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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 CO_2. Biogas produced from anaerobic digestion typically comprises of 60% methane and 40% CO_2. The P2G system substitutes for the conventional upgrading system by using hydrogen (derived from surplus wind electricity) to react with CO_2 and increases the methane output. The potential CO_2 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 H_2 from curtailed electricity. Wind energy curtailment in 2020 in Ireland is assessed conservatively at 2175GW$_e$h/a. Thus P2G is limited by levels of curtailment of electricity rather than biogas systems. It is shown that 1 GW$_e$h of electricity used to produce H_2 for upgrading biogas in a P2G system can affect a savings of 97 tonnes CO_2. The cost of hydrogen is assessed at €0.96/m^3 renewable methane when the price of electricity is €c5/kW$_e$h. This leads to a cost of compressed renewable gas from grass of €1.8/m^3. This drops to €1.1/m^3 when electricity is purchased at €c0.2/kW$_e$h.

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: Continously 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: Slaugterhouse 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 500MW_e 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 GW_eh of energy from wind farms was estimated to be dispatched down in 2013; this is an increase of 86 GW_eh 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 CO_2 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 Thamsiriroj [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. CO_2 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].

$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$ $\Delta Hr = 286$ kJ/mole (at 25° C, 1 bar) (Eq. 1)

$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$ $\Delta H = -165$ kJ/mol (Eq. 2)

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 CO_2 is free from impurities (such as siloxanes); however, biological methanation requires less stringent quality and may use the CO_2 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^{o}C and 45-60 ^{o}C, respectively [7]. "In-situ" and "ex-situ" biogas upgrading are two methods for biological methanation. When H_2 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 H_2 react in a separate reactor (filled with hydrogenotrophic methanogenic archae), 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 CH_4 (40-75%) and CO_2 (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 CO_2 [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 CO_2) and gas cleaning (to remove impurities such as water and H_2S) 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.

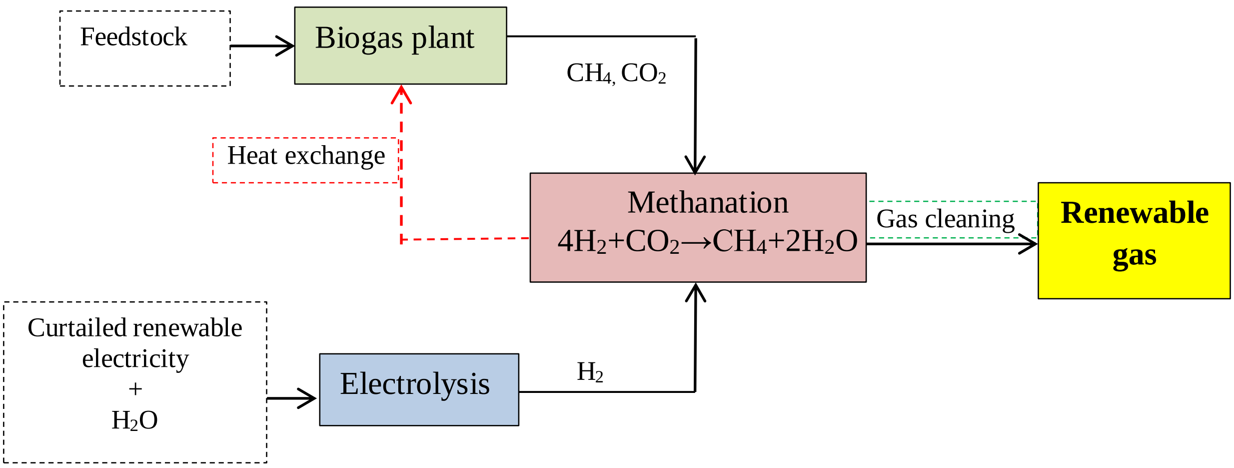

Figure 1: Design of biological P2G system as a biogas upgrading process

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 Mm^3/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 CO_2 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 seperate 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 finacial 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 CO_2 associated with potential levels of biogas in Ireland;
- Determining the limiting factor for power to gas: curtailed electricity or CO_2 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 = (wind generation + high voltage direct current imports)/ (system demand + 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 H_2 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 CO_2 from biogas is combined with H_2 to produce methane. The short term CO_2 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):

$$E = E_1 - E_2 \quad (3)$$

Where:

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).

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, slaugter 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 CH_4 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 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.

