

The production costs of biomethane from biological P2G with H₂ production, compression and distribution included are in Table 9. Compression and distribution are included for the purposes of assessing compressed renewable gas (CRG) as a transport fuel. The costs are variable according to different types of feedstocks. Due to the gate fee supports for SHW and OFMSW, the cost of biomethane from these two feedstocks are lowest. Meanwhile, the lower methane yield of slurry and the high capital and operational cost of seaweed biogas plants make the biomethane costs of these two feedstocks quite high. Comparing with conventional upgrading, the costs are much higher (Table 9). The cost of H₂ production accounts for a high portion in producing renewable gas, in which the cost of electricity used for H₂ production, plays an important role. It must be borne in mind in comparing the two systems that the quantity of renewable gas generated is significantly increased when the P2G system is incorporated and that this electricity would otherwise be curtailed.

3.3.4. Sensitive analysis for renewable gas costs

There are a lot of assumptions in the calculation of compressed renewable gas costs. This study will not focus on the sensitivity of the biogas production but instead focus on the biological methanation. The H₂ production cost is the most expensive element of the total renewable gas cost, therefore, the variability of electricity price used to produce H₂ will be analysed.

On March 1st 2013, the Single Electricity Market committee decided that “*The cessation of compensation for curtailment on January 1 2018*” [63]. This means that in 2020, the price of electricity associated with wind energy curtailment in Ireland could be free in theory. However there may be a market for this surplus electricity and the manufacturer is likely to pay for curtailed wind energy used for electrolysis. The results show that if the surplus electricity price is 0.2c€/kWh, the biomethane costs from grass feedstock of conventional upgrading and biological methanation are the same (Table 10). To this must be added the

benefit of carbon savings which was assessed as potentially € 17 million per year (section 3.3.1)

Table 9: Production of compressed renewable gas from biological methanation systems (excluding VAT)

Total production cost in €/m³ biomethane	Grass	Slurry	SHW	OFMSW	Seaweed
Renewable gas production	0.7	1.3	0.5	0.3	1.4
H ₂ production	0.96	0.96	0.96	0.96	0.96
Compression and distribution	0.149	0.149	0.149	0.135	0.149
Cost of CRG production	1.8	2.4	1.6	1.4	2.5
Cost of CRG production from conventional upgrading	1.02-1.21 ¹		0.54 ²	0.3 ²	

¹[64]: ²[39]

Table 10: Impacts of surplus electricity prices on CRG production costs.

Cost of CRG production (€/m³ biomethane)	Grass	Slurry	SHW	OFMSW	Seaweed
5 c €/kWh (Base case)	1.8	2.4	1.6	1.4	2.5
At 0.2 c €/kWh	1.1	1.6	0.9	0.7	1.8
At 4 c €/kWh	1.7	2.3	1.5	1.3	2.4
At 6 c €/kWh	2.0	2.6	1.8	1.6	2.7

4. Conclusions

The potential CO₂ production from biogas in Ireland associated with typical wet substrates (grass, slurry, slaughter house waste, the organic fraction of municipal solid waste and

seaweed) is 431 Mm³/a. If this CO₂ were used in a biological power to gas system, this would require 1722 Mm³/a of H₂. This would in turn require 7653 GW_eh/a of electricity. Wind energy curtailment in 2020 in Ireland is assessed conservatively at 2175 GW_eh/a. H₂ produced from curtailed electricity would be sufficient to combine with 28.4% of CO₂ from potential biogas sources. Thus P2G is limited by electricity rather than biogas systems. It is shown that 1 GW_eh of electricity used to produce H₂ for upgrading biogas in a P2G system can affect a savings of 97 tonnes CO₂. In total, compressed renewable gaseous transport fuel offers GHG savings of 117% compared to diesel fuel, which satisfies the requirement of the EU Renewable Energy Directive.

