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Article

Investigation of the Multi-Point Injection of Green Hydrogen from Curtailed Renewable Power into a Gas Network

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Abstract: Renewable electricity can be converted into hydrogen via electrolysis also known as power-to-H_2 (P2H), which, when injected in the gas network pipelines provides a potential solution for the storage and transport of this green energy. Because of the variable renewable electricity production, the electricity end-user's demand for "power when required", distribution, and transmission power grid constrains the availability of renewable energy for P2H can be difficult to predict. The evaluation of any potential P2H investment while taking into account this consideration, should also examine the effects of incorporating the produced green hydrogen in the gas network. Parameters, including pipeline pressure drop, flowrate, velocity, and, most importantly, composition and calorific content, are crucial for gas network management. A simplified representation of the Irish gas transmission network is created and used as a case study to investigate the impact on gas network operation, of hydrogen generated from curtailed wind power. The variability in wind speed and gas network demands that occur over a 24 h period and with network location are all incorporated into a case study to determine how the inclusion of green hydrogen will affect gas network parameters. This work demonstrates that when using only curtailed renewable electricity during a period with excess renewable power generation, despite using multiple injection points, significant variation in gas quality can occur in the gas network. Hydrogen concentrations of up to 15.8% occur, which exceed the recommended permitted limits for the blending of hydrogen in a natural gas network. These results highlight the importance of modelling both the gas and electricity systems when investigating any potential P2H installation. It is concluded that, for gas networks that decarbonise through the inclusion of blended hydrogen, active management of gas quality is required for all but the smallest of installations.

Keywords: gas network; energy system; hydrogen; renewable storage; curtailed wind power

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1. Introduction

The challenge of reducing Green House Gas (GHG) emissions is a growing global concern as average global temperature continue to rise. Increasing human consumption patterns, recent wild fires, as well as nearly 90% of the global energy share coming from fossil fuels, can be counted as the major reasons for global GHG emissions, increasing by 11% in the last two decades [1,2]. Fossil fuels are accessible and cheap, and investments in associated infrastructure and developments are still prevalent. Within fossil fuels, there is a shift towards Natural Gas (NG), while this is partially due to NG having the lowest carbon emissions, it is primarily due to developments in the shale gas industry. NG had a 23% share of global primary energy consumption in 2018, with a 0.18% per annum increase [3]. The current contribution of NG to electricity generation in the world is 22%, while, in the EU, this figure is 19% [4]. In some countries, like Singapore, 95% of the electricity is generated from NG, while, in Ireland, 50% of the annual electricity is produced by NG and on occasions it can supply up to 80% of peak power demand [5]. As well as the increasing share of NG in thermal power generation, further reductions in GHG emissions can be achieved by increasing the share of renewables in the energy systems. However, due to the unpredictable nature of renewable generation, an increasing share of renewable generation makes balancing the supply and demand across large infrastructure networks very challenging. The gas network and electrical grid are historically interconnected through compressor stations and power plants. An increase in these network interconnections can be a way of achieving a more reliable and flexible energy system [6]. Gas pipelines can play a key energy storage role, and gas networks can provide back-up to variable renewable power, due to the quick start up time of gas fired power plants.

In weakly interconnected regions, such as the island of Ireland, supplying a higher share of primary energy from renewable electricity is a significant challenge, as resilience and flexibility must be largely contained within the system. According to the Sustainable Energy Authority of Ireland, Renewable Energy Sources (RES) contribute 10.6% of the gross final energy consumption, avoiding of 4.1 million tonnes of CO_2 emissions. The share of electricity generated from renewable sources in 2018 was 32.9%, and increased in 2019 to 36.8%, so it will be close to the 40% 2020 target [7]. Wind is the main renewable energy resource in Ireland and it is supplied by approximately 350 installed wind farms with a capacity of 4976 MW [8,9]. Constraints in the electrical grid, and stability considerations, can lead to periods of wind curtailment, i.e. wind power that cannot be transported to customers [10]. In 2017, the total value of Curtailed Wind (CW) was 386 GWh, which equaled 4% of available wind in Ireland [11], while, in 2018, the total electrical power generated was 11,076 GWh, with 707 GWh or 6% of the total available wind energy being curtailed. The majority of the CW typically occurs during the winter months, but it can vary quite dramatically through the year or even within a given day, depending on the available wind resources and the power demand. This CW is renewable energy that is currently lost and results in no benefit to either wind-farm or network operators, it is a missed opportunity to further reduce CO_2 emissions of the power system. The Irish National Development Plan (NDP) draws a long-term plan to reduce the country's GHG emissions, in which renewable power is projected to reach 70% by 2030, with natural gas continuing to be a key contributor to Ireland's primary energy needs, making up balance of the energy requirements for electricity [12].

Newly developed Power to Hydrogen (P2H) technology has the potential to be used for storage of this non-transportable renewable electricity by generating hydrogen or if the hydrogen is converted to methane or Synthetic Natural Gas (SNG) via methanisation, the process is known as Power to Gas (P2G) [13]. Hydrogen that is generated via electrolysers can be injected into the the natural gas pipelines, and/or it can be stored externally for use as the energy source for fuel cells or thermal batteries [14]. Currently, only pilot plant scale P2G system investments are occurring in Europe although numerous projects are in planning. The pilot plants have been in operation for a short period of time. Bassano (2019) [15] presented a global review on P2G pilot plants, the paper concluded that Polymer Electrolyte Membrane (PEM) electrolysers are the most suitable technology for this application due to their suitability for fast response time and high efficiency (up to 90%), with a specific energy consumption of 3 kWh/Sm^3. In contrast, configuring alkaline electrolysers that have a much lower capital cost is highly complex and they are not well suited for variable operation [15]. The main advantages of using P2G for RES are that it serves large-scale systems (bigger than 1 MW) and long term storage (more than one year) [16], reduces curtailed renewable power, reduces fossil fuel usage, and consequently the need for CO_2 capture [17].

In recent years, there has been increasing interest in P2G systems and their role for interconnecting electrical and gas networks. The article of Ameli et al. 2017 [18] investigated the potential role of battery storage and P2G systems when power generation included a large capacity of wind and solar sources.

A combined gas and electricity network model was utilised for the optimisation of an integrated Great Britain (GB) energy system over a predicted winter and summer of 2030. It was concluded that both systems present a contribution to reducing the operating cost. Energy supplier investment can be economically beneficial when the capital cost of the technologies reach a threshold of £0.5 million/MW for P2G, and £0.4 million/MW for battery energy storage systems. Research by Qadrdan et al. [19] performed a cost evaluation of P2G in an integrated gas and electricity system with varying levels of SNG. The major finding was that the overall operating cost of gas and electricity grids was reduced when using surplus wind to generate methane via P2G. In their paper, the focus was on steady-state modeling of a gas network, while injecting hydrogen as an alternative gas. The gas network was simplified in order to validate the method, and the results showed the pressure profile assuming various gas supply sources, which can support network management for reducing carbon emissions. It was found that making hydrogen using an electrolyser and injection into the GB gas grids can substantially reduce curtailed wind when there is high wind availability, which improves the optimal distribution for combined gas and electricity systems, while using cheap power to make hydrogen in P2G units. This causes a reduction in compression requirements when transporting hydrogen through the pipelines, and can also reduce the operational costs for both gas and power grids.

A steady-state model [20] described the optimisation of a power system operation when linked to a P2G plant for storing curtailed renewable power in gas pipelines. The outputs identify that for the GB network, P2G can lead to an additional annual integration of approximately 36 TWh of renewable power generation and 24 TWh of produced SNG which will increase renewable production by 15.6%. Moreover, it was identified that the introduction of P2G supplied gas into the gas network can decrease the annual natural gas cost by up to 4%. The sensitivity to blended hydrogen in different elements of the gas networks due to P2G has been undertaken by Gondal (2019) [21]; from the results, it is concluded that in the transmission network, compressors are the critical element and have a limiting value of 10% hydrogen, while the allowable hydrogen concentration in a gas turbine is 20%. Multi-vector energy analysis for the combined electrical and gas systems of the GB and Ireland was presented by Devlin et al. [22]. Both of the systems incorporated a share of wind energy and gas. In the Irish gas system, entry node congestion was shown to deliver a 40% increase in power generator run costs. Gas storage, using linepack capacity of pipelines, was shown to reduce the impact of high demand driven congestion delivering a reduction in total generation costs of 14% in the period studied and reducing electricity imports from GB, significantly contributing to security of supply.

The exact hydrogen concentration restriction depends on the type of network and the materials used. Compressors in transmission pipelines typically have an upper constraint of 10% hydrogen [21]. The distribution network could have up to 50% or 100% concentration of hydrogen without any safety concerns, depending on the type of pipeline materials and engineering standards [20]; however, due to end-user device requirements the allowable hydrogen fraction is less than 50% [23]. UN Regulation No. 110 [24] stipulates that compressed tanks in Compressed Natural Gas (CNG) vehicles (as end-users) have a hydrogen limit of 2–5%; most current gas turbines were specified for up to 5% hydrogen, but with some modifications they can be increased up to 10%. Some new or upgraded devices, such as burners, vehicle engines, and boilers, will be able to reach hydrogen concentration up to 20% [21]. Abeysekera, (2016) [25] investigated a gas network with a single injection point of alternative gas (hydrogen/biogas). The impact of blended gas on the operational pressure of the gas network was discussed, and the results showed that appropriately managed mixing of renewable-derived gas with natural gas could ensure satisfactory gas supply demand.