The $CO_{2\ emission}$ from well to wheel of diesel fuel was calculated through Eq. (5):

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

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_eh/t	10 kW_eh/t	10 kW_eh/t	6 kW_eh/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/kWeh			
Gas grid connection	€300,000			
CNG service station	€500,000			

*. CSTR: Continously stirred tank reactor

3. Results and discussion

3.1. The sources of CO_2 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 Mm^3 CO_2/a (58 m^3 CO_2/tonne feedstock) as a by-product of anaerobic digestion as illustrated in Table 2. This represents a significant available resource of concentrated CO_2 in Ireland.

Table 2: Quantifying the CO_2 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 CO_2 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 CH_4/kg VS [42]. Thus the methane yield may be calculated as 24.6 m^3 CH_4/tonne feedstock with the ratio of CH_4 to CO_2 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 tonnes*238m^3/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 ≈ 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%	2,255,098m^3/a*12MJ/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 CO_2 from biogas in Ireland in the year 2020 would be 430.6 Mm^3/a predominantly originating from agricultural slurries, slaughter waste, OFMSW and grass (Table 2); with just 0.6 Mm^3/a from seaweed (Table 3). If the total CO_2 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 H_2 through an electrolysis process, the H_2 amount would be sufficient to combine with 28.4% of CO_2 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 CO_2 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 H_2: $12MJ/m^3$, 1GWh = 3.6 TJ

- Efficiency from power to H_2: 75%
- H_2 volume is 4 times that of CO_2 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 CO_2 from biogas is utilised

The combination of CO_2 from biogas with H_2 creates additional value from CO_2 by utilising that CO_2 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 CO_2 can be fixed from biogas in a P2G system.

Box 1: CO_{2eq} saved when CO_2 in biogas is utilized to produce CH_4

Assumptions:

- Efficiency from Power to H_2: 75%;

Calculations:

E_1- CO_{2eq} saved to produce CH_4 by biogas upgrading:

Sabatier equation:	**$4H_2 + CO_2 = CH_4 + 2H_2O$**
Wind electricity curtailed in 2020:	2,175 GWh/a. 7.83 PJ
H_2 produced from curtailed electricity:	= (7.83 PJ/12 MJ/m^3)*75%= 489 Mm^3/a
CO_2 required ($H_2 : CO_2 \approx 4:1$):	= 489 Mm^3/4= 122 Mm^3/a
	= (122 Mm^3*1.96 kg/m^3)/1000=239,120 tonnes/a
CH_4 produced from combination of CO_2 and H_2 process[1] (1 $CO_2 \approx$ 1 CH_4)	122 Mm^3/a
E_2 – Total CO_2eq emitted from P2G process when producing CH_4:	= 122 Mm^3* 37.8 MJ/m^3 * 6 g CO_2/MJ =27,670 tonnes CO_2eq/a
Total CO_{2eq} saved (**E**) through utilisation of CO_2 from anaerobic digestion in P2G and CH_4 used as biofuel for transport[2]:	= 239,120 tonnes/a - 27,670 tonnes/a = 211,450 tonnes CO_2/a

Notes:

- E was calculated as Eq.(3)
- Density of CO_2 : 1.96 kg/m^3
- Energy value of H_2: 12 MJ/m^3;
- Energy value of CH_4: 37.8 MJ/m^3;
- Density of methane: 0.714 kg/m^3
- CO_2eq emitted from producing CH_4 by catalyst P2G process: 6 gCO_2/MJ [44]. The CO_2eq emitted from producing CH_4 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 CH_4 from biogas process.

[2] The CO_2 from the biogas plant will be released to the environment by conventional upgrading, therefore when it is utilised in combination with H_2, it is considered as CO_2 saved.

