Title	The potential of power to gas to provide green gas utilising existing CO2 sources from industries, distilleries and wastewater treatment facilities
Author(s)	O'Shea, Richard; Wall, David M.; McDonagh, Shane; Murphy, Jerry D.
Publication date	2017-07-25
Original citation	O'Shea, R., Wall, D. M., McDonagh, S. and Murphy, J. D. (2017) 'The potential of power to gas to provide green gas utilising existing CO2 sources from industries, distilleries and wastewater treatment facilities', Renewable Energy, 114, pp. 1090-1100. doi:10.1016/j.renene.2017.07.097
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://dx.doi.org/10.1016/j.renene.2017.07.097 Access to the full text of the published version may require a subscription.
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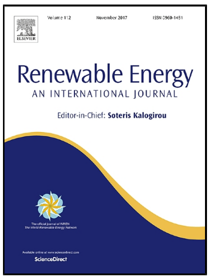
Embargo information	Access to this article is restricted until 24 months after publication by request of the publisher.
Embargo lift date	2019-07-25
Item downloaded from	http://hdl.handle.net/10468/4638



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PII: S0960-1481(17)30724-3

DOI: 10.1016/j.renene.2017.07.097

Reference: RENE 9072

To appear in: *Renewable Energy*

Received Date: 20 April 2017

Revised Date: 06 July 2017

Accepted Date: 24 July 2017

Please cite this article as: R. O'Shea, D.M. Wall, S. McDonagh, J.D. Murphy, The potential of power to gas to provide green gas utilising existing CO_2 sources from industries, distilleries and wastewater treatment facilities, *Renewable Energy* (2017), doi: 10.1016/j.renene.2017.07.097

The potential of power to gas to provide green gas utilising existing CO_2 sources from industries, distilleries and wastewater treatment facilities

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Abstract

The suitability of existing sources of CO_2 in a region (Ireland) for use in power to gas systems was determined using multi criteria decision analysis. The main sources of CO_2 were from the combustion of fossil fuels, cement production, alcohol production, and wastewater treatment plants. The criteria used to assess the suitability of CO_2 sources were: annual quantity of CO_2 emitted; concentration of CO_2 in the gas; CO_2 source; distance to the electricity network; and distance to the gas network. The most suitable sources of CO_2 were found to be distilleries, and wastewater treatment plants with anaerobic digesters. The most suitable source of CO_2, a large distillery, could be used to convert 461GWh/a of electricity into 258GWh/a of methane. The total electricity requirement of this system is larger than the 348GWh of renewable electricity dispatched down in Ireland in 2015. This could allow for the conversion of electricity that would be curtailed into a valuable energy vector. The resulting methane could fuel 729 compressed natural gas fuelled buses per annum. Synergies in integrating power to gas at a wastewater treatment plant include use of oxygen in the wastewater treatment process.

Keywords: Power to gas; Multi Criteria Decision Analysis; Renewable Energy; Energy Storage; Bioresource; Renewable Gas.

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1 Introduction

The 2020 climate and energy package aims to achieve by 2020: a reduction in greenhouse gas emissions of 20% compared to 1990 levels [1]; a supply of 20% of energy consumed in the EU from renewables [1]; and a 20% increase in energy efficiency [2]. In Ireland, the target for renewable energy by 2020 as a share of gross final consumption (GFC) is 16% [1]. This is to be achieved through a renewable energy supply in electricity (RES-E) of 40% of GFC, a renewable energy supply in transport (RES-T) of 10% of total final consumption (in line with Directive 2009/28/EC [1]), and a renewable energy supply in heat (RES-H) of 12% of total final consumption.

In 2015, Ireland's RES-E was 25.3%, with 84% of all of the renewable electricity generated by wind turbines [3]. The intermittent nature of the renewable energy generated in the Irish electricity system presents difficulties in matching supply with demand. The permitted quantity of non-synchronous variable renewable generation is governed by the system non-synchronous penetration (SNSP) metric as calculated as in Equation 1.

Equation 1: Calculation of system non-synchronous penetration

$$SNSP = \frac{Wind\ Generation + High\ Voltage\ DC\ Imports}{System\ Demand + High\ Voltage\ DC\ Exports}$$

When SNSP limits are reached the output of wind farms must be reduced, also termed as being "dispatched down". In 2015, ca. 348GWh was dispatched down, approximately 5% of the total wind generation in Ireland [4].

Increased limits for SNSP would result in a lower quantity of electricity being dispatched down, as a greater portion of system demand could be met by wind generation. Alternatively, increasing system demand for a given quantity of wind generation would reduce the instantaneous SNSP. Efforts to increase the SNSP limit in Ireland from 50% are underway with an expected SNSP limit of 75% to be achieved [5] by 2020; despite this, a certain amount of curtailment will occur, with estimates at 7% of total electricity generation from wind turbines [6].

A number of potential pathways for the use of excess renewable electricity have been proposed which include: use as source of energy and a reducing agent in the steel manufacturing industry [7], use in coal to liquid facilities to produce methane gas [8], and production of hydrogen and injection into the natural gas network [9]. Issues with integrating high levels of variable renewable electricity generation, and deploying power to gas (PtG) systems as a potential storage solution for surplus electricity have been discussed in several countries [10–15]. PtG (in this case power to methane) is the conversion of electrical energy into hydrogen (H_2) via electrolysis, followed by the conversion of this H_2 and carbon dioxide (CO_2) to methane (CH_4) via a Sabatier process ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$). While the conversion of electrical energy to CH_4 is a less efficient process than utilising the H_2 directly, CH_4 can be injected into the existing natural gas infrastructure. This allows for easier transportation, distribution, and use of the resulting energy vector.

In investigating PtG systems, prior work by Schneider and Kotter [15] identified sources of CO_2 which were in close proximity to the gas network and renewable electricity generators in Germany. A similar assessment was conducted for Austria by Reiter and Lindorfer [16]. However, neither study identified the most suitable sites for PtG facilities. Furthermore, the total potential use of electricity in PtG systems was not compared to the quantity of electricity dispatched down in either region. Ahern et al. [17] assessed the potential PtG resource in Ireland based on the theoretically available biogas resource. No assessment of the resource of PtG from existing CO_2 sources in Ireland was conducted.

The innovation in this work is associated with meeting the objectives of the paper, which are:

- To assess the suitability of existing sources of CO_2 for use in a PtG system in a region with a high level of installed wind capacity, in this case Ireland;
- Determine the energy resource of the most suitable CO_2 sources (in terms of CH_4 produced) and estimate the electrical energy required by the PtG systems;
- Compare the energy resource to natural gas demand and energy used in transportation;

- Outline potential configurations for the integration of power to gas facilities with the identified CO_2 sources.

2 Methods

2.1 Analysis criteria

The methodology used to assess the suitability of CO_2 sources for use in PtG systems was the Multi Criteria Decision Analysis (MCDA) method [18]. The MCDA method determines the suitability (S_i) of a given source of CO_2 (i) based on the score ($x_{i,j}$) that a given source of CO_2 achieves for a number of criteria ($j=1\rightarrow M$). The relative importance of each criterion can also be accounted for in the MCDA method by the application of weightings (w_j) to each. In this assessment each criterion was assigned an equal weighting, in the same manner as that applied by Smyth et al. [19] in assessing the biomethane potential of regions in Ireland. The suitability of a given CO_2 source was calculated using Equation 2.

