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Green Hydrogen Blends with Natural Gas and Its Impact on the Gas Network

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Abstract: With increasing shares of variable and uncertain renewable generation in many power systems, there is an associated increase in the importance of energy storage to help balance supply and demand. Gas networks currently store and transport energy, and they have the potential to play a vital role in longer-term renewable energy storage. Gas and electricity networks are becoming more integrated with quick-responding gas-fired power plants, providing a significant backup source for renewable electricity in many systems. This study investigates Ireland's gas network and operation when a variable green hydrogen input from excess wind power is blended with natural gas. How blended hydrogen impacts a gas network's operational variables is also assessed by modelling a quasi-transient gas flow. The modelling approach incorporates gas density and a compressibility factor, in addition to the gas network's main pressure and flow rate characteristics. With an increasing concentration of green hydrogen, up to 20%, in the gas network, the pipeline flow rate must be increased to compensate for reduced energy quality due to the lower energy density of the blended gas. Pressure drops across the gas pipeline have been investigated using different capacities of P2H from 18 MW to 124 MW. The results show significant potential for the gas network to store and transport renewable energy as hydrogen and improve renewable energy utilisation without upgrading the gas network infrastructure.

Keywords: green hydrogen; hydrogen blends; gas network; energy storage; renewable energy; power grid; curtailed wind; wind power

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1. Introduction

Currently, fossil fuels are still the primary sources of global energy, being accountable for 86% of the total energy produced in the world [1]. Fossil fuels are still widely available; while society might want to weaken dependency due to environmental concerns [2], significant investments in fossil fuels are still occurring, and a rapid transition away would undoubtedly make societies vulnerable [3]. Therefore, reducing reliance on fossil fuels and the associated CO_2 emissions means finding an alternative economic and reliable energy source to replace them [4]. This can be achieved by making better use of renewable energy sources (RES). In many regions throughout the world with limited fossil energy resources, there is enormous potential for renewable energy generation [5]. Still, the availability of renewable power does not always match the demand. Due to their unique and different behaviour corresponding to fluctuating renewable energy availability and various end uses demands can be challenging. Using the potential of the existing fossil fuel infrastructure, such as gas networks, can be a solution to store renewable energy as gas and play a significant role in adding flexibility across other energy systems [6]. For the island of Ireland, approximately 60% of the natural gas (NG) supply is imported, which is expected to increase as indigenous production falls [7]. Natural gas is a critical component of Ireland's electricity generation, with 50% of the country's annual electricity produced from natural gas and, on occasion, up to 80% of peak power demand [7]. Furthermore, wind power is the leading renewable energy resource in Ireland.

Integrating renewable energy across all end users is needed to reduce fossil fuel dependence. A combined energy system results when producers, suppliers, and end users have the flexibility to use, produce, and manage energy resources with the goal of providing reliable, safe, and clean energy. However, both individual gas and electricity networks are heavily regulated, and producers have limitations to produce as they choose.

Traditionally, interconnections between the gas network and the electrical grid have been in the form of compressor stations, and power plants [8]. The gas network can play a crucial role in energy storage, storing the fuel for fast-responding gas-fired power stations, which provide backup for the renewable electricity supply [9]. In addition, the gas network can store non-transportable renewable electricity through power to gas (P2G) systems. The P2G option achieves an interconnection between the electricity grid and gas network by converting excess renewable power to hydrogen (P2H) using electrolysers or using H_2 conversion process (methanation) with an external CO_2 source into synthetic gas, methane (SNG). Figure 1 shows a process block diagram of the P2H (highlighted in green colour in the figure) and P2G system. The orange line is the power carrier line, and the blue line represents the gas network as an energy carrier from suppliers to demand nodes. Two important applications of P2G are:

- make use of excess renewable energy.
- Increase renewables share in an energy system to reduce air pollutants and GHG emissions.

Hydrogen or SNG can be stored by injection into (gas) pipelines (transmission/distribution) and mixing with the NG [10–12]. One of the potential options to store green hydrogen is a salt cave. Portarapillo in [13] investigates how salt caves can be used as a solution for high-pressure hydrogen storage with minimum risk of leakage. If hydrogen is injected directly into the NG network, then care must be taken regarding the permissible upper hydrogen limit. Hydrogen is lighter than air and, due to its small molecule size with high diffusivity, may increase leaks from the network [14]. In addition, there are concerns about the risk of hydrogen fracture of metal pipes at elevated hydrogen concentrations [15].