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

The total CO_2 from the feedstock needed to combine with H_2 produced from surplus wind energy is 122 Mm^3/a. The data from Table 2 shows that one feedstock source alone will not meet the demand of CO_2 for biological P2G. Therefore, it is assumed that the CO_2 will be sourced from biogas from SHW, OFMSW, agricultural slurries (Table 2) and seaweed (Table 3). The remainder (57.4 Mm^3/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 119.6m^3/tonne and energy content of biogas as 26MJ/m^3), 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 $kgCO_2$eq/tonnes dry seaweed [44], which equates to 35 gCO_2eq/MJ (at 133 m^3 methane yield/tonne dry seaweed and energy content of methane at 37.8 MJ/m^3); 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 Mm^3/a. Gas Networks Ireland have a target to fuel 10% of buses, 10% of trucks and 5% of commercial vans in 2020 (305 Mm^3/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: CO_2 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
		271 Mm^3/a
	Total CH_4 produced:	= (271 Mm^3/a * 37.8 MJ/m^3)/10^9 =10.24 PJ/a
	Energy content of biogas from OFMSW	0.57 PJ/a
E_4	CO_{2eq} emitted from cultivation, processing, transport and distribution of biogas from OFMSW:	= 0.57 PJ/a * 14.83 gCO_2eq/MJ **= 8,453 t/a**
	Energy content of biogas from agricultural slurries	1.88 PJ/a
E_5	CO_{2eq} emitted from cultivation, processing, transport and distribution of biogas from agricultural slurries:	= 1.88 PJ/a * 14.23 gCO_2eq/MJ =**26,752 t/a**
	Energy content of biogas from slaughter waste	0.68 PJ/a
E_6	CO_{2eq} emitted from production of biogas from slaughterhouse waste:	= 0.68 PJ/a * 10 gCO_2eq/MJ = **6,800 t/a**
	Energy content of biogas from grass	2 PJ/a
E_7	CO_{2eq} emitted from cultivation, processing, transport and distribution of biogas of from grass	= 2 PJ/a * 17.24 gCO_2eq/MJ = **34,480 t/a**
	Energy content of biogas from seaweed	0.026 PJ/a
E_8	CO_{2eq} emitted from cultivation, processing, transport and distribution of biogas of from biogas of seaweed:	=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	**CO_2 saved when biomethane and renewable methane replace diesel fuel:**	865,765 tonnes/a

Notes:

- $E_d = E_9 - E_4 - E_5 - E_6 - E_7 - E_8 + E$ 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 CH_4 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 CO_2 emitted for transport fuels was stated in the Irish Governmental Budget of 2012 [50]. If the renewable methane produced from wind energy curtailment and CO_2 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 2,190,000m^3 methane per year (at 1 $m_n^3CH_4 \approx$ 0.01MWh). For an ex-situ process, with biomethane at 98% methane content, this is equivalent to 2,234,694 m^3 biomethane. It may be assumed that half of the biomethane is derived from the original biogas, therefore approximately 1,117,347 m^3CH_4/a is from biogas. Taking the methane yield of each feedstock in Table 2 and 24.6 m^3CH_4/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):

$$y = 558.89 * x^{-0.159} \tag{6}$$

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 H_2S removal prior to digestion. The capital cost of a seaweed biogas plant in this study is assummed 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 varition 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 microrganisims are used as a biocatalyst is the poor solubility characteristic of H_2. Continuously stirred tank reactors, trickle-bed reactors and memberane 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 satisified 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 charactesitics 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_eh/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 assummed 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 H_2 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 biding price of electricity for P2G is 0.05 €/kWh therefore Ce in this study is assumed as 5 c€/kWh. Thus, the production cost of H_2/m^3 of methane in 2020 in Ireland is assessed as €0.96/m^3 renewable methane as shown in Box 3.

Box 3: Hydrogen production cost

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

= 3.53 * 5 = 17.65 €/GJ

Cost of hydrogen (excluding capital cost) per kWh = 17.65€/GJ /278kWh = 0.06 €

In which Ce 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 €/kWh

Sabatier equation: $4H_2 + CO_2 = CH_4 + 2H_2O$

To produce one cubic meter of methane, requires four cubic meters of H_2

1 m^3 H_2 contains 3 kWh

Cost of H_2/m^3 biomethane= 0.08 x $4m^3H_2/m^3CH_4$ x 3 kWh/m^3H_2 = 0.96 €/m^3

The production costs of biomethane from biological P2G with H_2 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 H_2 production accounts for a high portion in producing renewable gas, in which the cost of electricity used for H_2 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 H_2 production cost is the most expensive element of the total renewable gas cost, therefore, the variability of electricity price used to produce H_2 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 CO_2 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 Mm^3/a. If this CO_2 were used in a biological power to gas system, this would require 1722 Mm^3/a of H_2. 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. H_2 produced from curtailed electricity would be sufficient to combine with 28.4% of CO_2 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 H_2 for upgrading biogas in a P2G system can affect a savings of 97 tonnes CO_2. 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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