Equation 2: Calculation of CO_2 Source Suitability

$$S_i = \frac{\left(\sum_{j=1}^{M} x_{i,j} * w_j\right)}{M}$$

Five criteria were selected to determine the suitability of CO_2 sources for PtG: total annual quantity of CO_2 produced (m_{CO2}); volumetric concentration of CO_2 in the gas stream (C_{CO2}); biological or fossil production of CO_2 (P_{CO2}); distance to the electricity network (D^{Elec}_{CO2}); and distance to the gas transmission network (D^{Gas}_{CO2}). The scoring system was on a scale of 1 to 10, with 1 being the least suitable and 10 the most. The range of values for each criterion was divided into 10 equal segments with the exception of biological or fossil production of CO_2 in which biological production was assigned a value of 10 and fossil production of CO_2 was assigned a value of 1 (elaborated upon in Section 2.3).

2.2 Annual quantity of CO_2 produced

2.2.1 Energy related CO_2 production

Annual energy related CO_2 production from the combustion of fuels for 76 of the largest emitters of CO_2 in Ireland, registered in the Emission Trading System (ETS), was obtained from annual environmental reports (AERs) from the Environmental Protection Agency (EPA) for 2015 [20]. Each facility had an installed thermal capacity in excess of 20MW. The activity class of each source was identified; the number of facilities in each activity class and the total CO_2 emissions per activity class can be seen in Table 1. The total annual emission of energy related CO_2 from each potential source was compared to the ETS licence for each site [21], to ensure that the figures were consistent.

Table 1 Industrial Sources of CO_2

Activity Class	Number of Facilities	Energy Related CO_2 emissions (t/a)
Brewing[a]	1	56,020
Cement Production	6	2,369,507
Confectionary	2	4,555
Dairy Processing	16	479,733
Distilling[a]	1	37,866
Meat Processing	7	34,288
Medical Devices	1	7,465
Mineral Extraction	2	216,295
Oil Refining	1	279,270
Pharmaceuticals	17	174,203
Power Generation	18	11,099,006
Processor Manufacturing	1	28,429
Wood Processing	3	7,510

[a] Emissions of energy related CO_2 from brewing and distilling in this instance are from the combustion of fuel onsite for energy production and do not include CO_2 emissions from the fermentation process

2.2.2 Alcohol production industry

Three large breweries and three large distilleries were identified as sites with high purity CO_2 generated in the production of alcohol. The three breweries were disregarded due to the on-site capture and use of CO_2 from the fermenters on site as outlined in their respective AERs. The annual CO_2 production of two of the distilleries (Distillery DA and Distillery DB) was based on information from personal communications with plant staff. Weekly production of pure alcohol was provided from Distillery DA and Distillery DB, this was used to estimate weekly and annual CO_2 production as outlined in Box 1 for Distillery DA.

Production of ethanol $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

Producing 1 mol C_2H_5OH produces 1 mol CO_2

46gC_2H_5OH also yields 44gCO_2

1gC_2H_5OH also yields 44/46=0.957gCO_2

Density of C_2H_5OH: 0.7893t/m^3

Weekly ethanol production: 1.23*10^{6}L

Weekly CO_2 production:

(1.23*10^6/1000)*0.7893*0.957=929.1tCO_2

Box 1: Calculation of CO_2 production based on distillery output for Distillery DA

Weekly production of CO_2 was sourced directly from Distillery DC (personal communication Distillery DC) and amounted to 92tCO_2 per week. Annual production of CO_2 from the distilleries assuming 52 weeks of operation per year can be seen in Table 2.

Table 2 Production of CO_2 at distilleries

Distillery	***Annual CO_2 Production (kt/a)***
DA	48.3
DB	1.58
DC	4.71

Note on distilleries: Only one distillery was large enough to be included in the ETS, the remaining two facilities have a thermal rating of less than 20MW

None of the distilleries capture the CO_2 produced in the fermentation process, as such it could be considered available for use in a PtG system as there is no significant on-site use for CO_2 at the distilleries.

2.2.3 Wastewater treatment

An additional source of CO_2 was biogas from the anaerobic digestion of sewage sludge at wastewater treatment plants (WWTPs). A total of 9 WWTPs with anaerobic digestion of sewage sludge were identified. Data on the annual biogas production by WWTPs was estimated using a biogas production per population equivalent (PE) of 24L_{Biogas}/PE/day [22]. Biogas was assumed to be 40%$_{vol}$ CO_2 [22,23]. The PE loading of each WWTP in 2015 was calculated using the total influent biological oxygen demand (kg BOD_{in}) in 2015 [20] and the BOD production per population equivalent of 60gBOD/day [24] as per Equation 3.

Equation 3 Calculation of PE loading of wastewater treatment plants

$$PE\ Loading = \frac{(kgBOD_{in}) * 1000}{60 * 365}$$

Calculation of the biogas production from WWTPs was also carried out based on the calculated sludge production and biogas yield outlined in Fernandes et al. [23] as a check. Both methodologies yielded similar results. The biogas production and associated CO_2 resource of each WWTP is shown in Table 3.

Table 3 Production of CO_2 at wastewater treatment plants

Wastewater Treatment Plant	***Loading (PE/day)***	***Biogas production (m^3/a)***	***CO_2 Production (t/a)^a***
WWTP1	1,933,205	1.69×10^7	13,299
WWTP2	250,011	2.19×10^6	1,720
WWTP3	214,409	1.88×10^6	1,475
WWTP4	97,832	8.57×10^5	673
WWTP5	88,876	7.78×10^5	611
WWTP6	84,820	7.43×10^5	583
WWTP7	72,226	6.33×10^5	497
WWTP8	54,322	4.76×10^5	374
WWTP9	45,503	3.99×10^5	313

[a] Annual mass of CO_2 produced based on 40%$_{vol}$ concentration of CO_2 in biogas, a molar mass of 44g, and a molar volume of 22.414L/mol.

2.2.4 Weightings applied to CO_2 emissions

For the MCDA, the range of CO_2 emissions was divided into 10 equal bands with a score of 1 to 10 applied to each, the highest CO_2 emission band was assigned a score of 10, the lowest CO_2 emission band was assigned a score of 1. The emission band of each source of CO_2 was determined and its score was found.

2.3 Volumetric concentration of CO_2 in gas stream

The volumetric concentration of CO_2 in exhaust gas from the combustion of fuel is dependent on the fuel type, the combustion technology, and the level of excess air used. This can be seen in Table 4, which is taken from scientific literature.

Table 4 Concentration of CO_2 in exhaust gas stream

Fuel	**Combustion method**	**CO_2 concentration (%volume)**	**CO_2 concentration (%volume)**	**CO_2 Concentration (%volume)**
Reference		[25]	[15]	Values used in this work
Natural Gas	Boiler	7-10	5-15	6.5
Natural Gas	Turbine	3-4	5-15	4
Oil	Boiler	3-8	5-15	3.5
Coal	Boiler	12-15	5-15	13.5
Cement kiln off gas		14-33		20
Biomass	Boiler	3-8		NA

Biogas was assumed to be 60% CH_4 and 40% CO_2 [22,23], while the concentration of CO_2 in gas from fermenters in distilleries was taken to be 99%. CO_2 present in the exhaust gas stream from a boiler or a turbine must be separated from the remainder of the gases present (such as N_2, O_2 and H_2O) before it can be sent to the methanation phase of a PtG system. The concentration of CO_2 in a gas stream influences the energy required to separate the CO_2 from the other gases present with higher concentrations of CO_2 reducing the energy requirement for separation and vice versa. The minimum theoretical thermodynamic work required, in an isobaric and isothermal process, for separation into a stream with a high concentration of CO_2 (for use in a PtG system) and a waste gas stream (with low CO_2 concentration), can be calculated as the negative of the difference of the Gibbs free energy of the final separated streams [26]. The work required per kg of CO_2 separated from each source of CO_2 can be seen in Figure 1. The sources of CO_2 were reclassified depending on the fuel they used and the combustion method if the exhaust gas originated from fuel combustion. The energy requirement was calculated according to the methodology outlined in Wilcox [26]. The concentrations of CO_2 in each gas stream were varied by +/-5% of the original concentrations to give an estimate of the variation in energy required for CO2 separation. A variation of +/-5% in the percentage of CO_2

captured and the CO_2 purity was also applied where applicable to indicate the range of potential energy requirements.