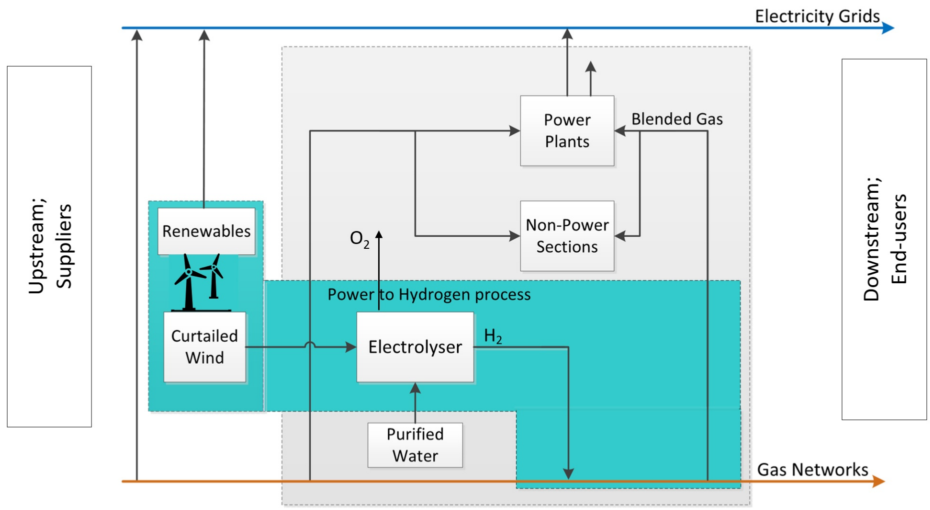

Figure 1. Power to gas process diagram and proposed case study process highlighted in green colour.

There are plans to increase the number and variety of gas and renewable power interconnections. In Europe, some ongoing projects are planned to investigate the impact of hydrogen in gas networks. Testing of hydrogen blends from 2% to 20% blends with natural gas is an experimental project in Network Innovation Centre in Ireland. This project investigates the admissible hydrogen limits within different end-user segments on the national scale [16]. The HyDeploy project was the UK's first hydrogen blending project. The H2NG project in France studied the capabilities of domestic appliances in using hydrogen blend (20% hydrogen blended with natural gas).

Different modelling approaches have been proposed for investigating an integrated gas and power system. Some researchers have mainly focused on modelling an integrated system to study the main physical interactions and analyse the impacts of both gas and power system interactions, e.g., gas compressor stations and power plants. Other publications have focused on the security of energy supply in a combined NG and renewable power system, evaluating the energy storage potential and considering the injection of either hydrogen or SNG into the gas network [17,18]. Qadradan et al. (2015) [19] performed a cost evaluation of P2G in an integrated gas and electricity system with varying levels of synthetic methane. Their main finding was that gas and electricity grids' overall operating cost was reduced when the surplus wind was used to generate methane from P2G. Ameli et al. (2017), [20] investigated the potential role of battery storage or heat pumps [21] as an alternative options for renewable storage, and P2G systems when power generation incorporated a considerable renewable capacity. A combined gas and electricity network model was utilised for optimising an integrated UK system over the winter and summer of 2030. It was concluded that both systems contribute to reducing operating costs. Nevertheless, their investment can be economically beneficial when the capital cost of the technologies reaches less than the threshold of £0.5 million/MW for P2G, and £0.4 million/MW for battery energy storage systems. In [19], the authors focused on steady-state modelling of a gas network while injecting hydrogen as an alternative gas. It has been found that creating hydrogen using an electrolyser and injecting it into the GB gas grid can substantially reduce curtailed wind during high wind periods. Long-term P2G application was discussed in [22], with the study investigating the P2G potential for storing energy on a national scale in Italy. Hydrogen generation from excess renewable electricity (from solar and wind) was determined, and the modelling outputs showed hydrogen produced from curtailed renewables equalled 5–6% of total NG consumption; however, it could be increased up to 6–8% of total consumption if the transportation sector was also considered. In addition, a comparison with the German case shows that a mainly wind-based power system in Germany provides a higher energy capacity for P2G; mainly, the potential of Germany's offshore wind contribution to produce hydrogen using P2G is substantial. Hence, in the long-term P2G will be used in Germany on a larger scale than in Italy.

A few studies have examined the potential of the gas system in providing a storage option for excess renewable electricity [23–27]; however, most studies modelled and analysed natural gas without considering the quality of the natural gas, which includes different volumetric concentrations of hydrocarbons from C_1 to C_4 with other components such as hydrogen, nitrogen, CO_2 and even water. Recently, research studies have addressed gas quality with different compositions in their calculations of gas network models to investigate the potential impacts of admissible hydrogen or synthetic gas in a gas network. Such investigations can help to evaluate how gas networks can be best used to store renewable energy. In [28], a combined gas and power system with P2G interconnection has been modelled. This paper presented a methodology to investigate different P2G processes and evaluated their operational effects on the power and gas transmission systems. The integrated model analysed techno-economic and environmental parameters but without considering the gas quality. The end users in that study are gas-fired power plants. The results of this research show that installing P2G systems close to gas terminals, which has the benefit of using curtailed wind to produce Hydrogen/SNG for mixing with natural gas at the terminal, can be achieved with limited disruption to the operation of the gas network in terms of gas flow rates. Furthermore, concluded that P2G increases system flexibility and interconnection for supplying energy as a boost.