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REFERENCES

- [1] Sustainable Energy Authority of Ireland. Renewable energy in Ireland 2011. 2012. Available from: http://www.seai.ie/Publications/Statistics_Publications/Renewable_Energy_in_Ireland/Renewable_Energy_in_Ireland_2011.pdf, accessed 15.4.2014.
- [2] Persson T, Murphy J, Liebetrau J, Trommler MT, J. A perspective on the potential role of biogas in smart energy grids. 2014. Available from: http://www.iea-biogas.net/files/daten-redaktion/download/Technical%20Brochures/Smart_Grids_Final_web.pdf, accessed 1.3.2015.
- [3] Department of Jobs, Enterprise and Innovation. Priority Area J: Marine renewable energy action plan. 2013. Available from: http://www.djei.ie/science/technology/rpmaps/J_Action_Plan.pdf, accessed 15.4.2014.
- [4] Mc Garrigle E, Deane J, Leahy PG. How much wind energy will be curtailed on the 2020 Irish power system? Renewable Energy. 2013;55:544-53.
- [5] EirGrid and SONI. Annual Wind Constraint and Curtailment Report 2013. 2014. Available from: http://www.eirgrid.com/media/Annual_Wind_Constraint_and_Curtailment_Report_2013.pdf, accessed 11.05.2015.
- [6] Connolly D. An investigation into the energy storage technologies available, for the integration of alternative generation techniques. University of Limerick 2007. Available from: <http://www.iwea.com/technologicaldevelopments>, accessed 20.5.2014.
- [7] Grond L, Paula S, Johan H. System analyses Power to Gas: A technology review, 2013. 2013. Available from: http://issuu.com/ggnl/docs/systems_analyses_power_to_gas_-_tec, accessed 30.4.2014.
- [8] Murphy JD, Thamsiroj T. What will fuel transport systems of the future? Materials Today. 2011;14:518-24.
- [9] Buchholz O, van der Ham A, Veneman R, Brilman D, Kersten S. Power-to-Gas: Storing Surplus Electrical Energy. A Design Study. Energy procedia. 2014;63:7993-8009.
- [10] Troncoso E, Newborough M. Electrolysers for mitigating wind curtailment and producing 'green' merchant hydrogen. Int J Hydrogen Energy. 2011;36:120-34.
- [11] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy. 2013;38:2039-61.
- [12] Ahern EP, Deane P, Persson T, Gallachóir BÓ, Murphy JD. A perspective on the potential role of renewable gas in a smart energy island system. Renewable Energy. 2015;78:648-56.
- [13] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, et al. Renewable Power-to-Gas: A technological and economic review. Renewable Energy. 2016;85:1371-90.
- [14] Díaz I, Pérez C, Alfaro N, Fdz-Polanco F. A feasibility study on the bioconversion of CO₂ and H₂ to biomethane by gas sparging through polymeric membranes. Bioresource Technology. 2015;185:246-53.
- [15] Benschmann A, Hanke-Rauschenbach R, Heyer R, Kohrs F, Benndorf D, Reichl U, et al. Biological methanation of hydrogen within biogas plants: A model-based feasibility study. Applied Energy. 2014;134:413-25.

- [16] Benjaminsson G, Benjaminsson J, Rudberg RB. Power-to-Gas—A technical review. Tech. rep., Svenskt Gastekniskt CenterAB (SGC); 2013. Available from: http://www.sgc.se/ckfinder/userfiles/files/SGC284_eng.pdf, accessed 21.9.2014.
- [17] Burkhardt M, Koschack T, Busch G. Biocatalytic methanation of hydrogen and carbon dioxide in an anaerobic three-phase system. *Bioresource technology*. 2015;178:330-3.
- [18] Browne JD, Allen E, Murphy JD. Assessing the variability in biomethane production from the organic fraction of municipal solid waste in batch and continuous operation. *Applied Energy*. 2014;128:307-14.
- [19] Browne JD, Murphy JD. Assessment of the resource associated with biomethane from food waste. *Applied Energy*. 2013;104:170-7.
- [20] Browne JD, Murphy JD. The impact of increasing organic loading in two phase digestion of food waste. *Renewable Energy*. 2014;71:69-76.
- [21] Singh A, Smyth BM, Murphy JD. A biofuel strategy for Ireland with an emphasis on production of biomethane and minimization of land-take. *Renewable and Sustainable Energy Reviews*. 2010;14:277-88.
- [22] Smyth BM, Smyth H, Murphy JD. Determining the regional potential for a grass biomethane industry. *Applied Energy*. 2011;88:2037-49.
- [23] Murphy JD, Power NM. An argument for using biomethane generated from grass as a biofuel in Ireland. *Biomass and Bioenergy*. 2009;33:504-12.
- [24] Smyth BM, Murphy JD, O'Brien CM. What is the energy balance of grass biomethane in Ireland and other temperate northern European climates? *Renewable and Sustainable Energy Reviews*. 2009;13:2349-60.
- [25] Allen E, Wall DM, Herrmann C, Xia A, Murphy JD. What is the gross energy yield of third generation gaseous biofuel sourced from seaweed? *Energy*. 2015;81:352-60.
- [26] Petersson A, Wellinge, A. Biogas upgrading technologies – developments and innovations. 2009. Available from: http://www.iea-biogas.net/files/daten-redaktion/download/publi-task37/upgrading_rz_low_final.pdf, accessed 21.07.2015.
- [27] Luo G, Angelidaki I. Integrated biogas upgrading and hydrogen utilization in an anaerobic reactor containing enriched hydrogenotrophic methanogenic culture. *Biotechnology and bioengineering*. 2012;109:2729-36.
- [28] Cottrell B. Is CNG the future for Ireland's freight and fleet vehicles? 2014. Available from: <http://www.engineersjournal.ie/cng-future-irelands-freight-fleet-vehicles/>, accessed 24.3.2015.
- [29] Twomey D. Compressed Natural Gas (CNG) in Ireland. 2011. Available from: <http://www.ngvireland.com/download/ngv2011/denisTwomey.pdf>, accessed 11.05.2015.
- [30] DKM economic consultant. CNG as a Transport Fuel - Economic Benefits. 2011. Available from: <http://www.ngvireland.com/download/ngv2011/annetteHughesJohnLawlor.pdf>, accessed 13.5.2015.
- [31] Smyth B, Gallachóir BÓ, Korres N, Murphy J. Can we meet targets for biofuels and renewable energy in transport given the constraints imposed by policy in agriculture and energy? *Journal of Cleaner Production*. 2010;18:1671-85.