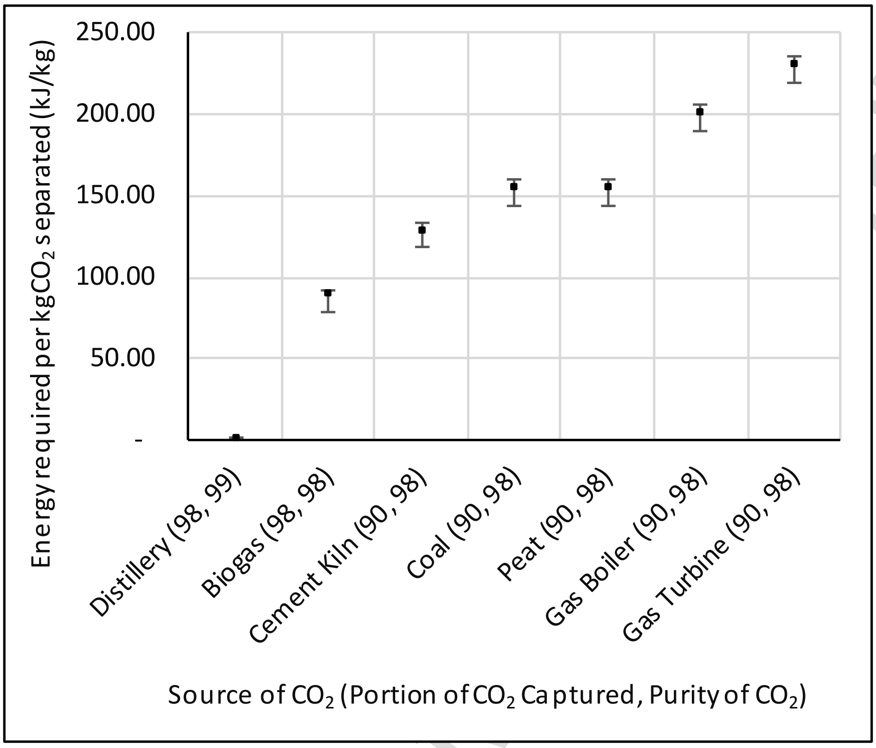

Figure 1: Theoretical work (kJ) required per kg of CO_2 separated from each source. Values in brackets correspond to the percentage of total CO_2 that is captured from a source, and the purity of the captured CO_2 respectively. Error bars illustrate the range in values for a variation of +/-5% of CO_2 concentration in the original gas stream and in the percentage of CO_2 captured and the CO_2 purity where applicable.

The range of energy requirement for CO_2 separation was divided into 10 equal bands, the band with the lowest energy requirement was assigned a score of 10, and the band with the highest energy consumption was assigned a score of 1. With respect to the MCDA, the score assigned to each source for the CO_2 concentration criteria was based on the band of energy consumption for CO_2 separation in which it was located.

2.4 Biological or fossil production of CO_2

The source of CO_2 used in power to gas systems can impact overall CO_2 emissions from the system. Approximate CO_2 emissions from 4 scenarios depending on whether the source of CO_2 used in the PtG system was biogenic (i.e. arising from a biological process) or non-biogenic (the combustion of fossil fuels) were determined based on the final quantity of CO_2 emitted by: the CO_2 source; PtG facility; and end user of the produced CH_4. Four idealised scenarios were considered as per Table 5.

Table 5 Scenarios of biogenic and non-biogenic CO_2 use in power to gas systems

Scenario	Source of CO_2	Fuel used in vehicle
S1	Combustion of fossil fuel at a power station	Combustion of diesel in a vehicle producing CO_2
S2	Capture of the CO_2 from combustion of fossil fuel at a power station and conversion to CH_4	Combustion of CH_4 offsetting diesel use in a vehicle.
S3	Production of CO_2 at a distillery	Combustion of diesel in a vehicle producing CO_2.
S4	Capture of CO_2 from the distillery and conversion to CH_4	Combustion of CH_4 offsetting diesel use in a vehicle.

The assumption in these scenarios is that $1m^3$ CO_2 can produce $1m^3$ CH_4 with an energy content of $37.78MJ/m^3CH_4$. The scenarios are based on the emission of $1m^3$ CO_2 from a fossil fuel fired power station, and the emission of CO_2 from the combustion of 30.98MJ of diesel (to account for a reduction in efficiency of CNG fuelled engines of ca. 18% [27]) with an emission factor of $94gCO_2/MJ$ [28,29]) in a diesel vehicle. The scenarios with a biogenic CO_2 source (a distillery) assume that the emission of $1m^3$ CO_2 is a result of the input of $1m^3$ CO_2 into the distillery in the form of the biomass accepted by the distillery. The CO_2 intensity of electricity used in the PtG system was taken to be $130gCO_2eq/MJ$ for Ireland [3]. The efficiency of the PtG system was taken to be 56% as per section 2.6. Scenarios S1 to S4 are illustrated in Figure 2.

The total amount of CO_2 emitted in each of the scenarios S1, S2, S3, and S4 is $4.875kgCO_2$, $10.733kgCO_2$, $1.483kgCO_2$, and $8.77kgCO_2$, respectively. The increase in CO_2 emissions in the system with PtG is a result of the CO_2 intensity of electricity used. If renewable electricity that would otherwise have been dispatched down is used the CO_2 emissions in S1, S2, S3, and S4 reduce to $4.875kgCO_2$, $1.963kgCO_2$, $1.483kgCO_2$, and $0kgCO_2$ respectively. Alternatively, guarantees of origin could be used to ensure that all of the electricity consumed by the PtG plant is sourced from renewable generators. In reality the CO_2 emissions from systems will be higher (owing to CO_2 arising in the operation of the process and the electricity used to produce the H_2 in the PtG system) however the total CO_2 emissions from a PtG system using biogenic CO_2 will be less than those from a PtG system using non-biogenic CO_2. As such, it was deemed important to distinguish whether the CO_2 source was in fact biogenic or non-biogenic. A biogenic source of CO_2 would result in lower emissions of CO_2 in the power to gas system than if a non-biogenic source of CO_2 were to be used. The score assigned to biogenic sources of CO_2 (distilleries, and WWTPs with anaerobic digestion systems) was 10 and the score assigned to a non-biogenic source of CO_2 (all other sources of CO_2 considered) was 1 as outlined in section 2.1.

2.5 Distance to electricity and gas networks

Proximity to both energy grids is important for the economic viability of PtG. Increased distance from each of the energy transmission grids leads to an increased cost of developing infrastructure to access these networks. The location of each source of CO_2 was determined from the AERs for each facility. A map of the electricity transmission network [30] was digitised manually in QGIS and the shortest distance from each potential CO_2 source to the network was determined.

Similarly, a map of the gas network, sourced from Gas Networks Ireland (GNI) was digitised manually in QGIS to allow for the calculation of the shortest distance from each potential source of CO_2 to the gas network. A map of the location of each of the identified CO_2 sources along with the electricity and gas transmission networks can be seen in Figure 3.

The distances from each energy grid were divided into 10 equal bands. The band with the shortest distance was assigned a score of 10, the band with the longest distance was assigned a score of 1 for these criteria. The score of each CO_2 source with respect to the distance to the electricity network, and gas network respectively, was based on the distance band it was allocated to.