Several studies have been published concerning the potential for gas networks to interact with electricity grids as a storage system for excess electricity; [26–31]; However, these studies modelled and analysed the gas network without considering gas quality. Previous research projects on integrating NG networks and power grids that have focused on either modelling the effects of incorporating hydrogen into the NG pipelines on the operational parameters of the network, or investigated the impact of the hydrogen on the gas quality [20,21,25,32]. In all of these studies, hydrogen injection at a single node was investigated; however, if P2H becomes a commonplace technology, then multiple injection points of hydrogen are the most likely reality. Therefore, in order to determine whether or not active management of gas network quality is required, this study focuses on a gas network model utilising only curtailed wind for hydrogen production via P2H. It combines both varying hydrogen production profiles with different gas end-user profiles in order to calculate the main physical characteristics of the NG network at all nodes and through pipelines. Through an investigation of the changes in the operation of the NG network along with gas quality following hydrogen injection from multiple points, gas network characteristics, including energy density, pressure drop, flow rate, compressibility factor, and density, have been determined. In addition, the operation of the gas network under the dynamic scenario is contrasted, with, incorporating hydrogen from the combined curtailed wind at three nodes of varying natural gas flowrates individually, as well as hydrogen at a constant rate.

2. Methodology and Modelling

In order to evaluate the impacts of incorporating multiple P2H injection points into a gas network, a simplified model of the Irish gas network was created, as in Figure 1. The network includes 28 pipelines and 25 nodes, including 3 natural gas supply nodes (nodes 1, 2, and 3), 19 demand nodes that are split into two groups; gas-fired power plants, and town gates. There are three hydrogen supply nodes 23, 24, and 25, which are located in the west, southwest, and northeast parts of the gas network. The location of the P2H nodes is due to electrical network congestion near these locations, where there is a large capacity of installed wind generation, but low electrical power demand. The pressure set-point at the gas supply (reference) nodes is 70 Barg, while the pressure at all other nodes is calculated in the model. Data from the dashboard reporting website of Gas Network Ireland (GNI) are used to estimate the energy required at each demand node. Full gas network details are provided in the Table A1 in Appendix A.

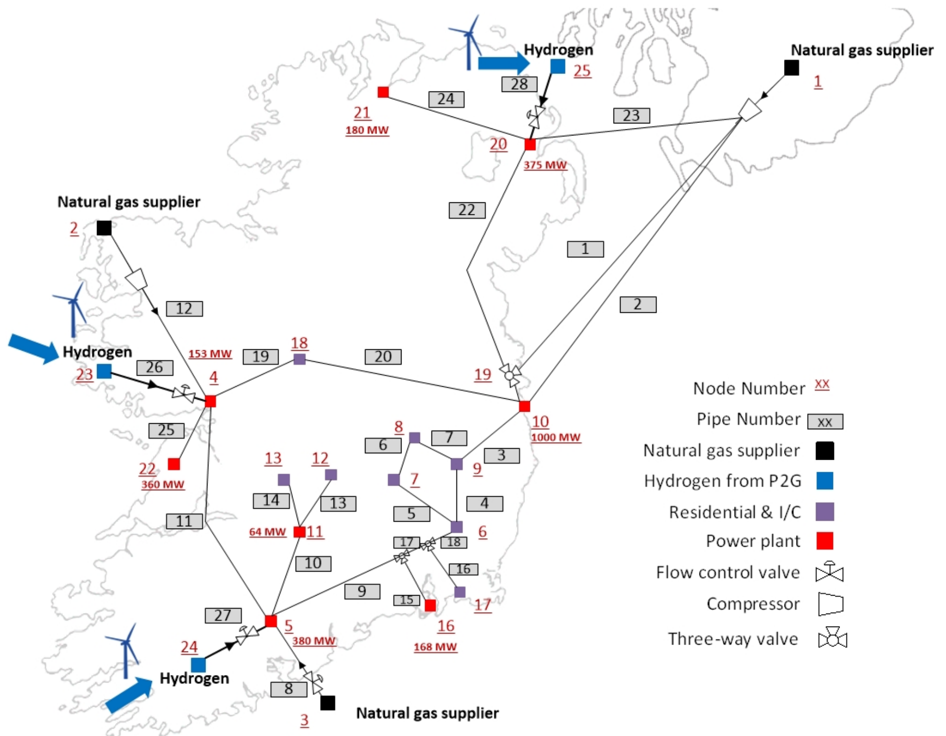

Figure 1. The simplified island of Ireland Gas network with multi P2H interconnection nodes.

Hydrogen generation profiles are mapped to the P2H nodes based on curtailed wind profile of a windy day in October 2017 in order to investigate the maximum potential levels of hydrogen concentration in the gas network. It is assumed that all potential curtailed wind is sent to the P2H units to generate hydrogen with a conversion efficiency of 65%. The operation of the electrolyser is not investigated in this work.

2.1. Gas System Modelling

The approach taken to modelling the gas network is similar to the approach taken by Osiadacz (1987) [33] and it has been previously used by Ekhtiari et al. (2019) [34]. Where using Matlab, a set of differential equations solve the flow and pressure requirements in the gas network. The equations satisfy the basic physical laws of mass conservation, conservation of momentum, and the first law of thermodynamics. A schematic representation of the forces acting on the pipeline can be observed in Figure 2. Through a combination of Bernoulli's equation of fluid flow Equation (1) and Newton's second law of forces Equation (2), the pressure drop due to the flow of the gas in the pipeline can be determined.

$$\frac{p}{\rho g} + \frac{v^2}{2g} + z = \frac{p + dp}{\rho g} + \frac{(v + dv)^2}{2g} + (z + dz) + dh_f \tag{1}$$

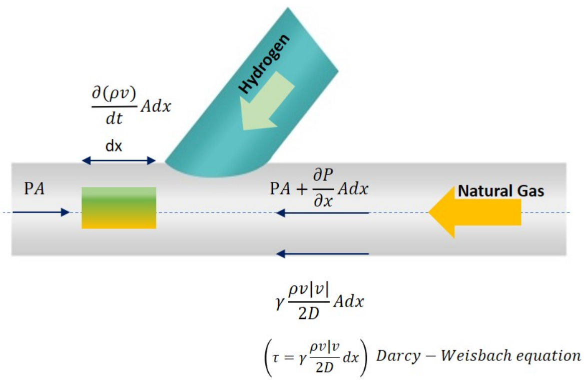

Figure 2. Effective forces on a specific volume of gas flow through a pipeline.

In Equation (1), "dh_f" is the head losses and "z" is the height parameter. The variable pressure, p, and displacement, x, have been changed to $p + dp$ and $x + dx$, respectively.

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v^2)}{\partial x} + \frac{\partial p}{\partial x} + \frac{f \rho v|v|}{2D} + \rho g sin(\theta) = 0 \tag{2}$$

In Equation (2), the constituent terms are:

$\frac{\partial(\rho v)}{\partial t}$: inertia force (acting against the flow direction through the pipe)

$\frac{\partial(\rho v^2)}{\partial x}$: convective term

$\frac{\partial p}{\partial x}$: pressure force

$\frac{f \rho v|v|}{2D}$: shear force

Equation (3) is the sum of internal energy associated with molecular and atomic behaviour ,"U", kinetic energy "$\frac{1}{2}mv^2$" , and the potential energy that is associated with the height "mgz". When no work is done on a system and the pipeline temperature changes can be neglected ([33,35–37]), the change in energy of the gas flowing is due to the frictional losses in the pipeline.

$$E = U + \frac{1}{2}mv^2 + mgz \tag{3}$$

$$d\Omega = \frac{\partial(\rho A dx)}{\partial t}(u + \frac{v^2}{2} + gz) + \frac{\partial(\rho v A)}{\partial x}(u + pv + \frac{v^2}{2} + gz)dx = 0 \tag{4}$$

$$\frac{\partial p}{\partial x} = -\frac{\rho_n}{A}\frac{\partial Q}{\partial t} - \frac{f\rho_n^2 ZRTQ|Q|}{2\eta_t^2 DA^2 p} - \frac{gsin(\theta)}{ZRT}p \tag{5}$$

$$\frac{\partial p}{\partial t} = -\frac{\rho_n ZRT}{A}\frac{\partial Q}{\partial x} \tag{6}$$

where "ρ_n" and "Q" are the density at standard conditions and gas flow rate. "A" and "D" are the cross sectional area and inner diameter of the pipe, and "p" in Equation (5) is the average pressure between two nodes. "η_t" is the efficiency of pipe friction factor to convert theoretical friction to actual friction factor (Equation (7)) .

$$\sqrt{\frac{1}{f}} = \eta_t\sqrt{\frac{1}{f_t}} \tag{7}$$

The compressibility factor "Z" depends on the pressure and temperature of gas, and it was calculated by the PAPAY-equation, which is applicable for high pressure networks [38] Equation (8).

$$Z = 1 - 3.52(\frac{p}{p_c})exp[-2.260(\frac{T}{T_c})] + 0.274(\frac{p}{p_c})^2 exp[-1.878(\frac{T}{T_c})] \tag{8}$$

$$\frac{\partial p}{\partial x} = -\frac{f_t\rho_n^2 ZRTQ|Q|}{2\eta_t^2 DA^2 p_{avg}} - \frac{gsin(\theta)}{ZRT}p_{avg} \tag{9}$$

Because of the relatively slow response time of pipeline variables and large time spans in hourly steps, a quasi-transient approach is taken in combining the Equations (6) and (9) (the continuity and pressure drop equations). The gas network model calculates network variables and parameters while using the Newton–Raphson numerical iteration method [34]. For a given pipe$_{ij}$, then the volumetric flow rate Q_{ij} through the pipe can be expressed by Equation (10).