Clegg et al. (2016) [18] proposed an integrated gas and electricity grid model with an interlinked P2G node to inject hydrogen or synthetic gas into the gas network. The case study is based on the GB NG and power transmission networks. It presented how increasing the hydrogen contribution can impact the pressure drop for power plant end users. The simulation outputs identify that for the national network, P2G can bring an additional annual combination of 35.6 TWh of renewable electricity generation and 23.9 TWh of gas. Gonal et al. (2019) [17] addressed the sensitivity of blending hydrogen with NG distribution pipelines. It concluded that a mixture of 50% hydrogen by the volumetric unit is a non-critical issue for distribution pipelines. For end uses such as burners, vehicle engines, and boilers, it has been assumed a 20% hydrogen concentration limit; however, gas cookers and CHP can receive up to 50% blending hydrogen. Furthermore, gas compressors in transmission pipelines are the critical element that restricts hydrogen blending in NG up to 10%. Therefore, for developing a "perfect" energy system based on introducing hydrogen to satisfy energy needs, a simulation study is proposed which considers all characteristics of the natural gas (with hydrogen) transmission system. Ozturk In their study [29] analysed blending natural gas with the addition of 20% hydrogen by volume. The sources of green hydrogen production, wind, solar, and wave, have been considered for this research.

Some recent published paper investigated using 100% hydrogen in the distribution pipelines [30].

This research investigates the effects of the integration of excess wind in the form of hydrogen into gas networks and how its contribution can influence the overall energy system. For the case study presented in this paper, wind power, which is the main source of renewable energy on the island of Ireland (with a 37% share of Ireland's electricity in 2020 [31] is taken as the primary RES source. Local limitations of the electrical network and stability considerations can lead to wind dispatch down at certain times, i.e., wind power that cannot be securely utilised for energy production.

2. Methodology

A simplified model of the Ireland gas network shown in Figure 2 is studied, incorporating a source node representing a P2H system (power to hydrogen) with various capacities, producing hydrogen and injecting it into the NG transmission pipeline system. On the presented map, Residential, IC (Industrial and Commercial), and Power plants are end-users types on the gas network shown in red or violet colors. The pipe numbers are identified in the grey boxes. Each square represents the demand point with its end-user type. This study does not consider the technical details of P2G or different electrolysers. Due to blending hydrogen with a lower heat value than NG in volumetric terms (MJ/m^3) will reduce the energy density in the pipeline. Therefore, the volumetric gas flow rate should be increased to compensate for the lower energy density. An energy balance at each node determines this. The model solves the gas flow equations by calculating the compressibility factor, density, and line pack capacity of blended hydrogen with NG, considering the gas quality due to different component concentrations, often neglected in previous works. The energy capacity of NG before and after blending with hydrogen has also been calculated to investigate how the integrated gas network might perform in reality. This analysis is particularly interesting for gas network operators that intend to de-fossilise their gas network, even if only with low hydrogen concentrations.

The gas flow equation considering all parameters in this proposed model has been calculated. For this study, a quasi-transient model was constructed for different time periods of curtailed wind to calculate the main characteristics of the gas through the pipelines and the average network pressure.

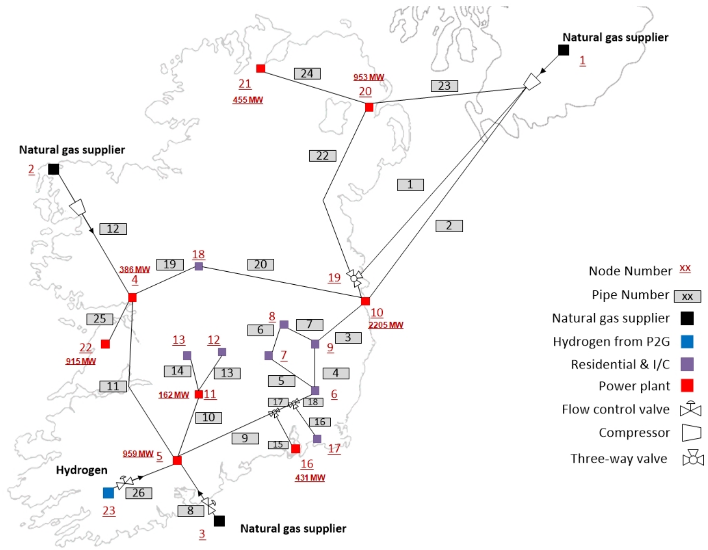

Figure 2. Simplified island of Ireland gas network with P2G interconnection node.

2.1. Gas Network and Renewables Model

A simplified Ireland's gas network is taken as a case study. The taken gas network includes 23 nodes, three supplier nodes of natural gas (1, 2, and 3 with 70 barg set point pressure). The natural gas sources are from Moffat (gas terminal in Scotland), and the internal gas resources of Corrib (in the west) and Kinsale located in the south of Ireland [32]. A hydrogen injection point at node 23, located in the southwest of the network, supplies P2G for different capacities, ranging from a low capacity of 18 MW to a high curtailed wind quantity of 124 MW, depending on daily wind dispatch down.