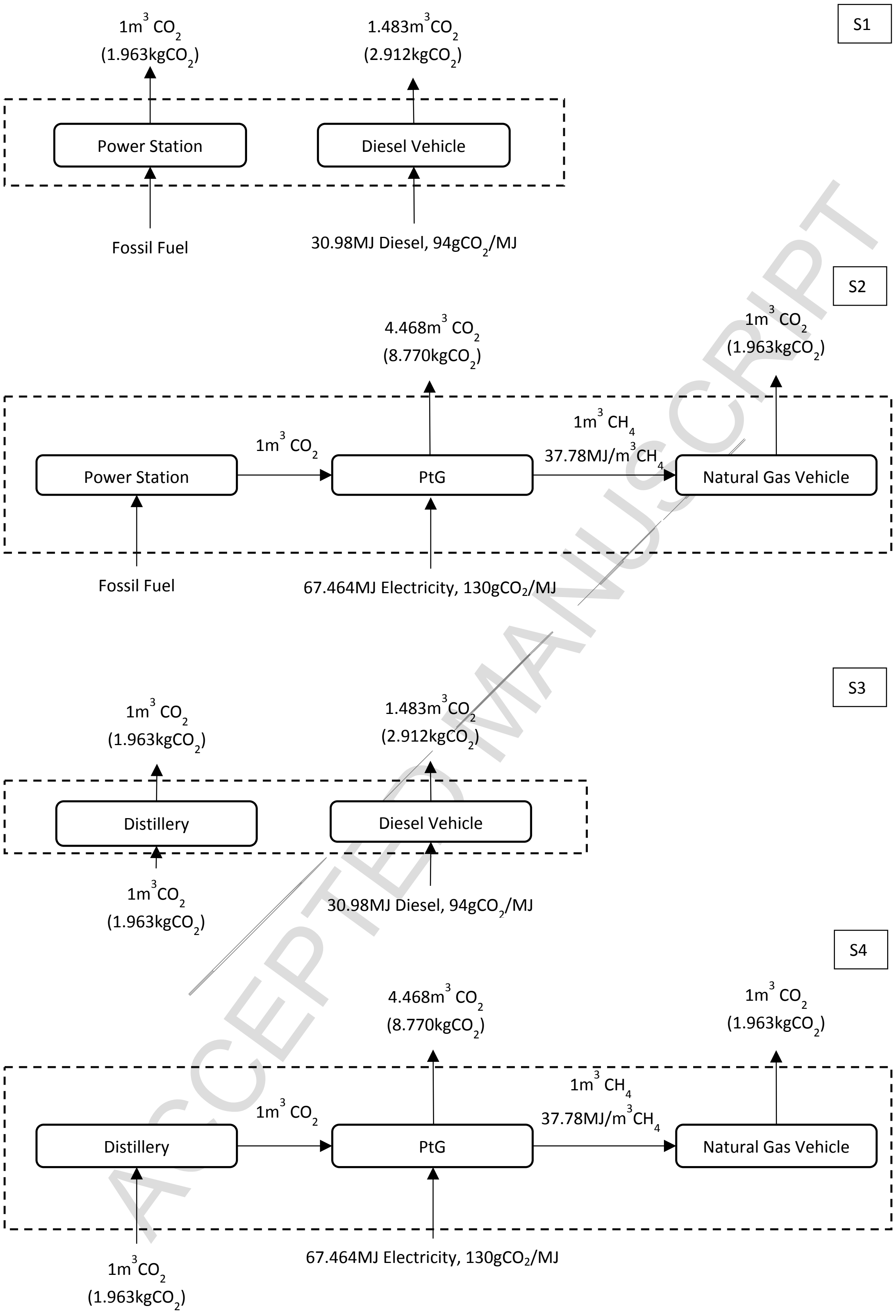

Figure 2: Scenarios for the use of non-biogenic or biogenic CO_2 in a PtG system.

2.6 Energy resource associated with sources of CO_2

The production of CH_4 from CO_2 according to the Sabatier process can be seen in Equation 4.

Equation 4: Production of CH4 from CO2 according to the Sabatier process

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The production of 1m³ CH_4 requires 1m³ CO_2. Knowing the annual mass of CO_2 (m^{CO2}_i) emitted at each CO_2 source (i), the potential volumetric resource of CH_4 (V^{CH4}_i) of each source was calculated according to Equation 5. In Equation 5 "M_{CO2}" corresponds to the molar mass of CO_2 (44g/mol) and "V_m" is the molar volume at STP, taken to be 22.414 l/mol.

Equation 5: Calculation of volumetric CH_4 resource associated with source of CO_2.

$$V_i^{CH_4}(m^3) = \frac{m_i^{CO_2}}{M_{CO_2}} * V_m$$

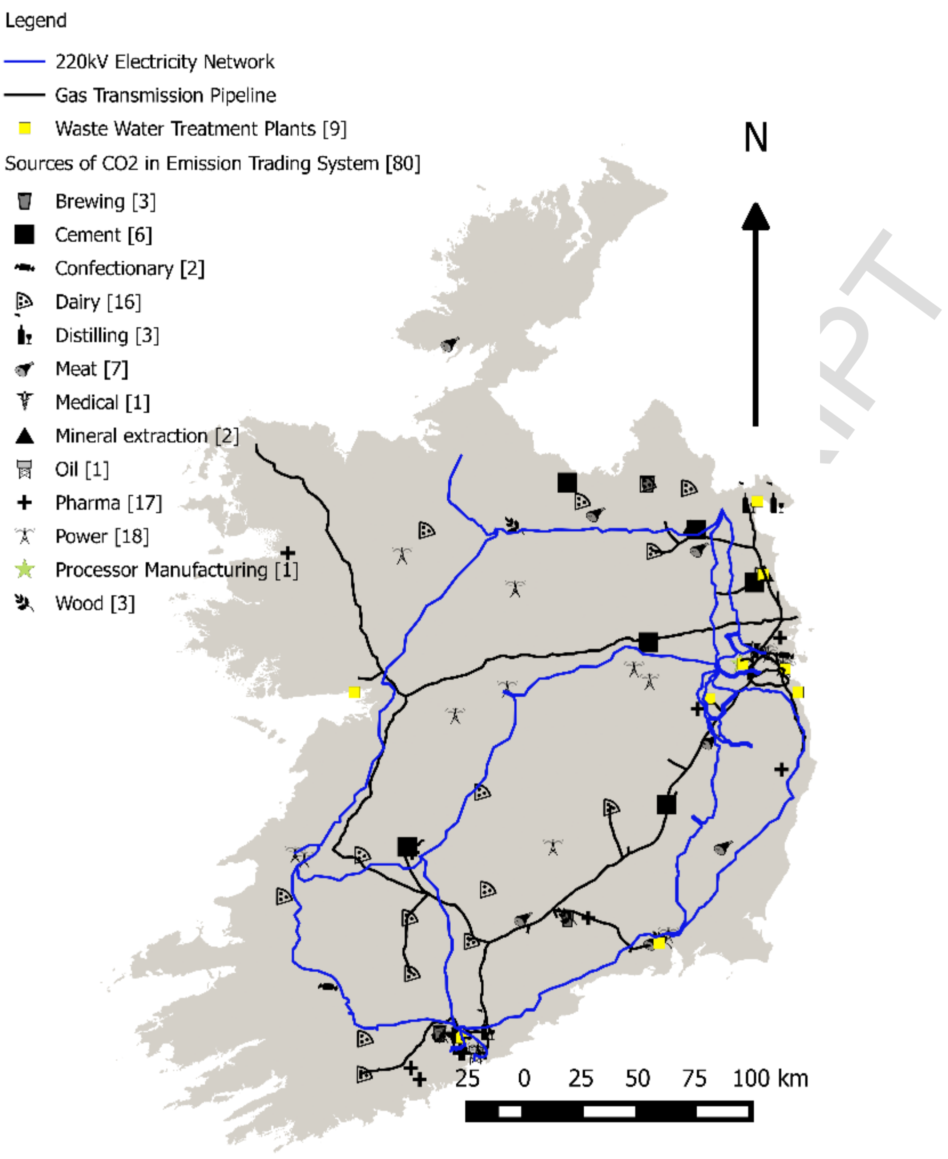

Figure 3: Map of sources of CO_2, electricity network, and gas transmission network. Energy transmission networks were manually digitised in QGIS and are a general guide of network locations only.