$$\forall\, i,j(in\,\&\,out) \in \mathcal{L}_{length}, \,, t \in T_{time\,span}: \left[p_{i,t}^2 - p_{j,t}^2 = a_{ij}^t|Q_{ij}^t|Q_{ij}^t + b_{ij}^t(p_{i,t} + p_{j,t})^2\right] \tag{10}$$

$$where: a_{ij} = \frac{16 f_{ij}\rho_n^2 Z_{ij} RT l_{ij}}{\pi^2 D^5},\; b_{ij} = \frac{g l_{ij} sin(\theta)}{2Z_{ij}RT} \tag{11}$$

2.2. Variable Gas Composition

The Higher Heating Value, HHV$_i^m$ is the measure of energy content per unit mass of a gas, if the hydrogen fraction makes up X_{H2}, and natural gas components are X_i, then the energy content (HHV, MJ/m^3) of the blended gas in the pipelines can be calculated while using Equation (13). In the model that is presented in this work, the energy demand at each node is specified at each time point; therefore, as the composition of gas changes, so too does the HHV and the associated gas demand. To account for this additional variation in HHV through out the network, the gas network model is run and the specific natural gas demand for that hour is determined. The generated hydrogen profile is then incorporated and the model recalculated in order to assess how blending hydrogen impacts the gas flow rate downstream of the hydrogen injection and the delivery of energy to the end-user when considering the change in gas quality based on its composition. Then to satisfy end-users energy requirements the flow rate in a subsection of network is adjusted in order to compensate for the energy shortfall.

$$\forall\, i \in \mathcal{NG}_{composition(i)} : X_i = \left[X_i^{NG} \times (1 - X_{H_2})\right] \quad (12)$$

$$\forall\, i \in \mathcal{NG}_{composition(i)} : HHV_{blended\,gas} = \sum[HHV_i \times X_i \cdot \rho_{ni}] \quad (13)$$

$$\forall\, i \in \mathcal{NG}_{composition(i)} : HHV_{NG} = \sum[HHV_i \times X_{NG(i)} \times \rho_{ni}] \quad (14)$$

$$\forall\, i, j \in \mathcal{L}_{ij} : Energy\,Flow_{ij} = HHV_{ij} \times Q_{ij} \quad (15)$$

$$\forall\, i \in \mathcal{L}_d : Energy\,Demand(i) = L_{d,i} \times HHV_{NG} \quad (16)$$

$$\forall t \in time(hour),\ k \in hydrogen\,source: \quad H_2^{k,t}\,Energy = \frac{HHV_{H_2},(MJ/m^3)}{SG_{H_2}} \times V_{H_2}^{k,t},(m^3) \quad (17)$$

where ρ_{ni} represents the normal density of each natural gas component (C_1, C_2, C_3, nC_4, iC_4, N_2, H_2, CO_2) and $L_d i$ is the gas load at each $node_i$.

2.3. Scenario

The Irish energy system makes an ideal case study in which to investigate the potential benefits and associated impact of P2H due to the limited interconnection with other networks, and the high dependence of the power system on natural gas as a back up fuel. In Ireland, due to the North Atlantic Stream, the majority of low pressure weather events come from the south west and these events often result in the curtailment of excess wind power. The coastal regions in Ireland of the South, West, and North have particularly good wind resources, while the major population lives in the east, leading to the possibility of network constraints. In 2017, total wind dispatch-down a combination of curtailment and constraint in the Island of Ireland was 386 GWh, while curtailment (oversupply) is relatively easy to determine, the lost wind due to constraints is very network specific and not investigated in this study. The gas network while having a larger capacity than the electrical network has limited coverage. Therefore, in order to present a somewhat realistic scenario, three locations were chosen for P2H. The main criteria identified for identifying suitable locations for P2H are:

- P2H location should be close to source of renewable electricity so that the impact of local electrical network constraints are minimised;
- P2H location should be close to gas pipelines; and,
- injection of hydrogen into pipelines with a high flow rate of the NG will minimise variations in the hydrogen fraction.

During October 2017, there were a number of high wind periods, which resulted in wind power curtailment. In this research, a "windy" day in October 2017 is chosen as the case study for a weather event that brought about an significant increase in curtailed wind. Because the goal of this research is to investigate the impact which Hydrogen will have on the gas network 24 h was deemed a sufficient time period. This event occurred on 11 October 2017 and the wind speed profiles were obtained from "Met Eireann" data base Figure 3a for 24 h at the three different regions in Ireland. This operation of the gas network during this scenario is then compared with the operation of the gas network, incorporating H2 from a 10MW electrolyser at a single node over the same time period. A 10 MW PEM electrolyser is currently the largest commercially available unit.

2.4. Curtailed Wind and Gas Demand

The wind power generated in each region has been calculated from the wind speed profile using a linear correlation between wind speed and power produced. A direct liner relationship between the wind speed and produced power is proposed by "ElectroRoute" [39] in their analysis of the impact of a windy day on the Irish power system. However, these calculations are just an estimation of available wind power in each region, extracting a precise profile would require a more detailed knowledge of all the wind farm characteristics and status on the day, which is not part of this study. According to EirGrid report [10], 5.5 to 6% in the south and the west and about 9% of available wind power was curtailed in the north regions of Ireland on 11 October 2017. Therefore, the CW for each available wind profile can be calculated by multiplying these percentages by available wind profiles Figure 3b.

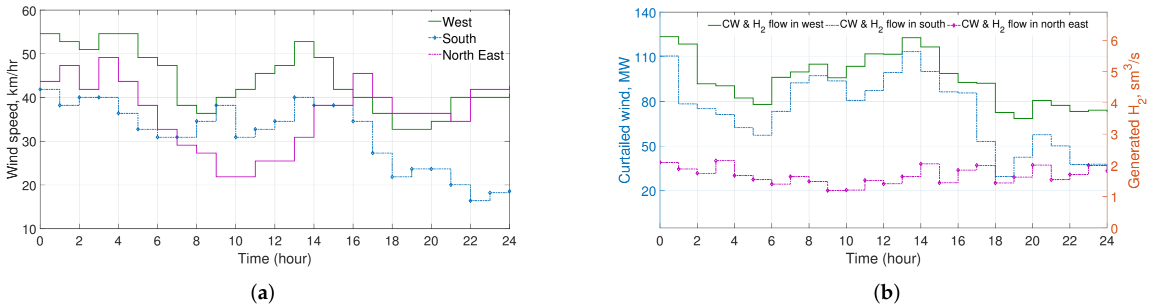

Figure 3. Comparison between(**a**) Wind speed profile in three different regions of Ireland and (**b**) Variable CW and H_2 generated in three different regions of Ireland on 11 October 2017.

Based on the three curtailed wind profiles, a profile for hydrogen generation capacity is developed in each of the regions. Three nodes in the gas network are identified for incorporating the hydrogen, node 4 (in West), node 5 (located in the south), and node 20 (in Northern Ireland (NI)). Equation (18) is used in order to determine the quantity of hydrogen produced from the curtailed wind power.

$$\mathcal{F}low\,rate\,of\,\mathcal{H}_2 = \frac{The\,CW \times 0.65\,(electrolyser\,efficiency)}{Voumetric\,heat\,value\,of\,H_2\,(12.7\,MJ/m^3)} \tag{18}$$

The energy demand for gas consumption in different sectors (power and non-power) has been extracted from Gas Network Ireland (GNI) online dashboard of gas use on the 11 of October and a profile relative to the maximum Irish peak demand for both types of end-user generated over the 24 h (Figure 4). Table 1 shows the natural gas composition with its fractions of various components, which is a typical natural gas composition in Ireland and the GB transmission pipelines [40]. Additionally, the table shows the density and the higher heat value (per mass unit, MJ/kg) of natural gas components.

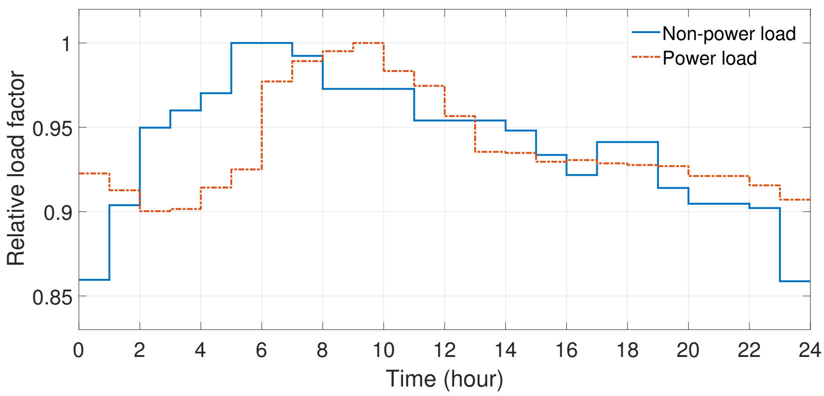

Figure 4. Load profiles of gas consumption relative to maximum demand in power plant and other segments.

Table 1. Composition properties of natural gas.