- [32] Korres NE, Singh A, Nizami AS, Murphy JD. Is grass biomethane a sustainable transport biofuel? *Biofuels, Bioproducts and Biorefining*. 2010;4:310-25.
- [33] Ryan F, Caulfield B. Examining the benefits of using bio-CNG in urban bus operations. *Transportation Research Part D: Transport and Environment*. 2010;15:362-5.
- [34] Krupnick AJ. *Energy, Greenhouse Gas, and Economic Implications of Natural Gas Trucks*. Backgrounder Washington, DC: Resources for the Future. 2010.
- [35] Thamsiriroj T, Murphy JD. A critical review of the applicability of biodiesel and grass biomethane as biofuels to satisfy both biofuel targets and sustainability criteria. *Applied Energy*. 2011;88:1008-19.
- [36] Bacenetti J, Fusi A, Negri M, Guidetti R, Fiala M. Environmental assessment of two different crop systems in terms of biomethane potential production. *Science of The Total Environment*. 2014;466–467:1066-77.
- [37] Irish academy of Engineering pa. *The future of oil and gas, 2013*. 2013. Available from: <http://www.iae.ie/publications/publication/policy-advisory-the-future-of-oil-and-gas-in-irela/document/>, accessed 12.3.2015.
- [38] Official Journal of the European Union. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/39. EC; 2009. Available from, accessed.
- [39] Browne J, Nizami A-S, Thamsiriroj T, Murphy JD. Assessing the cost of biofuel production with increasing penetration of the transport fuel market: A case study of gaseous biomethane in Ireland. *Renewable and Sustainable Energy Reviews*. 2011;15:4537-47.
- [40] Burton T, Lyons H, Lerat Y, Stanley M, Rasmussen MB. *A review of the potential of marine algae as a source of biofuel in Ireland*. Dublin: Sustainable Energy Ireland-SEI; 2009. Available from: http://www.seai.ie/Publications/Renewables_Publications_/Bioenergy/Algaereport.pdf, accessed 22.2.2015.
- [41] Murphy JD, Drosig B, Allen E, Jerney J, Xia A. *A perspective on algal biogas*. 2015. Available from: http://www.iea-biogas.net/files/daten-redaktion/download/Technical%20Brochures/AD_of_Algae_ebook_end.pdf, accessed 21/09/2015.
- [42] Adams J, Toop T, Donnison IS, Gallagher JA. Seasonal variation in *Laminaria digitata* and its impact on biochemical conversion routes to biofuels. *Bioresource technology*. 2011;102:9976-84.
- [43] Xia A, Cheng J, Murphy JD. Innovation in biological production and upgrading of methane and hydrogen for use as gaseous transport biofuel. *Biotechnology advances*. 2015.
- [44] Reiter G, Lindorfer J. Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology. *The International Journal of Life Cycle Assessment*. 2015:1-13.
- [45] Adams R, Home D. *Compressed Natural Gas (CNG) Transit Bus Experience Survey*. Golden: National Renewable Energy Laboratory; 2010. Available from: <http://ngvamerica.org/pdfs/CNG%20Transit%20Bus%20Survey.pdf>, accessed 12.3.2015.