The energy associated with the potential resource of CH_4 at each CO_2 source was determined using an energy content of 37.78MJ/m^3 for CH_4 (e^{CH4}). Calculation of the electrical energy (E^{elec}) required (GWh) for the production of H_2 at each source was determined as per Equation 6. based on an 80% efficiency (η_{Meth}) of methanation, an average of efficiencies sourced from literature [10,11,16,31–41] and seen to be a conservative estimate, and a 70% electrolyser efficiency ($\eta_{Electro}$), the average of alkaline electrolysis system efficiencies sourced from literature [10,11,36,39,42–47]. Thus, the overall efficiency of PtG was 56%.

Equation 6: Calculation of electrical energy required for the production of H2 to be used in the PtG system. Division by a factor of 3,600,000 is to facilitate the conversion from MJ to GWh

$$E_i^{elec} = \frac{V_i^{CH_4} * e^{CH_4}}{\eta_{Meth} * \eta_{Electro}} * \frac{1}{3{,}600{,}000}$$

The efficiency of electrolysis and methanation were also varied by +/-5% of the values stated above to indicate the range of possible results.

The electrolyser size ($P_{electro}$) in MW_e required in a PtG facility was calculated assuming a number of full load run hours ($FLH_{electro}$) as per Equation 7. The value of $FLH_{electro}$ will depend upon a number of factors such as: electricity prices; gas prices; incentives; and maintenance schedules. Calculation of the value of $FLH_{electro}$ incorporating these parameters is beyond the scope of this work and a value of 8,000, which can be considered optimistic was used in this work. The number of full load hours was also varied by +/-5%, again to given an indication of the range of potential results.

Equation 7: Calculation of electrolyser size required at a potential PtG facility. Multiplication by 1,000 facilitates the conversion from GWe to MWe

$$P^{electro}_{i} = \frac{E^{elec}_{i}}{FLH_{electro}} * 1{,}000$$

2.7 Scale of potential energy resource and potential uses

The potential electricity consumption and CH_4 resource associated with the most suitable sites were compared to national values of curtailed electricity and natural gas demand. The total electrical energy dispatched down in the Republic of Ireland in 2015 amounted to ca. 348GWh [4]. Potential uses of the CH_4 produced in PtG facilities at the identified sources of CO_2 include combustion in gas boilers to produce heat, and use as a transport fuel in heavy goods vehicles and buses. Total natural gas consumption in the Republic of Ireland in 2015 was approximately 47,136GWh with 15,013GWh consumed in the industrial commercial sector [48]. The final energy consumption of road freight activities in 2015 for the Republic of Ireland was approximately 7,268GWh [3] of which 557GWh arose from the two main bus fleets in the country [49].

The number of Compressed Natural Gas (CNG) powered buses that could be fuelled using CH_4 from a PtG facility was based on a bus traveling 58,163 km per year [50] with a specific energy consumption of 22 MJ/km[51–56].

3 Results

The suitability score of the 12 highest ranking CO_2 sources can be seen in Table 6 along with the potential CH_4 resource available at each facility, the electrical energy required, and the electrolyser size. The locations of these facilities are also shown in Figure 4. The electrical energy required by each potential facility as a fraction of the total dispatched down electricity in 2015 in the Republic of Ireland can be seen in Table 7 coupled with a comparison to the total consumption of natural gas by industry, and the total energy consumed in heavy goods vehicles and buses in Ireland.

Table 6: Suitability score of 12 highest scoring CO_2 sources. Values shown are baseline results with results for -5% variation in input parameters and +5% variation in input parameters in parenthesis respectively.

Facility	***Facility Number***	m_{CO2}	C_{CO2}	P_{CO2}	D^{Elec}_{CO2}	D^{gas}_{CO2}	***Suitability***[a]	***Potential CH_4 Resource (GWh/a)***[b]	***Electrical Energy Required (GWh/a)***[c]	***Electrolyser size (MW)***[d]
Distillery DA (64ML/a)	1	1	10	10	10	10	8.2	258.21 (245.3, 258.21)	461.09 (485.36, 418.23)	57.637 (63.83, 49.78)
Distillery DC (6.24ML/a)	2	1	10	10	9	10	8	25.18 (23.92, 25.18)	44.96 (47.32, 40.78)	5.62 (6.23, 4.85)
WWTP2 (PE of 250,011)	3	1	8	10	10	10	7.8	9.19 (8.73, 9.19)	16.42 (17.28, 14.89)	2.052 (2.27, 1.77)
WWTP5 (PE of 88,876)	4	1	8	10	10	10	7.8	3.27 (3.11, 3.27)	5.84 (6.14, 5.29)	0.73 (0.81, 0.63)
WWTP7 (PE of 72,226)	5	1	8	10	10	10	7.8	2.66 (2.52, 2.66)	4.74 (4.99, 4.30)	0.593 (0.66, 0.51)
WWTP4 (PE of 97,832)	6	1	8	10	10	10	7.8	3.6 (3.42, 3.60)	6.42 (6.76, 5.83)	0.803 (0.89, 0.69)
WWTP6 (PE of 84,820)	7	1	8	10	10	10	7.8	3.12 (2.96, 3.12)	5.57 (5.86, 5.05)	0.696 (0.77, 0.6)
WWTP1 (PE of 1,933,205)	8	1	8	10	9	10	7.6	71.1 (67.54, 71.1)	126.96 (133.64, 115.15)	15.87 (17.58, 13.71)
Distillery DB (2.1ML/a)	9	1	10	10	7	9	7.4	8.47 (8.05, 8.47)	15.13 (15.93, 13.72)	1.891 (2.1, 1.63)
WWTP9 (PE of 45,503)	10	1	8	10	8	10	7.4	1.67 (1.59, 1.67)	2.99 (3.15, 2.71)	0.374 (0.41, 0.32)
WWTP8 (PE of 54,322)	11	1	8	10	8	10	7.4	2 (1.9, 2.0)	3.57 (3.76, 3.24)	0.446 (0.49, 0.39)
WWTP3 (PE of 214,409)	12	1	8	10	8	10	7.4	7.89 (7.48, 7.89)	14.08 (14.82, 12.77)	1.76 (1.95, 1.52)

[a] Suitability = $(m_{CO2}+C_{CO2}+P_{CO2}+D^{Elec}_{CO2}+D^{gas}_{CO2})/5$ as per Equation 2

[b] Sample calculation for Distillery DA: *(48,300,521kgCO_2)*(22.414/44)*(37.78)/(3,600,000)=258.21 GWh* as per Equation 5

[c] Sample calculation for Distillery DA: *(258.21)/(0.7*0.8)=461.09 GWh* as per Equation 6

[d] Sample calculation for Distillery DA: *(461.09*1000)/8000=54.637 MW* as per Equation 7