Composition	Fraction v/v, %	N-Density, kg/m^3	HHV, MJ/kg
C_1	93.94	0.67	55.50
C_2	4.2	1.038	51.90
C_3	0.3	1.522	50.40
i-C_4	0.03	2.50	49.10
n-C_4	0.03	2.50	49.10
N_2	1	0.966	-
CO_2	0.5	1.977	-

3. Results and Discussion

This model of the Irish gas network calculates the operational variables and parameters of the gas network before and after hydrogen injection. The energy demand profile for the nodes in the gas network model varies during the course of the 24 h; however, when there is an elevated hydrogen concentration in the pipeline, the reduced heating value of the gas mixture results in an increased gas flow rate to maintain constant energy supply. Figure 5 shows the pressure drop over the 24 h period for a selected number of gas pipelines before and after the inclusion of the renewable hydrogen into the gas network. The highest pressure drop in both cases occurs in pipes 3 and 11. The maximum total pressure drop in pipe 11 increases from 2.6 bar to 2.85 bar after incorporating hydrogen. This is an 8% increase over only NG flowing through the pipe. The gas average-velocity through pipe 11, increases by 7% from 2 m/s to 2.16 m/s. This is still within the recommended velocity guidelines of up to 15 m/s, as specified in standards, such as API 14E [41]. The pressure drop in all other gas pipelines that are not shown in Figure 5 is below 0.5 Bar. While it can be observed that the pressure drop increases for some pipelines, due to the increased volumetric gas flowrate to compensate for reduction in calorific content, the pressure drop in all the NG supply pipelines 1, 2, 12, and 23, decrease due to the reduced NG requirement. The maximum increase in pressure drop in the case study by Clegg et al. (2016) [20] incorporating 17% hydrogen through the GB's gas network was 7%. In that case study, the lowest pressure occurred at the maximum demand node and was 45 Barg when only natural gas flowed in pipelines, while, with a 17% hydrogen concentration, the pressure reduced to 42 Barg. Despite the localised changes in pressure over the course of the 24 h modelled in this study, the average pressure in the gas network increased very slightly from 67.39 Barg to 67.43 Barg. Full details of all pressure drops and gas flow rates before and after the incorporation of hydrogen are given in the appendix (Tables A3 and A4).

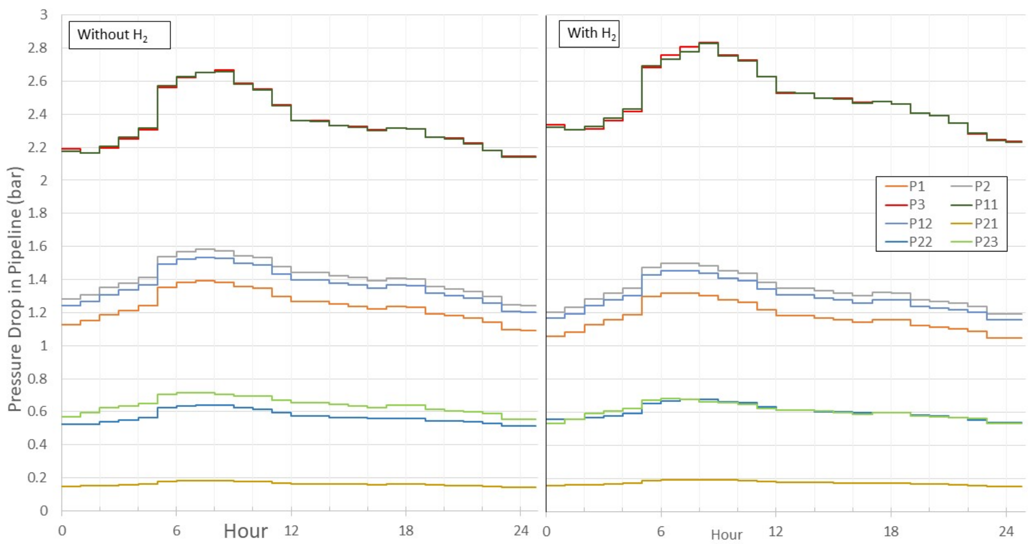

Figure 5. Pressure drop in selected pipelines (all other pressure drops < 0.5 bar).

In both this work and the work by Clegg et al. [20], the inclusion of hydrogen does not have a significant effect on network operation. As can be observed in this case study, the change in velocity and pressure drop due to the inclusion of hydrogen does not cause any operational issues. However, the gas networks of Great Britain and Ireland are both well designed networks. If a network was initially operating close to an operational limit, such as the upper gas velocity limit or a lower pressure limit, then the inclusion of hydrogen into the network, even when the hydrogen concentration is less than 15%, could push the operational parameters outside of safe limits.

Hydrogen concentrations vary in this case study throughout the network during the 24 h period due to variation of the CW, and also variation of gas consumption and the resultant gas flow rates. Table A2 examines the hydrogen concentration at regional nodes, the highest concentrations of hydrogen occur at the injection nodes and fluctuate between 2% and 16%, Figure 6. The maximum hydrogen fraction in nodes 4, 5, and 20 is 11%, 15.8%, and 6%, respectively. At all three injection points, the maximum hydrogen concentration is associated with low gas demand and high wind speeds. At demand nodes located in western regions of the network, there are only three hours of the day when hydrogen percentage is higher than 10%, in between 12 AM and 2 AM when the natural gas demand is at its lowest, as can be observed in Table 2. While, in the southern part of the network hydrogen exceeds 10% for 14 h on the selected day. In eastern regions, where the total energy demand of gas-power generators and other end-users is over 3500 MW and about 40% of Ireland's population live [42], hydrogen concentration remains within the acceptable limit of less than 10% during the 24 h. It is important to note that, during times with strong available wind and high potential for curtailment (>90 MW), less gas is being consumed by power generators and more hydrogen is produced by P2H units. However, the higher overall gas and electricity usage in the north and east is a significant factor in the hydrogen concentration remaining below 10%.

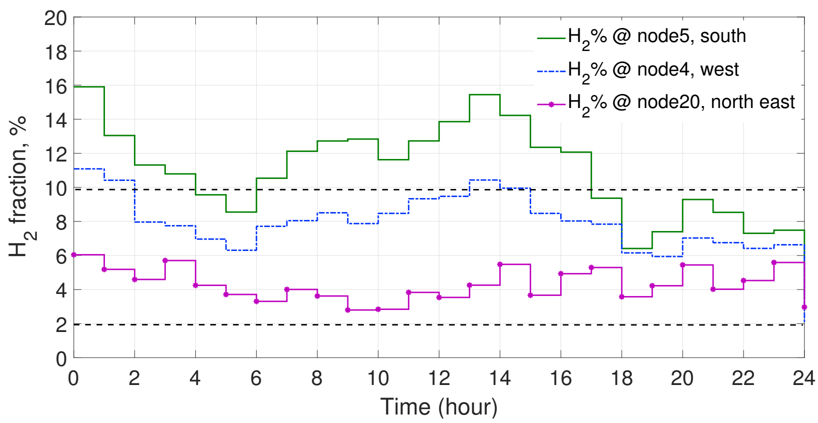

Figure 6. Hydrogen fraction % from different nodes (4, 5, 20) outputs.

Table 2. H_2 concentration in different regions of Ireland during simulated 24 h.

Location on the Map	Max. H2%	Min. H2%	Average H2%	Duration, hr 10% < H2%	Duration, hr 5% < H2% < 10%	Duration, hr H2% < 5%
West	11	2	7.8	3	20	1
South	15.8	3.5	10.8	14	9	1
North	6	3	4.3	0	8	16
East	3.5	0.3	1.8	0	0	24

Figure 7 identifies the maximum hydrogen fraction at the nodes in the Irish gas network. The current energy policy in Ireland include plans to install a 70-station CNG fuelling network co-located in existing forecourts on major routes in order to support a decarbonisation of HGV transport. The simulation results show that in the west, south and centre of the gas network, hydrogen concentrations higher than 5% occur during the simulated day. Therefore, it would not be possible to supply CNG fueling stations in these locations directly from the gas network during the day. During the periods when the inclusion of hydrogen from CW in the network would exceed operation limits for the end users, an alternative option is to store the produced hydrogen and incorporate it into the network at periods with low CW. In regions, like Ireland, with a lot of variability in renewable energy production, it is important to determine the appropriate size of storage facilities required, to maximise the green hydrogen potential while ensuring operation of the gas network within the permitted levels. The storage of hydrogen is difficult and costly [43], and so the requirements, including the frequency of use, would need to be thoroughly evaluated for each network and injection location. By expanding the current model to cover a wider time period it would be possible to evaluate storage requirements at the hydrogen injection locations.

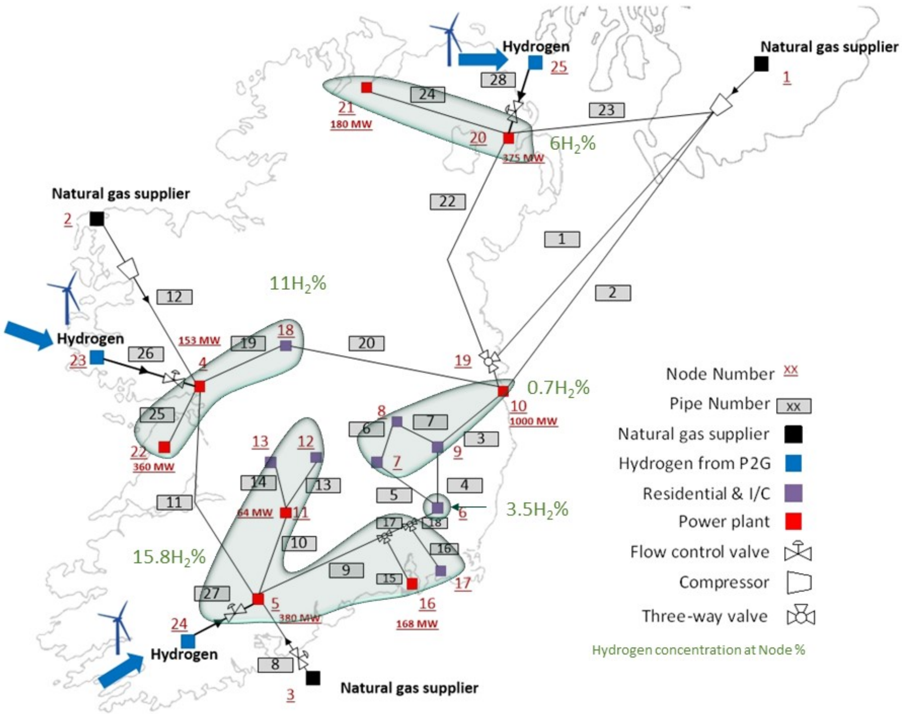

Figure 7. Hydrogen distribution in Irish gas network pipelines, Nodes with the same hydrogen concentration are surrounded by contour.