2.1.1. Gas Network Model

Modelling of the gas network follows a similar approach to Osiadacz (1987) [33] for solving partial differential Equations (PDE) of gas flows in pipelines. A novel method has previously been proposed by the authors for solving the non-linear equations, as described in Ekhtiari et al. (2019) and (2020) [6,34]. Using Matlab, the set of PDE equations is solved for the gas pressure drop and flow rate requirements in the gas network. The gas flow equations satisfy the primary physical laws of conservation of momentum, mass conservation, and the first law of thermodynamics. Figure 3 shows the force directions of the gas flow in a pipe. The gas flow equation is presented in Equation (1). After obtaining the integral of Equation (1) it can be expressed with Equation (2), where the pressure drop mainly depends on the frictional and inertial force in the pipelines.

$$\frac{\partial p}{\partial x} = -\frac{f_t \rho_n^2 ZRTQ|Q|}{2\eta_t^2 DA^2 p_{avg}} - \frac{gsin(\theta)}{ZRT} p_{avg} \tag{1}$$

$$\forall\, i, j(in\,\&\,out) \in \mathcal{L}_{length},\ node_j \in \mathcal{L}_d\,, t \in \mathcal{T}_f:$$

$$\left[p_{i,t}^2 - p_{j,t}^2 = a_{ij}^t |Q_{ij}^t| Q_{ij}^t + b_{ij}^t (p_{i,t} + p_{j,t})^2 \right] \tag{2}$$

$$where:$$

$$a_{ij} = \frac{16 f_{ij} \rho_n^2 Z_{ij} RT l_{ij}}{\pi^2 D^5},\ \ b_{ij} = \frac{g l_{ij} sin(\theta)}{2Z_{ij} RT} \tag{3}$$

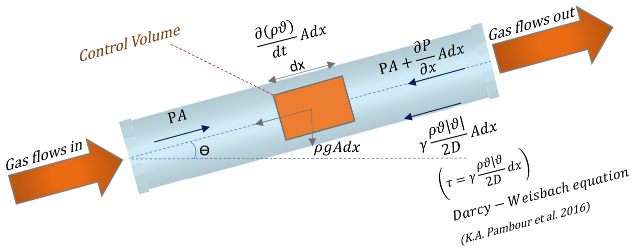

Figure 3. Effective forces on a specific volume of gas flow through a pipeline [35].

The compressibility factor "Z" depends on the gas average pressure and temperature and was calculated using the PAPAY equation, which is applicable for high-pressure networks [36]. In Equation (4), all pressures in this equation are average values between both ends of each pipe of the network.

$$Z = 1 - 3.52(\frac{p_{average}}{p_c})exp[-2.260(\frac{T}{T_c})] + 0.274(\frac{p_{average}}{p_c})^2 exp[-1.878(\frac{T}{T_c})] \tag{4}$$

The average pressure can be calculated using Equation (5)

$$\forall\, i, j \in \mathcal{L}_{length} : P_{average} = \frac{2}{3}(\frac{p_i^2 + p_1 p_2 + p_j^2}{p_1 + p_2}) \tag{5}$$

2.1.2. Variable Gas Quality

At a node, a mixture of all entering gases is assumed. As a result, all gas flows leave a node to have the same quality (same calorific value). Considering the nodal gas quality value at node "i" by HHV_i, the energy balance is shown in Equation (6).

$$\forall i, j \in set\,of\,receiver\,and\,sender\,nodes : \sum_{i,j}^{n,m} HHV_i^{in} Q_{ij}^{in} = \sum_{i,j}^{n,m} HHV_i^{out} Q_{ij}^{out} \tag{6}$$

Substitution of energy balance can be shown in Equations (7)–(10).

$$Energy_{demand_i}^{NG} = HHV_i^{NG} \times Load_i^{NG} \tag{7}$$

$$Energy_i^{out} = HHV_i^{out} \times \sum Load_i^{NG} \tag{8}$$

$$(Energy\,compensate)_i = Energy_{demand_i}^{NG} - Energy_i^{out} \tag{9}$$

$$(Flow\,rate\,increase)_i = \frac{(Energy\,compensate)_i}{HHV_i^{out}} \tag{10}$$

The energy contribution that must be supplied by natural gas can be calculated using Equation (11). Then the hydrogen concentration at the outlet of each node can be calculated.

$$Energy^{NG} = (Energy\,demand_i)^{NG} - Energy\,supplied\,by\,Hydrogen \tag{11}$$

After calculating the pressures and flow rates of the gas network, the energy shortage that should be compensated by a rise in the gas flow rate can be calculated using Equation (9). Then, after calculating the new flow rate supplied at each demand node, the model will redetermine the pressure drop for all pipelines. Gas quality tracking is summarised in the following process:

1. Define an initial gas quality using components percentages.
2. Calculate the nodal pressures and pipe flow rates.
3. Calculate the gas quality through the pipeline, including gas density in and hydrogen concentration at each node of the network.
4. Recalculate the pressures and flow rates.

The model outputs show that the iterative process in connection to the Newton–Raphson approach works well. This numerical method for solving gas networks' equations was developed by Osiadacz [33] by linearising the differential equations.

The higher heating value, HHV_i^m, is the measure of energy content per unit volume of a gas. If the hydrogen concentration is X_{H_2}, the NG components are X_i. The higher heat value (HHV, MJ/m^3) of the blended gas in each pipeline can be calculated using Equation (13). In the model presented here, the energy demand at each node is specified for each time point. Therefore, as the gas composition changes, so do the HHV and the associated gas demand.