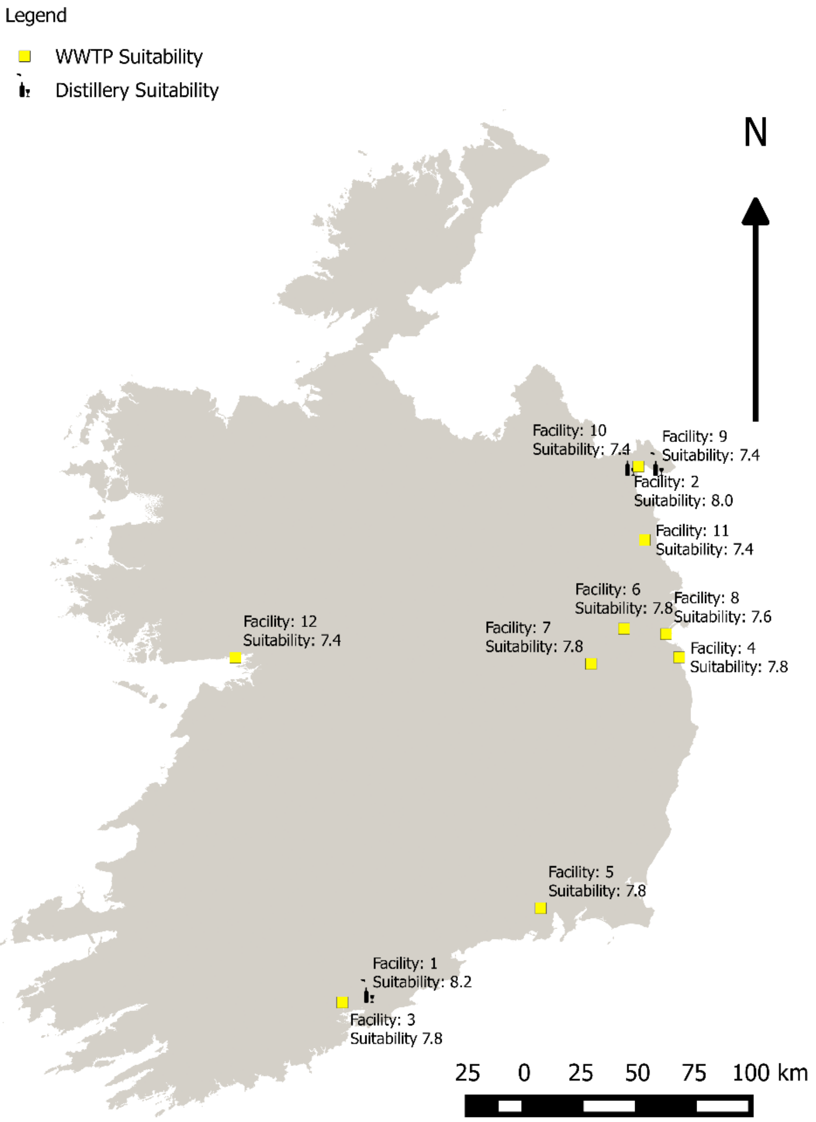

Figure 4 Location of most suitable CO_2 sources

Table 7: Comparison of results to annual figures of electricity dispatch down, industrial gas demand, freight transport energy use, and energy use in the main bus fleets in Ireland. Values shown are baseline results with results for -5% variation in input parameters and +5% variation in input parameters in parenthesis respectively.

Facility	*Facility Number*	*Share of dispatched down electricity in 2015 (%)*	*Share of industrial natural gas use in Ireland in 2015 (%)*	*Share of fuel consumption of heavy goods vehicles in Ireland in 2014 (%)*	*Share of fuel consumption of diesel buses in main fleets in 2015 (%)*
Distillery DA (64ML/a)	1	132.6 (139.6, 120.29)	1.72 (1.63, 1.72)	3.55 (3.37, 3.55)	46.38 (44.06, 46.38)
Distillery DC (6.24ML/a)	2	12.9 (13.61, 11.73)	0.17 (0.16, 0.17)	0.35 (0.33, 0.35)	4.52 (4.30, 4.52)
WWTP2 (PE of 250,011)	3	4.7 (4.97, 4.28)	0.06 (0.06, 0.06)	0.13 (0.12, 0.130	1.65 (1.57, 1.65)
WWTP5 (PE of 88,876)	4	1.7 (1.77, 1.52)	0.02 (0.02, 0.02)	0.04 (0.04, 0.040	0.59 (0.56, 0.59)
WWTP7 (PE of 72,226)	5	1.4 (1.44, 1.24)	0.02 (0.02, 0.02)	0.04 (0.03, 0.04)	0.48 (0.45, 0.48)
WWTP4 (PE of 97,832)	6	1.8 (1.95, 1.68)	0.02 (0.02, 0.02)	0.05 (0.05, 0.05)	0.65 (0.61, 0.65)
WWTP6 (PE of 84,820)	7	1.6 (1.69, 1.45)	0.02 (0.02, 0.02)	0.04 (0.04, 0.04)	0.56 (0.53, 0.53)
WWTP1 (PE of 1,933,205)	8	36.5 (38.44, 33.12)	0.47 (0.45, 0.47)	0.98 (0.93, 0.98)	12.77 (12.13, 12.77)
Distillery DB (2.1ML/a)	9	4.4 (4.58, 3.95)	0.06 (0.05, 0.06)	0.12 (0.11, 0.12)	1.52 (1.45, 1.52)
WWTP9 (PE of 45,503)	10	0.9 (0.9, 0.78)	0.01 (0.01, 0.01)	0.02 (0.02, 0.02)	0.3 (0.29, 0.3)
WWTP8 (PE of 54,322)	11	1 (1.08, 0.93)	0.01 (0.01, 0.01)	0.03 (0.03, 0.03)	0.36 (0.34, 0.36)
WWTP3 (PE of 214,409)	12	4 (4.26, 3.67)	0.05 (0.05, 0.05)	0.11 (0.1, 0.11)	1.42 (1.35, 1.42)
Total		203.5 (214.29, 184.65)	2.63 (2.51, 2.63)	5.46 (5.18, 5.46)	71.62 (67.64, 71.62)

Based on Table 6, the facilities with the highest suitability and potential energy resource are Distillery DA, Distillery DC (see Figure 4). Both facilities currently burn natural gas; the total consumption of natural gas of each facility in 2015 was approximately 188GWh and 60GWh respectively. The potential CH_4 resource available at Distillery DA and Distillery DC could meet 137% and 42% of the in house natural gas demand of each facility, respectively. The total number of CNG buses that could be fuelled by CH_4 from Distillery DA and Distillery DC would be 729 and 71 per annum, respectively.

Of the remaining facilities, all but one are WWTPs with existing anaerobic digestion facilities. The two WWTPs with the largest potential CH_4 resource areWWTP1 (PE of 1,933,205) and WWTP2 (PE of 250,011). Both plants thermally dry the digestate produced onsite using a combination of natural gas and biogas. The thermal energy required for the evaporation of 1kg of water from dewatered digestate was taken to be 0.98kWh (drying from 23% to 95% dry matter content). The total annual energy demand for the thermal drying of sludge was calculated to be ca. 49GWh and 8GWh for the WWTP1 and WWTP2 respectively. The potential energy resource associated with converting CO_2 from these facilities to CH_4 could meet 146% and 111% of the thermal demand for sludge drying in each WWTP. The total number of CNG buses that could be fuelled from each facility was found to be 200 and 26 per annum, respectively.

4 Discussion

4.1 Scale of resource and potential CO_2 emission reductions

The results of the MCDA show that the most suitable sources of CO_2 for the development of PtG facilities in Ireland were those, which had high concentrations of CO_2 and produced the CO_2 in a biological process such as alcohol fermentation, and anaerobic digestion. This is in agreement with work by Reiter and Lindorfer [16]. Additionally, these facilities were in close proximity to both the gas and electricity networks. The total resource of CH_4 (396GWh), which could potentially be produced by PtG systems was ca. 2.6% of industrial natural gas consumption, or 4.5% of the energy consumption of heavy goods vehicles in Ireland in 2015. The total electrical energy required to produce this potential CH_4 resource was found to be greater than the total quantity of dispatched down electricity from renewable sources (mainly wind turbines) in 2015. As such, PtG could be seen as an energy conversion mechanism for significant quantities of renewable electricity that would otherwise be dispatched down. As Ireland (as an EU state) heads to 80% reduction in GHG by 2050 and the associated increase in intermittent renewable electricity, as an island nation, the levels of electricity that will be dispatched down are likely to increase.