Along with multiple injection points, another strategy to minimise the hydrogen concentration in the gas network is to incorporate hydrogen at nodes with high flowrates. An analysis of this strategy is presented in Table 3 for nodes 4, 5, and 10. Converting all of the CW during the modelled 24 h period to hydrogen and incorporating directly into the gas network at one node, leads to elevated, but more stable hydrogen concentrations at each node. While this approach reduces variability of hydrogen through the network, it puts additional pressure on the electrical network to transmit the power from the wind farms to the regions with high gas flowrates and does not utilise the available transmission capacity of the gas network. Additionally, it would lead to increased hydrogen concentration variability, between windy and calm periods.

Continuously operating electrolysers are the most likely initial scenarios for P2H in natural gas networks. Despite a steady rate of hydrogen production, the varying gas demand and flowrates in the network will result in variable hydrogen concentrations and pressures. To demonstrate this, the gas network model was adapted in order to evaluate operation with hydrogen from a 10 MW electrolyser at node 4, Figure 8. Evaluating these results in comparison with the curtailed wind scenario demonstrates that the incorporation of P2H into the gas network will require additional gas network monitoring and management, regardless whether or not the electrolyser is operating on solely on renewable power.

While average hydrogen concentration remains less than 1% its variation is inversely related to gas demand. The highest rate of green hydrogen production must be evaluated in order to maximise the renewable energy storage potential of the gas network.

Table 3. Hydrogen concentration at three different nodes comparing the variation in H2% which occurs when the same quantity of hydrogen from curtailed wind is spread across multiple injection points or injected into one single injection point.

Node	Max Energy Demand	Multiple Injection Points		Single Injection Point	
		Node 4 and Node 5 and Node 20		Node 4 or Node 5 or Node 10	
	MW	Max. H_2%	Min. H_2%	Max. H_2%	B_2%
4	2959	11	5.3	16.7	11.4
5	2018	15.8	3.5	23.6	16.4
10	3511	0.7	0.1	14.3	9.6

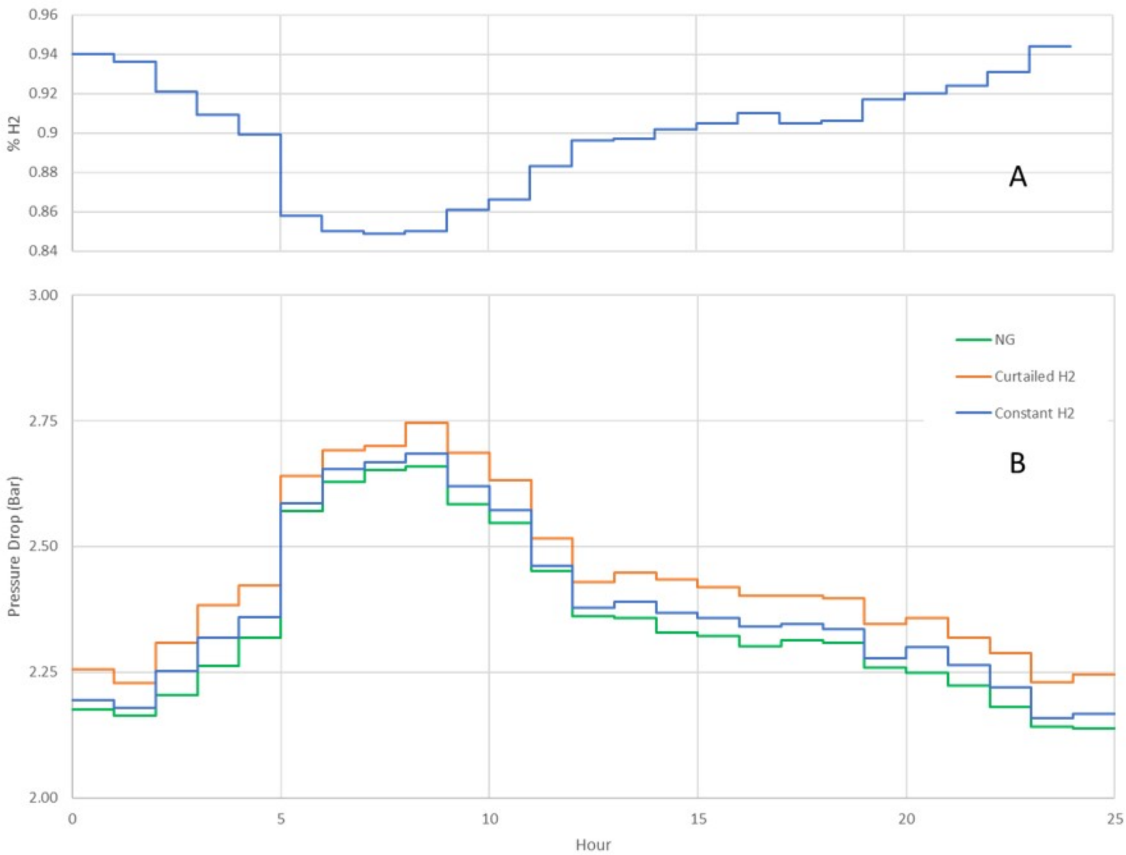

Figure 8. Impact on gas network due to the incorporation of hydrogen from a continuously operating 10MW electrolyser (**A**) Hydrogen percentage at node 4 (**B**) Pressure drop in Pipe 11 for Natural gas, Hydrogen from curtailed wind, and a constant 10 MW of Hydrogen.

The critical parameters for evaluating the suitability of a gas network for interconnection with renewable energy storage using P2H is the location of the renewable hydrogen generation, the location of the hydrgoen gas injection, energy demands on the network, and the type of end-user [44,45]. Wind farms throughout the world are distributed across regions and are not concentrated in a specific location. Therefore, by installing P2H facilities at different locations on the electrical network the locally available renewable energy can be converted into hydrogen, minimising electrical network losses and also minimising the potential magnitude of hydrogen concentration variation in the gas network. Having multiple injection points on a gas network has the potential to reduce the size of hydrogen storage facilities required for concentration balancing, but additional management of the interaction between the gas and electrical network is required to ensure both systems operate within their respective permitted safe parameters. Additionally, multiple hydrogen injection points will require additional compressors and lead to additional gas network operational and maintenance costs. The results that are presented in this study demonstrate that, in a well designed natural gas network, the direct blending of green hydrogen is possible without any gas network issues, but consideration must be given to end users down stream of the hydrogen injection. The incorporation of green hydrogen should occur in regions with a high gas flowrate, to minimise hydrogen concentration in the network. However, signification hydrogen concentration variation can still occur in the network with time. As P2H moves from the pilot plant scale to the full scale, hydrogen concentration management will become increasingly important and, for all but the smallest of P2H installations, hydrogen storage will be required to ensure gas quality remains steady and does not vary significantly. For all future potential P2G/P2H projects, as well as the optimisation of size and location with respect to the electricity network as proposed by [43], modelling of the impacts on the receiving gas network is required. Hydrogen concentration management through controlled operation of electrolysers to match gas flow rate while possible and relatively simple, does not take full advantage of the available renewable energy resources. It also minimises the demand/response benefits which P2G/P2H provides to the electrical network, therefore, hydrogen storage is a more likely management strategy. While in many cases the capacity of the network may be sufficient to receive and transport the green hydrogen, each network has its own unique critical parameters and a review of all downstream end-users is required in order to ensure gas quality is acceptable to all.

4. Conclusions

A potential future scenario for the decarbonisation of a gas network through the blending of green hydrogen in the natural gas network has been coupled with historical weather, electrical, and gas network data. The capability of the gas network to supply the required energy demand with variable quality of gas has been modelled, and the results from this study show that, based on a simplified Irish gas network, full use can be made of all curtailed wind power for P2H on a windy day. The injection of the generated hydrogen at three points on the gas network would lead to hydrogen concentrations that would exceed 15%. The injection of hydrogen into the gas pipelines will not significantly change the operational variables of the gas network, such as pressure drop, flow rate, or ability to deliver sufficient energy, but it will have an impact on the gas quality which varies significantly through out the network during the time period. The key findings of this research are that gas network analysis is just as important as the power network analysis in the evaluation of any potential P2H for renewable energy storage. In regions with variable excess renewable energy resources, there is a requirement for active management of the hydrogen concentration in the gas network. The use of hydrogen storage is required in order to fully maximise the benefits of P2H. The sizing and management of the storage facility will require thorough analysis of the operation of both the electrical and gas networks at the proposed hydrogen generation and hydrogen injection locations.