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

$$\forall\, i \in \mathcal{NG}_{composition(i)} : HHV_{blended\,gas} = \sum[HHV_i.X_i.\rho_n i] \tag{13}$$

$$\forall\, i \in \mathcal{NG}_{composition(i)} : HHV_{NG} = \sum[HHV_i.X_{NG(i)}.\rho_n i] \tag{14}$$

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

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

The generated hydrogen profile is then incorporated, and the model recalculates to assess how blending hydrogen impacts the gas flow rate downstream of the hydrogen injection point and the energy delivery to the end users, considering the change in gas quality based on its composition. Then, to satisfy end-user energy requirements, the flow rate in a network subsection is adjusted to compensate for the energy shortfall.

2.2. Scenarios

Local constraints on the power grid, and stability considerations, can lead to wind curtailment at specific times. On the island of Ireland, wind energy is the main renewable source for generating electricity. The total power generated was 13,768 GWh in 2020, while 1909 GWh, 12% of available wind energy, was curtailed [31] in the same period. EirGrid (electrical transmission system operator of Ireland) hourly CW with a monthly average value of that is shown in Figure 4. The simplified Irish gas network consists of 23 nodes, including three supplier nodes of natural gas (1, 2, and 3 with 70 barg set point pressure) from Moffat, a gas terminal in Scotland, and Corrib, a local gas terminal located on the west of Ireland, and Inch-Kinsale, also a gas field In Ireland, and chosen here as the P2H point for supplying hydrogen at node 23 which injects H_2 at node 5. The P2H node is assumed to be located in southwest Ireland, close to the wind farms, as shown in Figure 2. The hydrogen flow rate depends on the inlet power (here is the CW) and the efficiency of the electrolyser. The efficiency of typical electrolysers of P2H can be between 53 and 85% [11,37,38].

To investigate what capacities of P2H can be used to generate and blend hydrogen into the gas network, a statistical analysis could be an approach to look at the distribution of the daily CW values. Firstly, an hourly matrix of wind profile within 365 days is created. Then, the daily sum of CW was calculated to identify how much the maximum, mean, and median of CW and in which days of the year occurred. The outputs show that the maximum daily value of CW is 2523 MWh; also the mean, mode, and median values are 517 MWh, 312 MWh, and 275 MWh, respectively. Furthermore, the daily average of these scenarios in MW is 105, 21.5, 13 and 11.5. These four cases can be found on days 309th, 363rd, 8th, and 297th, respectively. The curtailed hourly profile for these selected days has been considered for the P2H inlet profile. Therefore, four P2Hs have been proposed with different capacities of 124 MW, 33 MW, 22 MW, and 18 MW. These variable capacities can make different amounts of hydrogen dependent on how much CW is as the inlet power of the electrolyser. Figure 5 shows how much hydrogen has been generated from the electrolyser. In this study, a PEM electrolyser is chosen with 63% efficiency. Equarion (17) is implemented to calculate the hydrogen flow rate [34]. For further study this paper provides more information on the practical use of a 2 MW PEM electrolyser.

$$\mathcal{F}low\, rate\, of\, \mathcal{H}_2 = \frac{The\, CW \times 0.63\, (electrolyser\, efficiency)}{Volumetric\, heat\, value\, of\, H_2\, (12.7\, MJ/m^3)} \tag{17}$$

Due to the nature and molecular flow in gas network pipelines, and to calculate all the main variables and parameters, such as pressure, flow rate, density, compressibility factor, and gas constant, a quasi-transient state model is proposed at an hourly resolution for each day ($0 \leq$ ts ≤ 24).

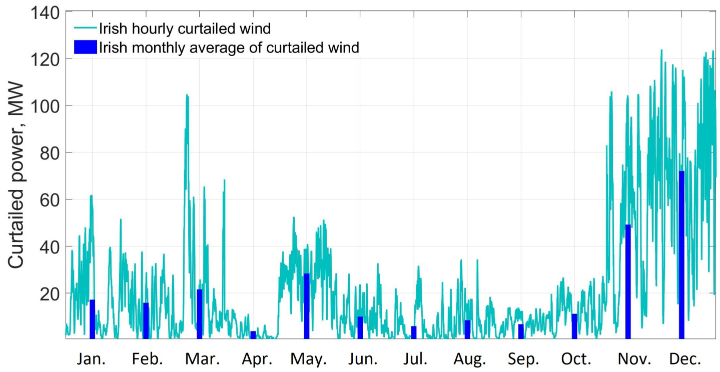

Figure 4. Curtailed wind profile in Ireland.