In terms of industrial gas use, the total theoretical resource of CH_4 arising from PtG facilities identified in this work could meet the annual energy requirement of the largest brewery in the country which consumed 291.5MWh of natural gas and has publically expressed interest in the use of renewable gas. It should also be noted that whiskey production in Ireland is undergoing significant growth, estimated to be approximately 220% between 2002 and 2012, with plans in place for up to 20 new distilleries and expansion of existing distilleries in order to increase production by 41% from 2015 levels [57]. GNI aim to supply approximately 1,440GWh of renewable gas in 2025 [48], the theoretical resource potential of PtG identified in this work could meet 28% of this goal.

In terms of energy consumption in transport, the total potential CH_4 resource identified could meet 71.6% of the energy consumption of the two main bus fleets in the country (the capital city bus service and the national bus service). The total theoretical CH_4 resource identified of 396GWh could fuel a total of 1,119 CNG fuelled buses. If the same number of buses, traveling the same distance were to be fuelled by diesel, with an approximate fuel efficiency of 17.36MJ/km, a total of 314GWh of diesel would be required. GNI have secured funding for the development of CNG service stations in line with Directive 2014/94/EU [58] to promote the use of natural gas as a transport fuel in Ireland, specifically in heavy goods vehicles and buses [59]. Development of a market for the use of CNG transport fuel would also allow for the use of methane gas produced in PtG systems in vehicles. GNI have a goal of supplying between 1,801-3,603GWh of CNG as a transport fuel in 2024-2025 [48].

CH_4 produced in the potential PtG facilities identified in this work could meet 11-22% of the projected CNG demand in transport.

4.2 Energy policy implications

The use of PtG systems to produce CH_4 from excess renewable electricity has a number of energy policy implications. Firstly, the use of PtG systems to convert renewable electricity into CH_4 gas acts as an energy storage mechanism for electricity that would otherwise have been wasted. Within Ireland this is significant as the only largescale energy storage system in existence is a pumped hydroelectric system (PHES), Turlough Hill. While new systems have been mooted, none have been developed in recent years. Within the EU, future potential for large scale energy storage systems such as PHES range from 4GWh to 123TWh depending on constraints considered [60]. There are concerns regarding the further development of PHES systems including the availability of environmentally acceptable sites [61]. In contrast the small footprint of PTG systems reduces the impact on the surrounding landscape and environment.

Secondly, PtG systems allow for the stored energy (in the form of CH_4) to be used in either the heat, transportation, or electricity sector [62]. In the case of transportation the renewable CH_4 produced from excess renewable electricity can be used as a source of renewable transport fuel within the EU and is classified as a renewable gaseous transport fuel of non-biological origin (Directive 2015/1513). The use of such renewable gaseous fuels is incentivised by weighting their energy contribution by a factor of 2 toward the target of renewable energy use in transportation of 10% by 2020 (Directive 2015/1513) [63]. Proposals for new EU legislation promoting the use of energy from renewable sources indicate that from 2021 fuel suppliers will be required to ensure that a minimum share of 1.5% of the fuel that they supply be in the form of advanced biofuels, these include renewable transport fuels of non-biological origin i.e. power to gas [64]. The proposed minimum share of advanced biofuels will increase to 6.8% by 2030, development of power to gas systems providing renewable transport fuel would aid in achieving this proposed target.

Thirdly, the implementation of PtG systems in Ireland would increase energy security in the transportation sector if the resulting CH_4 were to be used as a gaseous transport fuel. Ireland is heavily dependent on imported energy, 97.2% of the energy used in transportation in Ireland is derived from oil, all of which is imported [3] and 83% of biofuels (on an energy basis) currently used in Ireland are imported [65]. The potential resource of CH_4 from PtG systems that use existing sources of CO_2 could supply 71.6% of the current energy consumption of the two major public transportation bus fleets in the country if used in CNG fuelled buses. This would ensure that these public transportation fleets (which provided a total of 201.3 million passenger journeys in 2015 [50,66]) could be supplied with indigenously produced renewable energy. The potential to use excess renewable electricity in PtG systems to produce indigenous renewable transport fuel is not limited to Ireland, it is possible in any jurisdiction in which there is excess renewable electricity that cannot be stored.

4.3 Integration of a PtG facilities at a Distillery

Distillery DA, which has a theoretical CH_4 resource of 258GWh, could potentially fuel 729 CNG fuelled buses per annum. The bus fleet of the nearest city (24.7 km distant from Distillery DA) consists of 88 buses as of 2015, as such, if these buses were to convert run to on CNG, their annual fuel requirement would be a small fraction of the total theoretical CH_4 resource available at Distillery DA. It is also possible for the gas to be injected into the gas grid and become available for sale to any natural gas users on the natural gas grid, including other bus fleets in the country.

Integration of a PtG facility at Distillery DA could also result in potential synergies. One possible concept for the integration of a PtG facility at Distillery DA can be seen in Figure 4.

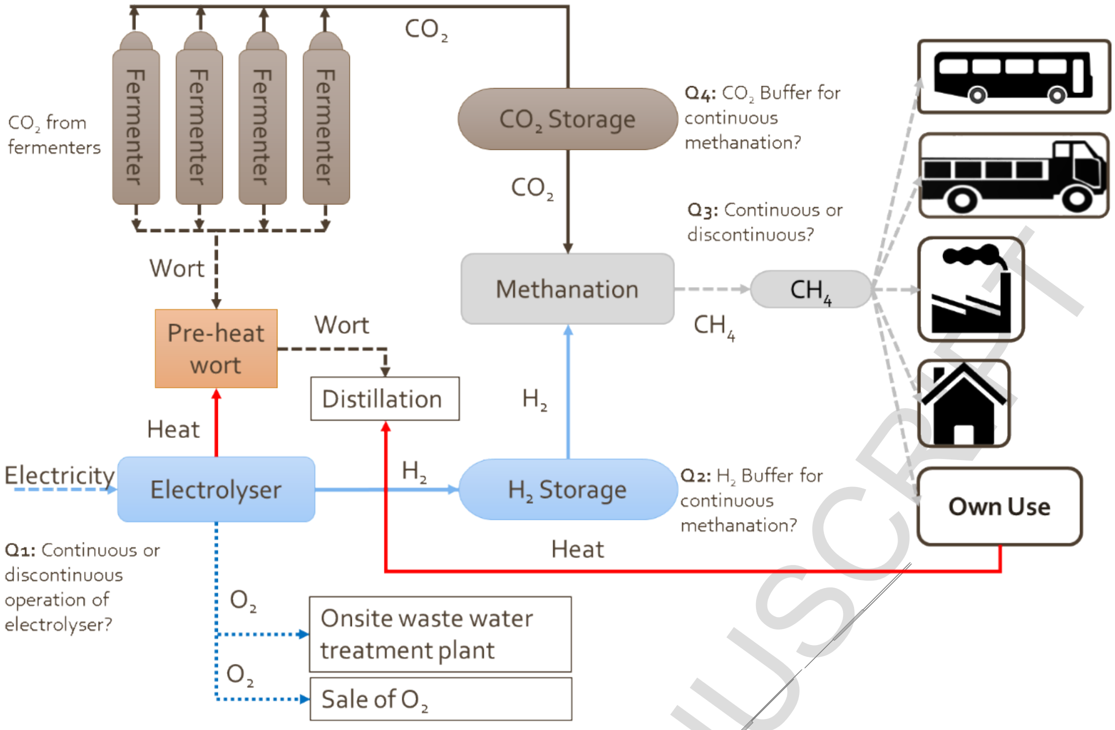

Figure 5: Possible integration of PtG facility with a distillery.