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Abbreviations

The following abbreviations are used in this manuscript:

Nomenclature

A	Cross Sectional area of pipe (m^2)
D	pipe inner diameter (m)
E	Energy (J)
f	friction factor
f_t	theoretical friction factor
g	gravitational acceleration (m^2/s)
dh_f	head losses (m)
i	sender node
j	receiver node
$\mathcal{L}_d$	set of nodal load (demand, m^3/s)
$\mathcal{L}_{ij}$	set of $pipe_{ij}$ from the branch list
l	pipe length (m)
$\mathcal{NG}_{composition(i)}$	set of natural gas compositions
p	nodal pressure (Pa)
p_b	basic pressure (Pa)
p_c	critical pressure (Pa)
dp	differential pressure
Δ p	pressure drop (Pa)
Q	flow rate (m^3/s)
R	gas constant ((kJ/kg^{o}K))
t	time
T	Temperature (K)
T_b	basic temperature (K)
T_c	critical temperature (K)
V	volume (m^3)
W	work (J)
U	internal energy (J)
x	pipeline coordinate
X_i	volumetric fraction of components (%)
X_q	flow rate variable matrix
z	elevation (m)
Z	compressibility factor
θ	inclination (rad)
ρ_n	normal density (kg/m^3)
ρ	density (kg/m^3)
η	pipe efficiency
τ	shear stress (Pa)
T	time span
ν	velocity (m/s)
Ω	heat energy (J)

Technical Acronyms

CW	Curtailed Wind
NG	Natural Gas
ODE	Ordinary Differential Equation
P2G	Power-to-Gas
P2H	Power-to-Hydrogen
PDE	Partial Differential Equation
PEM	Polymer electrolyte membrane
RES	Renewable Energy Source

Appendix A

Appendix A.1. Figures

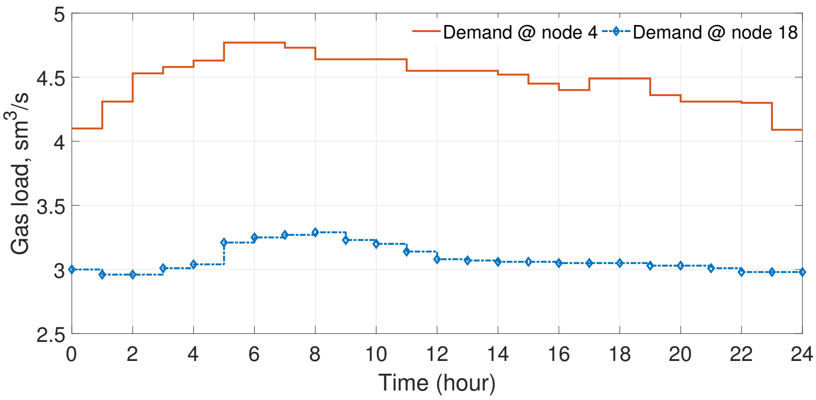

Figure A1. Gas load values at node 4 (gas-fired power generator), and node 18 as non-power node.

Table A1. Pipes details of the gas network.

Pipe No.	Sender Node	Receiver Node	Diameter, m	Length, km
Pipe 1	1	19	0.76	280
Pipe 2	2	10	0.6	300
Pipe 3	3	9	0.6	70
Pipe 4	9	6	0.6	15
Pipe 5	7	6	0.6	15
Pipe 6	8	7	0.6	15
Pipe 7	9	8	0.6	7
Pipe 8	3	5	0.6	15
Pipe 9	5	14	0.6	70
Pipe 10	5	11	0.6	35
Pipe 11	4	5	0.6	130
Pipe 12	2	4	0.6	113
Pipe 13	11	12	0.6	15
Pipe 14	11	13	0.6	13
Pipe 15	14	16	0.6	20
Pipe 16	15	17	0.6	20
Pipe 17	14	15	0.6	30
Pipe 18	15	6	0.6	30
Pipe 19	4	18	0.6	100
Pipe 20	18	10	0.6	65
Pipe 21	19	10	0.6	5
Pipe 22	20	19	0.6	160
Pipe 23	1	20	0.6	180
Pipe 24	20	21	0.6	100
Pipe 25	4	22	0.6	5
Pipe 26	24	5	0.6	20
Pipe 27	23	4	0.6	20
Pipe 28	25	20	0.6	20

Table A2. Demand, end user hydrogen limits and hydrogen percentages during simulated period

Node	Type	Demand, MW	H_2% Limit	H_2% at Node		
				Max	Mean	Min
1	Natural gas source	NaN	-	-	-	-
2	Natural gas source	NaN	-	-	-	-
3	Natural gas source	NaN	-	-	-	-
4	Power generator	153	5	11	7.8	2
5	Power generator	378	5	**15.8**	10.8	3.5
6	Other devices (CNG/Boilers/Heater/Residential)	1049	2 < x < 20	3.5	<1	<1
7	Other devices (CNG/Boilers/Heater/Residential)	298	2 < x < 20	<1	<1	<1
8	Other devices (CNG/Boilers/Heater/Residential)	75	2 < x < 20	<1	<1	<1
9	Other devices (CNG/Boilers/Heater/Residential)	862	2 < x < 20	<1	<1	<1
10	Power generator	2061	5	<1	<1	<1
11	Power generator	64	5	**15.8**	10.8	3.5
12	Other devices (CNG/Boilers/Heater/Residential)	488	2 < x < 20	**15.8**	10.8	3.5
13	Other devices (CNG/Boilers/Heater/Residential)	470	2 < x < 20	**15.8**	10.8	3.5
14	Connector	0	-	-	-	-
15	Connector	0	-	-	-	-
16	Power generator	168	5	**15.8**	10.8	3.5
17	Other devices (CNG/Boilers/Heater/Residential)	186	2 < x < 20	**15.8**	10.8	3.5
18	Other devices (CNG/Boilers/Heater/Residential)	112	2 < x < 20	11	7.8	2
19	Connector	0	-	-	-	-
20	Power generator	374	5	6	4.3	3
21	Power generator	180	5	6	4.3	3
22	Power generator	359	5	11	7.8	2
23	P2H	NaN	-	-	-	-
24	P2H	NaN	-	-	-	-
25	P2H	NaN	-	-	-	-

Table A3. Flow rate before injecting H2 in hourly steps.

Pipe No.	Flow Rate before Injecting H2 in Hourly Steps, Sm^3/s																								
	t0	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**	**t8**	**t9**	**t10**	**t11**	**t12**	**t13**	**t14**	**t15**	**t16**	**t17**	**t18**	**t19**	**t20**	**t21**	**t22**	**t23**	**t24**
P1	38.5	39.0	39.9	40.4	40.8	42.7	43.0	43.0	42.8	42.3	42.1	41.3	40.8	40.8	40.5	40.3	40.1	40.4	40.4	39.7	39.6	39.4	39.2	38.4	38.4
P2	22.0	22.3	22.7	23.0	23.3	24.3	24.5	24.5	24.4	24.2	24.0	23.6	23.3	23.3	23.1	23.0	22.9	23.0	23.0	22.7	22.6	22.5	22.3	21.9	21.9
P3	59.9	59.6	60.1	60.9	61.7	64.9	65.6	65.8	65.9	65.0	64.5	63.3	62.1	62.1	61.7	61.6	61.4	61.5	61.5	60.9	60.8	60.5	60.0	59.5	59.5
P4	19.7	19.8	20.1	20.4	20.6	21.7	21.9	21.9	21.8	21.5	21.4	21.0	20.6	20.6	20.5	20.4	20.3	20.4	20.4	20.2	20.2	20.1	20.0	19.7	19.7
P5	6.5	6.6	6.8	7.0	7.0	7.4	7.4	7.3	7.2	7.2	7.1	7.0	6.9	6.9	6.8	6.8	6.7	6.8	6.8	6.7	6.7	6.7	6.7	6.6	6.6
P6	14.7	14.7	14.9	15.2	15.3	16.1	16.2	16.3	16.3	16.0	15.9	15.6	15.4	15.3	15.2	15.2	15.1	15.2	15.2	15.0	15.0	14.9	14.8	14.7	14.7
P7	16.8	16.8	17.0	17.2	17.4	18.3	18.5	18.5	18.5	18.3	18.1	17.8	17.5	17.5	17.4	17.3	17.3	17.3	17.3	17.1	17.1	17.0	16.9	16.7	16.7
P8	4.1	4.1	4.1	4.1	4.2	4.4	4.5	4.5	4.5	4.4	4.4	4.3	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.1	4.1	4.1	4.1	4.1	4.1
P9	10.6	10.2	10.0	10.2	10.3	11.0	11.2	11.3	11.5	11.2	11.1	10.9	10.6	10.5	10.5	10.6	10.6	10.5	10.5	10.5	10.6	10.5	10.3	10.5	10.5
P10	27.4	27.1	27.3	27.6	28.0	29.5	29.8	30.0	30.1	29.6	29.4	28.8	28.2	28.2	28.0	28.1	28.0	28.0	28.0	27.7	27.7	27.6	27.3	27.2	27.2
P11	44.0	43.9	44.4	45.0	45.5	47.8	48.3	48.5	48.5	47.8	47.5	46.6	45.8	45.8	45.5	45.4	45.2	45.4	45.3	44.9	44.8	44.6	44.2	43.8	43.8
P12	63.7	64.4	65.8	66.6	67.4	70.4	71.0	71.0	70.7	70.0	69.6	68.3	67.4	67.4	67.0	66.6	66.2	66.7	66.7	65.6	65.4	65.1	64.7	63.4	63.4
P13	13.1	12.9	12.9	13.1	13.3	14.0	14.2	14.3	14.3	14.1	14.0	13.7	13.4	13.4	13.3	13.4	13.3	13.3	13.3	13.2	13.2	13.1	13.0	13.0	13.0
P14	12.6	12.4	12.4	12.6	12.8	13.5	13.7	13.7	13.8	13.6	13.4	13.2	12.9	12.9	12.8	12.9	12.8	12.8	12.8	12.7	12.7	12.6	12.5	12.5	12.5
P15	4.5	4.7	5.0	5.0	5.1	5.2	5.2	5.2	5.1	5.1	5.1	5.0	5.0	5.0	5.0	4.9	4.8	4.9	4.9	4.8	4.7	4.7	4.7	4.5	4.5
P16	5.0	4.9	4.9	5.0	5.1	5.3	5.4	5.5	5.5	5.4	5.3	5.2	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.0	5.0	5.0	5.0	5.0	5.0
P17	6.1	5.5	5.1	5.2	5.2	5.8	6.0	6.1	6.4	6.1	6.0	5.9	5.6	5.5	5.5	5.7	5.8	5.6	5.5	5.7	5.8	5.7	5.6	6.1	6.1
P18	1.1	0.6	0.1	0.2	0.2	0.4	0.5	0.7	0.9	0.8	0.7	0.7	0.4	0.4	0.4	0.6	0.7	0.5	0.5	0.7	0.8	0.7	0.7	1.1	1.1
P19	5.9	6.1	6.2	6.3	6.4	6.6	6.7	6.7	6.6	6.6	6.5	6.4	6.3	6.3	6.3	6.3	6.2	6.3	6.3	6.2	6.1	6.1	6.1	5.9	5.9
P20	2.9	3.1	3.3	3.3	3.3	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3	3.2	3.2	3.1	3.2	3.2	3.1	3.1	3.1	3.1	2.9	2.9
P21	58.2	58.7	59.8	60.6	61.3	64.2	64.7	64.7	64.5	63.8	63.4	62.2	61.4	61.3	61.0	60.7	60.3	60.7	60.7	59.8	59.6	59.4	59.0	57.9	57.9
P22	19.7	19.7	20.0	20.2	20.5	21.5	21.7	21.7	21.7	21.4	21.3	20.9	20.5	20.5	20.4	20.4	20.3	20.3	20.3	20.1	20.0	20.0	19.8	19.6	19.6
P23	34.5	35.3	36.3	36.7	37.2	38.7	38.9	38.8	38.5	38.2	38.0	37.3	37.0	37.0	36.7	36.4	36.1	36.5	36.5	35.8	35.6	35.5	35.3	34.4	34.4
P24	4.8	5.1	5.3	5.4	5.4	5.6	5.6	5.5	5.4	5.4	5.4	5.3	5.3	5.3	5.3	5.2	5.1	5.3	5.2	5.1	5.1	5.1	5.0	4.8	4.8
P25	9.6	10.1	10.6	10.7	10.8	11.2	11.2	11.1	10.9	10.9	10.9	10.7	10.7	10.7	10.6	10.4	10.3	10.5	10.5	10.2	10.1	10.1	10.1	9.6	9.6