2.3. Gas Network and Wind Power Data

An available Irish hourly curtailed wind data were obtained for 8760 h [31]. Values fluctuated between a minimum 0.1 MW and a maximum of 124 MW, and the average hourly CW was 21.5 MW. The mean, mode, median and maximum average daily ranges are extracted for Irish annual CW and are shown in Figure 5. As mentioned previously, it is assumed that the gas network has two different end uses, namely gas-fired power plants and non-power consumers. Following the base case scenarios of fluctuated CW and selected days, the relative load factor of gas consumption in these end uses has been extracted from Gas Network Ireland (GNI) reports, as shown in Figures 6 and 7 where "x-axis" indexes the time steps with a different value in "y-axis" of relative gas consumption. The relative load factor is the proportion of hourly gas consumption and maximum hourly gas consumption. As mentioned before, Figure 5 shows both the fluctuated CW and hydrogen generated from P2H with capacities of 124 MW, 33 MW, 22 MW, and 18 MW. Table 1 shows the natural gas composition with their concentrations coming from NG suppliers. In addition, Table A1 summarises the physical details of the gas network, including connection nodes, sender and receiver nodes, pipe length and diameters, and node types.

Table 1. Composition properties of natural gas.

Composition	Concentration (by Volume), %	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	-

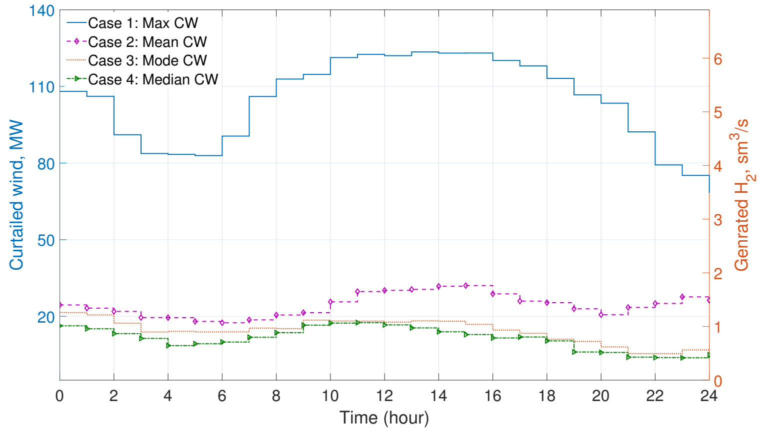

Figure 5. Mean, median, and maximum cases of curtailed wind extracted from annual Irish curtailed wind with generated hydrogen using (variable capacity) PEM electrolysers.

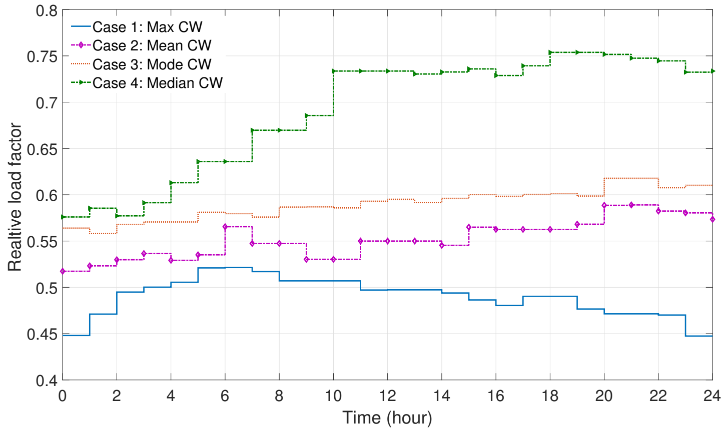

Figure 6. Relative load factor of gas consumption in power segment.

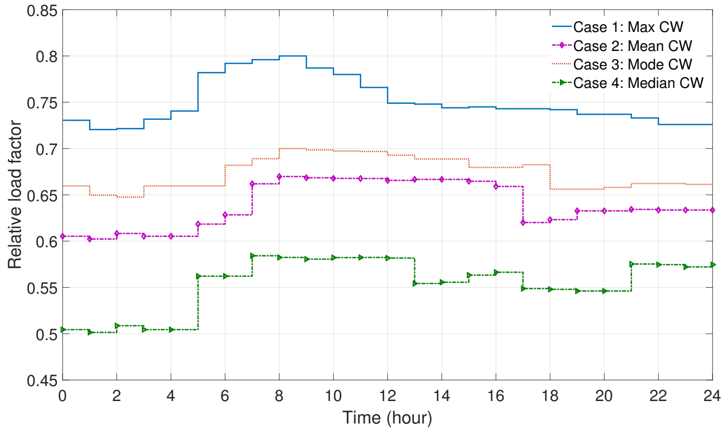

Figure 7. Relative load factor of gas consumption in non-power segment.