- [46] Singh A, Murphy JD. Biomethane from animal waste and grass for clean vehicular biofuel in Ireland. Proceedings Sardinia 2009, Twelfth International Waste Management and Landfill Symposium S. Margherita di Pula, Cagliari, Italy.
- [47] Alvarado-Morales M, Boldrin A, Karakashev DB, Holdt SL, Angelidaki I, Astrup T. Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. *Bioresource Technology*. 2013;129:92-9.
- [48] Murphy JD, Korres NE, Singh A, Smyth B, Nizami A-S, Thamsiriroj T. The Potential for Grass Biomethane as a Biofuel. 2011.
- [49] Irish Environmental Protection Agency. EPA projections show that Ireland faces considerable challenges to becoming a low-carbon economy. Available from: <http://www.epa.ie/newsandevents/news/previous/2014/name.54166.en.html#.VWxkz0ZSI8J>, accessed 22.03.2015.
- [50] Environment Protection Agency. Ireland's Environment: An Assessment. 2012. Available from: https://www.epa.ie/pubs/reports/indicators/00061_EPA_SoE_2012.pdf, accessed 22.4.2015.
- [51] Murphy JD, Browne J, Cork C, Allen E, Gallagher C. Assessment of the resource of biomethane.
- [52] Kommune S. Solrød Biogas - conception, project development and realization. 2014. Available from: <http://www.solrodbiogas.dk/en/documents.aspx>, accessed 16.11.2015.
- [53] Murrphy J, Drosig B, Allen E, Jerney J, Xia A, Herrmann C. A perspective on algal biogas. 2015. Available from: http://www.iea-biogas.net/files/daten-redaktion/download/Technical%20Brochures/AD_of_Algae_ebook_end.pdf, accessed 16.11.2015.
- [54] Herrmann C, FitzGerald J, O'Shea R, Xia A, O'Kiely P, Murphy JD. Ensiling of seaweed for a seaweed biofuel industry. *Bioresource Technology*. 2015;196:301-13.
- [55] Graf F, Krajete A, Schmack U. Techno-ökonomische Studie zur biologischen Methanisierung bei Power-to-Gas-Konzepten. 2014.
- [56] Montingelli ME, Tedesco S, Olabi AG. Biogas production from algal biomass: A review. *Renewable and Sustainable Energy Reviews*. 2015;43:961-72.
- [57] Murphy J, McKeogh E, Kiely G. Technical/economic/environmental analysis of biogas utilisation. *Applied Energy*. 2004;77:407-27.
- [58] Nkemka VN, Murto M. Evaluation of biogas production from seaweed in batch tests and in UASB reactors combined with the removal of heavy metals. *Journal of Environmental Management*. 2010;91:1573-9.
- [59] Allen E, Wall DM, Herrmann C, Murphy JD. Investigation of the optimal percentage of green seaweed that may be co-digested with dairy slurry to produce gaseous biofuel. *Bioresource Technology*. 2014;170:436-44.
- [60] Allen E, Wall DM, Herrmann C, Xia A, Murphy JD. What is the gross energy yield of third generation gaseous biofuel sourced from seaweed? *Energy*. 2015;81:352-60.
- [61] Dave A, Huang Y, Rezvani S, McIlveen-Wright D, Novaes M, Hewitt N. Techno-economic assessment of biofuel development by anaerobic digestion of European marine cold-water seaweeds. *Bioresource Technology*. 2013;135:120-7.

[62] González A, McKeogh E, Gallachóir BÓ. The role of hydrogen in high wind energy penetration electricity systems: The Irish case. *Renewable Energy*. 2004;29:471-89.

[63] SEM committee. Treatment of Curtailment in Tie-break situations. 2013. Available from:

http://www.allislandproject.org/en/transmission_current_consultations.aspx?article=2ac7b907-d8bf-4451-b111-34704b99d0c2, accessed 01.05.2015.

[64] Smyth BM, Smyth H, Murphy JD. Can grass biomethane be an economically viable biofuel for the farmer and the consumer? *Biofuels, Bioproducts and Biorefining*. 2010;4:519-37.