Table A4. Flow rate after injecting H2 in hourly steps.

Pipe No.	Flow Rate after Injecting H2 in Hourly Steps, Sm^3/s																								
	t0	**t1**	**t2**	**t3**	**t4**	**t5**	**t6**	**t7**	**t8**	**t9**	**t10**	**t11**	**t12**	**t13**	**t14**	**t15**	**t16**	**t17**	**t18**	**t19**	**t20**	**t21**	**t22**	**t23**	**t24**
P1	38.5	39.0	39.8	40.3	40.8	42.7	43.0	43.0	42.8	42.3	42.1	41.3	40.8	40.8	40.5	40.3	40.0	40.4	40.3	39.7	39.5	39.4	39.1	38.4	38.4
P2	21.9	22.2	22.7	23.0	23.2	24.3	24.5	24.5	24.4	24.1	24.0	23.5	23.2	23.2	23.1	22.9	22.8	23.0	23.0	22.6	22.5	22.4	22.3	21.9	21.9
P3	60.3	59.9	60.4	61.2	61.9	65.1	65.8	66.1	66.3	65.3	64.9	63.7	62.5	62.4	62.1	62.0	61.8	61.9	61.8	61.2	61.1	60.8	60.2	59.8	59.8
P4	20.0	20.1	20.4	20.6	20.9	21.9	22.1	22.1	22.1	21.8	21.7	21.3	21.0	20.9	20.8	20.7	20.6	20.7	20.7	20.5	20.4	20.3	20.2	19.9	19.9
P5	6.9	7.0	7.2	7.3	7.3	7.7	7.7	7.7	7.6	7.6	7.5	7.4	7.3	7.3	7.3	7.2	7.2	7.2	7.2	7.1	7.1	7.0	7.0	6.8	6.8
P6	14.9	14.9	15.1	15.3	15.5	16.2	16.4	16.4	16.4	16.2	16.1	15.8	15.5	15.5	15.4	15.4	15.3	15.4	15.4	15.2	15.1	15.1	15.0	14.8	14.8
P7	16.9	16.9	17.1	17.3	17.5	18.4	18.5	18.6	18.6	18.3	18.2	17.9	17.6	17.6	17.5	17.4	17.3	17.4	17.4	17.2	17.2	17.1	16.9	16.8	16.8
P8	4.1	4.0	4.1	4.1	4.2	4.4	4.5	4.5	4.5	4.4	4.4	4.3	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.1	4.1	4.1	4.1
P9	12.5	12.0	11.6	11.6	11.7	12.4	12.7	13.1	13.4	13.2	13.2	13.0	12.6	12.7	12.6	12.7	12.7	12.5	12.4	12.3	12.3	12.1	11.7	11.8	11.7
P10	28.3	28.0	28.0	28.3	28.6	30.1	30.5	30.8	31.0	30.5	30.3	29.8	29.2	29.2	29.0	29.0	28.9	28.9	28.8	28.6	28.6	28.3	28.0	27.9	27.8
P11	45.2	45.1	45.3	45.8	46.4	48.7	49.3	49.6	49.7	49.1	48.8	47.9	47.1	47.1	46.8	46.7	46.5	46.6	46.5	46.0	45.9	45.5	45.0	44.6	44.5
P12	63.6	64.4	65.8	66.6	67.3	70.4	71.0	71.0	70.6	69.9	69.5	68.2	67.3	67.3	66.9	66.5	66.1	66.6	66.6	65.6	65.3	65.1	64.6	63.4	63.4
P13	13.5	13.3	13.3	13.4	13.6	14.3	14.5	14.7	14.8	14.5	14.4	14.2	13.9	13.9	13.8	13.8	13.8	13.8	13.7	13.6	13.6	13.5	13.3	13.3	13.3
P14	13.0	12.8	12.8	12.9	13.1	13.8	14.0	14.1	14.2	14.0	13.9	13.7	13.4	13.3	13.3	13.3	13.3	13.2	13.2	13.1	13.1	13.0	12.8	12.8	12.8
P15	4.6	4.9	5.1	5.1	5.2	5.3	5.4	5.3	5.2	5.2	5.3	5.2	5.2	5.2	5.1	5.1	5.0	5.1	5.1	4.9	4.9	4.9	4.8	4.6	4.6
P16	5.2	5.1	5.1	5.1	5.2	5.5	5.5	5.6	5.6	5.6	5.5	5.4	5.3	5.3	5.3	5.3	5.3	5.2	5.2	5.2	5.2	5.2	5.1	5.1	5.1
P17	7.9	7.2	6.5	6.5	6.5	7.1	7.4	7.8	8.2	8.0	7.9	7.8	7.5	7.5	7.5	7.6	7.7	7.4	7.3	7.4	7.5	7.2	6.9	7.2	7.1
P18	2.7	2.1	1.4	1.3	1.3	1.6	1.8	2.2	2.6	2.4	2.4	2.4	2.2	2.2	2.2	2.3	2.4	2.2	2.1	2.2	2.3	2.0	1.8	2.2	2.1
P19	6.3	6.4	6.5	6.6	6.6	6.9	7.0	7.0	7.0	6.9	6.9	6.8	6.7	6.7	6.7	6.6	6.6	6.6	6.6	6.5	6.4	6.4	6.3	6.1	6.1
P20	3.2	3.3	3.5	3.5	3.5	3.6	3.6	3.6	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.5	3.4	3.5	3.5	3.4	3.3	3.3	3.3	3.1	3.1
P21	59.1	59.5	60.5	61.2	61.9	64.8	65.3	65.5	65.4	64.7	64.3	63.2	62.3	62.3	61.9	61.6	61.2	61.6	61.5	60.6	60.4	60.1	59.5	58.5	58.5
P22	20.5	20.5	20.6	20.8	21.1	22.1	22.4	22.5	22.6	22.3	22.2	21.8	21.5	21.5	21.4	21.3	21.2	21.3	21.2	20.9	20.9	20.7	20.4	20.2	20.1
P23	34.2	35.0	36.1	36.5	36.9	38.5	38.7	38.5	38.2	37.9	37.7	37.0	36.7	36.6	36.4	36.1	35.8	36.2	36.2	35.6	35.3	35.3	35.1	34.1	34.2
P24	5.0	5.2	5.4	5.5	5.5	5.7	5.7	5.7	5.6	5.6	5.6	5.5	5.5	5.5	5.5	5.4	5.3	5.4	5.4	5.3	5.2	5.2	5.2	4.9	4.9
P25	9.9	10.4	10.9	11.0	11.1	11.4	11.4	11.4	11.2	11.2	11.2	11.0	11.0	11.0	10.9	10.8	10.7	10.9	10.8	10.5	10.4	10.4	10.3	9.8	9.8
P26	1.9	1.8	1.6	1.5	1.4	1.4	1.6	1.8	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.0	1.9	1.8	1.6	1.4	1.3	1.2
P27	1.9	1.8	1.6	1.5	1.4	1.4	1.6	1.8	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.0	1.9	1.8	1.6	1.4	1.3	1.2
P28	1.6	1.6	1.4	1.2	1.2	1.2	1.3	1.6	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.6	1.5	1.4	1.2	1.1	1.0