3. Simulation Results and Discussion

Hydrogen concentrations in NG networks are currently restricted, with the upper level depending on the network type and the materials involved. According to API and ISO standards, transmission pipeline compressors have an upper constraint of 20% hydrogen [17]. A distribution network can have 50% to 100% hydrogen concentration [18]; UN Regulation No. 110 stipulates that compressed tanks in CNG vehicles have a hydrogen limit of 2%; most existing gas turbines were specified for a hydrogen concentration of up to 1%; nevertheless, with some modifications, they can permit 5%. Some upgraded equipment, such as burners and boilers, can operate with hydrogen blend up to 20% [17]. Beyond the device type, there are some other criteria which affect the hydrogen mixture, such as:

- Safety: since hydrogen is very flammable, the main concern is the potential for increased ignition and resulting damage compared to the risk posed by NG without blended hydrogen. In transmission networks, up to 20%, and in distribution pipelines, up to 50% has a minor risk
- Durability of pipes and facilities
- gas leakage from pipelines and connections

Operational Variable Changes

As discussed in the introduction, hydrogen will influence the gas flow rates and result in greater pressure drops throughout the network. By calculating the amount of hydrogen for the four case studies of max, mean, mode and medium wind profiles, the maximum concentration of blended hydrogen by volume in natural gas are 11.6%, 3.4%, 2.2%, and 2.1%, respectively. In Figure 8, the pressure drop and flow rate have been shown for the four scenarios, with the highest pressure drop increase being 1.4% and the flow rate increase being about 8.5% for pipe 10. The model results, Figure 9, show the hydrogen concentration after blending with NG for each case.

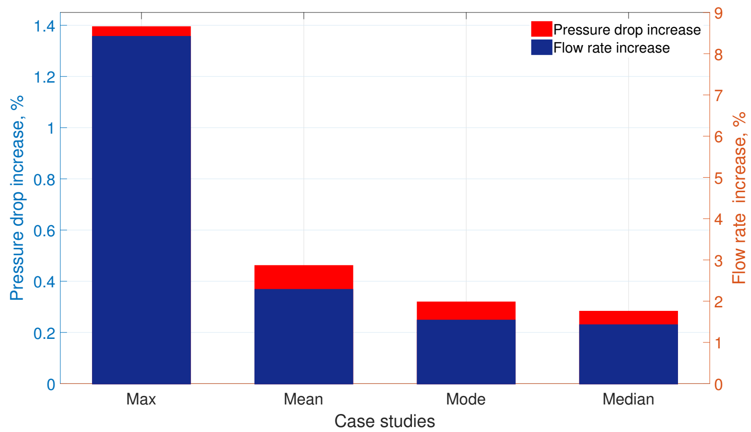

Figure 8. Pressure drop and flow rate increase after H_2 injection throughout pipe 10.

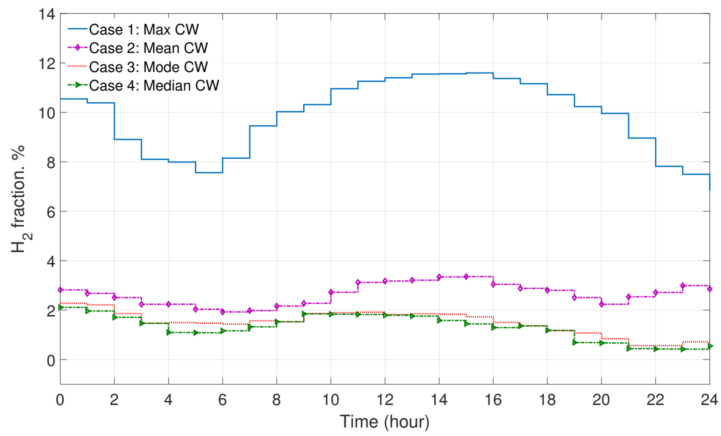

Figure 9. Hydrogen concentration at node 5 after blending with the NG.

Figure 10 shows the highest operational variables in pipes (9, 10, 13, 14, 15, 16, 17, and 18) that hydrogen is blended when there is the maximum capacity of wind curtailment (first case study). It can be seen that the maximum pressure drop occurred in pipe 9 by 12%, and the maximum flow rate increase is 15%. The pressure drop is 1.2 barg when natural gas (without hydrogen) flows, increasing to 1.3 barg. It shows operational variables by blending hydrogen concentration with nearly 11.6% will not increase substantially. The results have been validated by SAInt software [39]. Furthermore, a comparison of hydrogen concentration output at node 5 between the SAInt model and the proposed model is illustrated in Figure A1. There is less than a 1.5% deviation between the results found using the SAInt and Matlab model. This deviation is due to using different numerical and finite difference methods to solve the PDE gas equations.

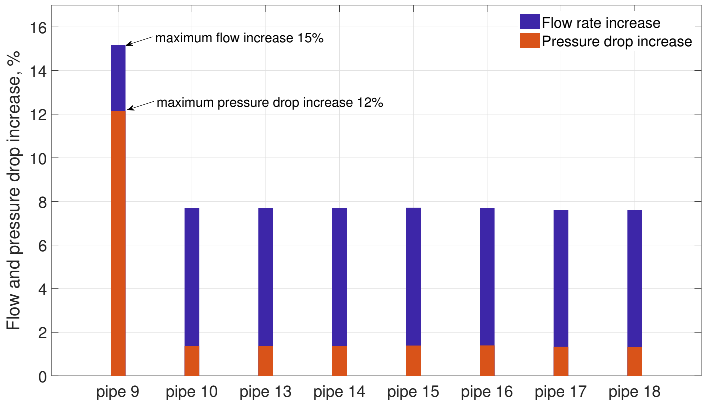

Figure 10. Pressure drop and flow rate increase after H_2 injection in pipes that have hydrogen mixture.