Integration of the PtG facility could allow for the use of waste heat from the electrolyser (or catalytic methanation system) to be used as a source of energy to pre-heat wort leaving the fermenters en route to the distillation process. Potentially reducing the consumption of natural gas by the distillery. Additionally, O_2 produced by the electrolyser could either be used in the on-site wastewater treatment plant, reducing the electricity demand for supplying air to the activated sludge (AS) process, or the O_2 could be captured and sold as a commodity. The produced CH_4 could be compressed and used as a transport fuel in CNG fuelled buses as outlined in prior sections, or it could be used as a transport fuel for heavy goods vehicles for transporting either raw materials to the distillery, or finished product from the distillery. Alternatively, the CH_4 could be compressed and injected into the gas network to be used by other industries, residential gas customers, or on-site to reduce the distillery's natural gas consumption. The optimal use of the produced CH_4 is outside the scope of this work. A number of questions (Q1 to Q4 in Figure 6) regarding the operation of the PtG plant remain. They relate to the optimal price that the PtG system pays for electricity, and whether the various components operate continuously or discontinuously. The answers to these questions would require a techno-economic model to determine the most cost effective mode of operation.

4.4 Integration of a PtG facilities at a Wastewater Treatment Plant

With regards to WWTP2, approximately 26 CNG fuelled buses could be fuelled by the CH_4 resource from a PtG facility at the plant. The integration of a PtG facility at the WWTP could have a number of configurations; three of these can be seen in Figure 5 outlined by the dashed boxes A, B, and C.

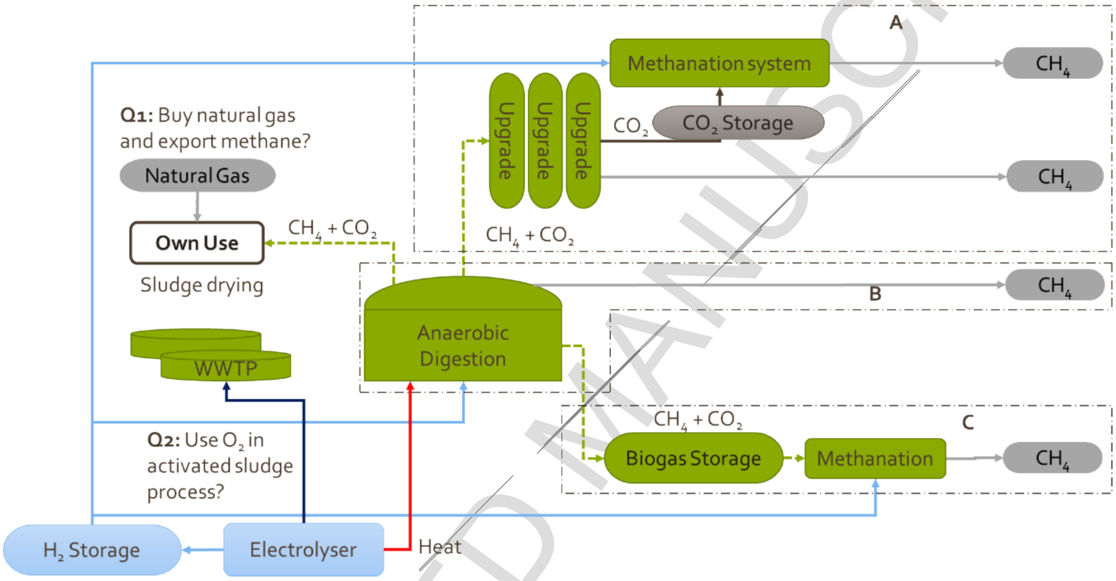

Figure 6: Potential integration of PtG facility with wastewater treatment plant

Box A outlines a setup in which biogas from the WWTP is separated into CO_2 and CH_4 in an upgrading plant. The CO_2 is then sent to an ex-situ methanation reactor via a possible intermediate CO_2 storage mechanism depending on whether or not the methanation system runs continuously. Such a system is similar to the Audi e-gas plant in Werlte, which utilises CO_2 from the upgrading system of a biogas plant adjacent to the PtG facility and is equipped with a catalytic methanation system. The Audi system (developed by ETOGAS GmBh) uses the waste heat from the methanation system in the biogas plant; a similar heat recovery system could be integrated at WWTP2 if a catalytic methanation system was used. The BioCat project in Denmark is aiming to trial a similar system. It will utilise CO_2 separated from biogas generated in a wastewater treatment plant and H_2 in an ex-situ biological methanation reactor to produce CH_4. The BioCat project also aims to investigate the use of O_2 produced by the electrolyser in the activated sludge process.

Box B outlines an in-situ biological methanation system in which H_2 is injected directly into the digester where it is consumed by hydrogenotrophic methanogenic archaea along with CO_2 to produce CH_4. Such systems have been proposed in the past; however, the impact of direct H_2 addition on the stability of the digestion process may be a limiting factor in the quantity of H_2 that can be added. Additionally, if the produced gas is to be compressed and injected into the natural gas network, the quantity of H_2 in the gas must be below the limits set by gas network operators.

Box C outlines an ex-situ methanation system, which is supplied with biogas directly from the digester (following a desulphurisation step). The methanation system can be either biological or catalytic; such systems have been proposed and developed by MicrobEnergy and BioCat using biological methanation systems, and by ETOGAS using catalytic methanation systems.

The most suitable method of integrating a PtG facility at WWTP2 is beyond the scope of this work, but would potentially take one of the routes proposed. Several questions concerning the operation of the system need to be investigated. These relate to the continuous or discontinuous operation of PtG system components, how the WWTP compensates for the electrical and thermal energy that was previously generated by biogas which is now sent to a PtG system, and what is the best use of the CH_4 produced in a PtG system. A techno-economic analysis of all the above scenarios should be carried out to determine the most suitable system.

5 Conclusions

Existing sources of CO_2, which could be used in PtG systems in Ireland were identified and their suitability was assessed using the MCDA method. The most suitable sources of CO_2 identified were distilleries and WWTPs. The potential CH_4 resource associated with the 12 sources of CO_2 with the highest suitability was approximately 396GWh, which would require over twice the total quantity of dispatched down renewable electricity in Ireland in 2015. The potential CH_4 resource represents

2.6% of the total natural gas consumption of Ireland in 2015, and 71.6% of the total energy consumption of the two main bus fleets in the country in 2015. The most suitable source of CO_2 for use in a PtG plant, Distillery DA, could in theory produce 258GWh of CH_4, which would require 132.6% of the total dispatched down electricity in 2015. This represents a significant possibility for the storage of renewable electricity that would otherwise have been wasted. The potential CH_4 resource from this single plant could fuel approximately 729 CNG fuelled buses, or completely offset its own natural gas consumption. Integration of a PtG facility in a distillery or WWTP can be achieved through several potential configurations, with potential synergies arising from the use of waste heat and O_2 produced by the electrolyser and methanation process. Further work is required in discerning the optimal method of integrating PtG plants with distilleries or WWTPs, as well as determining the optimal operational strategy to maximise plant profitability.

Acknowledgements

R. O'Shea, Dr. D. Wall, S. McDonagh, and Prof. J.D. Murphy were funded by the SFI centre MaREI (12/RC/2302) and Gas Networks Ireland through the Gas Innovation Group and by ERVIA.

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Highlights

- The suitability of 88 sources of CO_2 for use in a power to gas system was assessed
- The most suitable sources were distilleries and wastewater treatment plants
- Distillery A could produce 258GWh CH_4 from 461GWh of electricity to fuel 729 buses
- Distillery A could store 133% of curtailed electricity from wind turbines in 2015
- The top 12 CO_2 sources could supply 72% of energy used by the two main bus fleets