References

1. Ritchie, H.; Roser, M. CO_2 and Greenhouse Gas Emissions. Our World in Data. Available online: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions (accessed on 21 February 2020).
2. York, R.; Shannon, E. Energy transitions or additions: Why a transition from fossil fuels requires more than the growth of renewable energy? *Energy Res. Soc. Sci.* **2019**, *51*, 40–43.
3. IEA (International Energy Agency). World Energy Balances: Overview. IEA Report. 2019. Available online: https://www.iea.org/reports/world-energy-balances-overview (accessed on 21 February 2020).
4. IEA. The Role of Gas in Today's Energy Transitions. International Energy Agency. 2019. Available online: https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions (accessed on 8 May 2020).
5. GNI. Delivering a Reliable and Secure Gas Supply, Ireland's Gas Network. GNI Report 2016. Available online: https://www.gasnetworks.ie/corporate/company/our-network/18048_GNI_GasNetwork_ReliabilityCapacity_Doc_Update.pdf (accessed on 10 February 2020).
6. Yang, Z.; Gao, C.; Zhao, M. Coordination of integrated natural gas and electrical systems in day-ahead scheduling considering a novel flexible energy-use mechanism. *Energy Convers. Manag.* **2019**, *196*, 117–126.
7. SEAI (Sustainable Energy Authority of Ireland). *Energy in Ireland, Report 2018*; SEAI Annual Report; Dublin, Ireland, 2018.
8. IWEA. Wind Energy. Ireland's Wind Asscociation. 2019. Available online: https://www.iwea.com/about-wind/facts-stats (accessed on 22 November 2019).
9. EirGrid. Annual Renewable Energy Constraint and Curtailment Report 2019. Eirgrid-SONI Report. 2020. Available online: http://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2018-V1.0.pdf (accessed on 10 September 2020).
10. EirGrid. Annual Renewable Energy Constraint and Curtailment Report 2017. Eirgrid-SONI Report. 2018. Available online: http://www.eirgridgroup.com/Annual-Renewable-Constraint-and-Curtailment-Report-2017-V1.pdf (accessed 20 September 2019).
11. EirGrid. Annual Renewable Energy Constraint and Curtailment Report 2018. Eirgrid-SONI Report. 2019. Available online: https://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2018-Non-Technical-Summary-V1.0.pdf (accessed 20 September 2019).
12. EPA. Ireland's Greenhouse Gas Emissions Projections 2018–2040, Environmental Protection Agency. EPA Report. 2019. Available online: https://www.epa.ie/pubs/reports/air/airemissions/ghgprojections2018-2040/ (accessed on 10 February 2020).
13. Thema, M.; Bauer, F.; Sterner, M. Electrolysis and methanation status review. *Renew. Sustain. Energy Rev.* **2019**, *112*, 775–787.
14. Hang, Y.; Wang, L.; Wang, N.; Duan, L.; Zong, Y.; You, S.; Maréchal, F.; Van herle, J.; Yang, Y. Balancing wind-power fluctuation via onsite storage under uncertainty: Power-to-hydrogen-to-power versus lithium battery. *Renew. Sustain. Energy Rev.* **2019**, *116*, 109465.
15. Bassano, C.; Deiana, P.; Lietti, L.; Visconti, C.G. P2G movable modular plant operation on synthetic methane production from CO2 and hydrogen from renewables sources. *Fuel* **2019**, *253*, 1071–1079.
16. Ajanovic, A.; Haas, R. On the long-term prospects of power-to-gas technologies. *Wiley Interdiscip. Rev. Energy Environ.* **2019**, *1*, e318.
17. Gruber, M.; Weinbrecht, P.; Biffar, L.; Harth, S.; Trimis, D.; Brabandt, J.; Posdziech, O.; Blumentritt, R. Power-to-Gas through thermal integration of high-temperature steam electrolysis and carbon dioxide methanation-Experimental results. *Wiley Interdiscip. Rev. Energy Environ.* **2018**, *181*, 61–74.
18. Ameli, H.; Qadrdan, M.; Strbac, G.; Strbac, G. Techno-economic assessment of battery storage and Power-to-Gas: A whole-system approach. *Energy Procedia* **2017**, *142*, 841–848.
19. Qadrdan, M.; Abeysekera, M.; Chaudry, M.; Wu, J.; Jenkins, N. Role of power-to-gas in an integrated gas and electricity system in Great Britain. *Int. J. Hydrog. Energy* **2015**, *14*, 5763–5775.
20. Clegg, S.; Mancarella, P. Storing renewables in the gas network: Modelling of power-to-gas seasonal storage flexibility in low-carbon power systems. *IET Gener. Transm. Distrib.* **2016**, *10*, 566–575.
21. Gondal, I.A. Hydrogen integration in power-to-gas networks. *Int. J. Hydrog. Energy* **2019**, 44, 1803–1815.
22. Devlin, J.; Li, K.; Higgins, P.; Foley, A. A multi vector energy analysis for interconnected power and gas systems. *Appl. Energy* **2017**, *192*, 315–328.

23. Altfeld, K.; Pinchbeck, D. Admissible hydrogen concentrations in natural gas systems. *Gas Energy* **2013**. Available online: https://www.gerg.eu/wp-content/uploads/2019/10/HIPS_Final-Report.pdf (accessed on 10 February 2020).
24. UN/ECE. Agreement Concerning the Adoption of Uniform Technical Prescriptions for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these Prescriptions. *Off. J. Eur. Union* **2014**. Available online: https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/2015/R110r3e.pdf (accessed on 20th February 2020).
25. Abeysekera, M.; Wu, J.; Jenkins, N.; Rees, M. Steady state analysis of gas networks with distributed injection of alternative gas. *Appl. Energy* **2016**, *164*, 991–1002.
26. Pambour, K.; Sopgwi, R.; Hodge, B.M.; Brancucci, C. The value of day-ahead coordination of power and natural gas network operations. *Energies* **2018**, *11*, 1628.
27. Yang, L.; Zhao, X.; Li, X.; Feng, X.; Yan, W. An MILP-Based Optimal Power and Gas Flow in Electricity-gas Coupled Networks. *Energy Procedia* **2019**, *158*, 6399–6404.
28. Qadrdan, M.; Fazeli, R.; Jenkins, N.; Strbac, G.; Sansom, R. Gas and electricity supply implications of decarbonising heat sector in GB. *Energy* **2019**, *169*, 50–60.
29. Khalilpour, K.R. Interconnected Electricity and Natural Gas Supply Chains: The Roles of Power to Gas and Gas to Power. In *Polygeneration with Polystorage for Chemical and Energy Hubs*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 133–155.
30. Ordoudis, C.; Pinson, P.; Morales, J. An integrated market for electricity and natural gas systems with stochastic power producers. *Eur. J. Oper. Res.* **2019**, *272*, 642–654.
31. Nasrolahpour, E.; Kazempour, J.; Zareipour, H.; Rosehart, W.D. A Bilevel Model for Participation of a Storage System in Energy and Reserve Markets. *IEEE Trans. Sustain. Energy* **2018**, *9*, 582–598, doi: 10.1109/TSTE.2017.2749434.
32. Tabkhi, F.; Azzaro-Pantel, C.; Pibouleau, L.; Domenech, S. A mathematical framework for modelling and evaluating natural gas pipeline networks under hydrogen injection. *Int. J. Hydrog. Energy* **2008**, *33*, 6222–6231.
33. Osiadacz Andrzej, J. Numerical solution of algebralc equallons. In *Simulation and Analysis of Gas Networks*; E. & F.N. SPON: London, UK, 1987.
34. Ekhtiari, A.; Dassios, I.; Liu, M.; Syron, E. A novel approach to model a gas network. *Appl. Sci.* **2019**, *9*, 1047.
35. Moayeri, M.S. Fluid Mechanics. In *Fluid Mechanics*; Shiraz University: Shiraz, Iran, 1987.
36. Pambour, K.A.; Erdener, B.C.; Bolado-Lavin, R.; Dijkema, G.P. An integrated simulation tool for analyzing the operation and interdependency of natural gas and electric power systems. In *PSIG Annual Meeting*; Pipeline Simulation Interest Group: Houston, TX, USA, 2016.
37. Herrán-González, A.; De La Cruz, J.M.; De Andrés-Toro, B.; Risco-Martín, J.L. Modeling and simulation of a gas distribution pipeline network. *Appl. Math. Model.* **2009**, *33*, 1584–1600.
38. Heidaryan, E.; Salarabadi, A.; Moghadasi, J. A novel correlation approach for prediction of natural gas compressibility factor. *J. Nat. Gas Chem.* **2010**, *19*, 189–192.
39. *ElectroRoute Articles*. 2019. Available online: https://www.electroroute.com/storm-atiyah-8th-december-2019 (accessed on 8 December 2019).
40. UK National Grid: How We Regulate Gas Quality in the National Transmission System (NTS) as a Safety Measure, Including Details on Gas Contents and Components. *NTS Homepage*. Available online: https://www.nationalgridgas.com/data-and-operations/quality (accessed on 1 July 2019).
41. Ekhtiari, A.; Syron, E. Ireland's Future Natural Gas Supply: How Well Connected Is the Island. *Irelands Eng. J.* **2018**. Available online: https://www.engineersireland.ie/Engineers-Journal/More/Energy/irelands-future-natural-gas-supply-how-well-connected\-is-the-island (accessed on 28 March 2018).
42. Population of Ireland (2020). Available online: https://www.worldometers.info/demographics/ireland-demographics/ (accessed on 5th May 2020).
43. Gunawan, T.A.; Singlitico, A.; Blount, P.; Burchill, J.; Carton, J.G.; Monaghan, R.F. At What Cost Can Renewable Hydrogen Offset Fossil Fuel Use in Ireland's Gas Network. *Energies* **2020**, *13*, 1798.

44. Ipsakis, D.; Voutetakis, S.; Seferlis, P.; Stergiopoulos, F.; Elmasides, C. Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage. *Int. J. Hydrog. Energy* **2009**, *34*, 7081–7095.
45. Gahleitner, G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *Int. J. Hydrog. Energy* **2013**, *5*, 2039–2061.