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

Truc T.Q. Vo [a, b, *], Ao Xia [a, b, c], David M. Wall [a, b], Jerry D. Murphy [a, b]

[a] MaREI Centre, Environmental Research Institute, University College Cork, Cork, Ireland
[b] School of Engineering, University College Cork, Ireland
[c] Key Laboratory of Low-Grade Energy Utilization Technologies and Systems, Chongqing University, Chongqing, 400044, China

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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 $2175GW_eh/a$. Thus P2G is limited by levels of curtailment of electricity rather than biogas systems. It is shown that 1 $GW_eh$ of electricity used to produce $H_2$ 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/$kW_eh$. 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/$kW_eh$.



## 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

* Corresponding author. Environmental Research Institute, University College Cork, Ireland.
*E-mail address:* truc.vo@ucc.ie (T.T.Q. Vo).

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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 |

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 to 84% [10,11]. Additionally, the efficiency of solid oxide electrolyzers is the range of 90–95% [12]. Therefore, this paper assumes 75% is the efficiency of the electrolyser as in Ahern et al. [12].

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)\ \Delta Hr = 286\ \text{kJ/mol (at 25 °C, 1 bar)} \quad (1)$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O\ \Delta H = -165\ \text{kJ/mol} \quad (2)$$

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 °C and 45–60 °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%–75% [16]. When the biogas and the $H_2$ react in a separate reactor (filled with hydrogenotrophic methanogenic archaea), a high methane content (up to 98%) can be achieved; this is known as an "ex-situ" process [17].

### 1.3. Biogas production and biogas upgrading methods

Biogas consisting of $CH_4$ (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 Fig. 1.