In the model, the effect of hydrogen on system pressures and flow rates has been considered. To demonstrate Figure 11 compares how much flow increases before and after hydrogen injection through pipe 10. For maximum demand, the flow rate increased by 2 sm^3/s due to injecting hydrogen to compensate for the reduced energy density after blending H_2. In summary, a rise in hydrogen concentration in the gas network results in increased pressure drops and flow rates in the pipes.

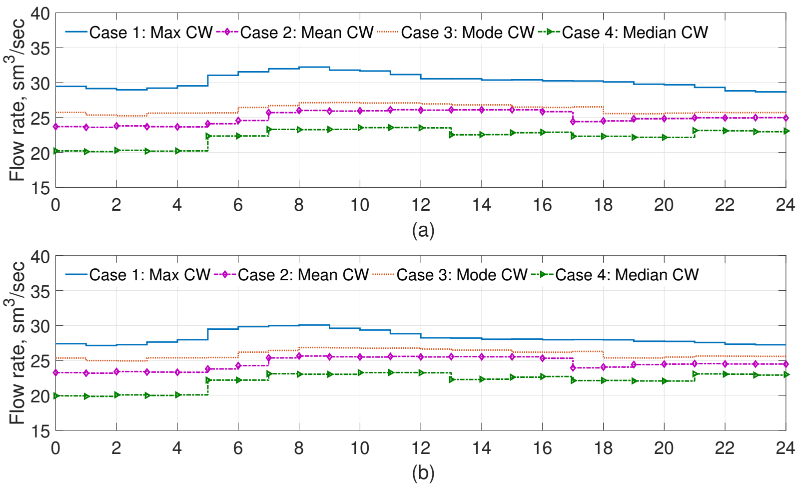

Figure 11. (**a**) Pipe 10 flow rate of blended gas with H_2, (**b**) Flow rate in Pipe 10 without hydrogen.

After blending hydrogen, it is of interest to know how much gas flow will be reduced from NG sources (Corrib at node 2 and Moffat at node 1). The model has been applied to consider additional capacity in the pipelines. Figure A2 shows a reduction of 0.8 sm^3/s of natural gas flow rate from Corrib and 1 sm^3/s from Moffat when there is the maximum daily curtailed wind. Further analysis examines the annual gas consumption of Ireland in 2020 and potential generated hydrogen and synthetic gas, methane, using P2G in Figure 12. When considering that all annual curtailed wind is injected into the gas network as hydrogen, there is a reduction in the natural gas consumed by 26 million m^3, offsetting 56,946-ton CO_2.

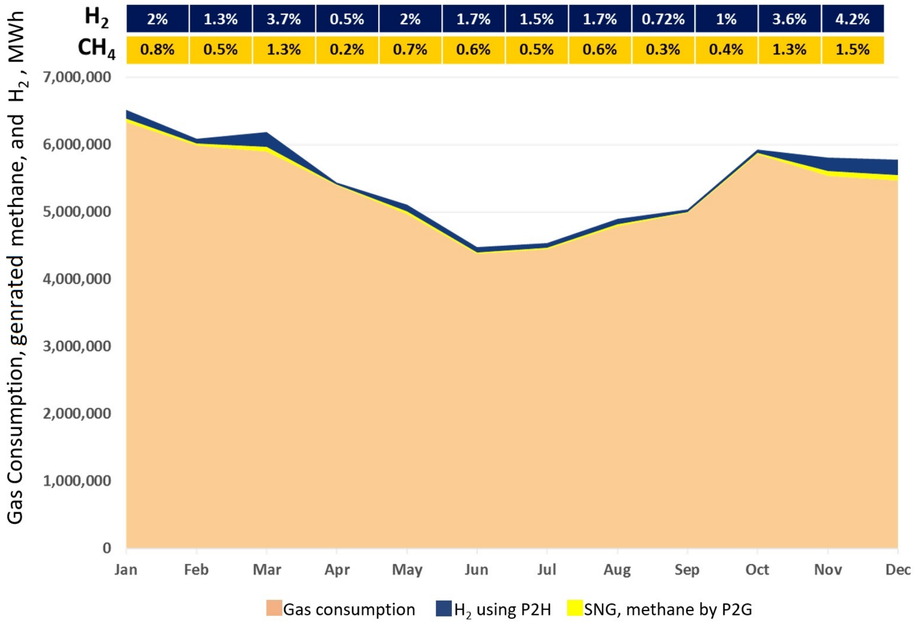

Figure 12. Annual gas consumption in Ireland and estimated hydrogen and synthetic gas methane (SNG) using P2G from renewable sources.

4. Conclusions

With the increasing levels of renewable power capacity on power networks, there is an associated increase in curtailed renewable energy. New technologies such as P2H are an alternative to use this curtailed power and generate green hydrogen, which can be blended with natural gas through the transmission and distribution pipelines. This research investigates the impact of hydrogen generated from wind farms on the gas network's pressure and flow rate operational variables. The Irish gas network has been studied as a case study. The results show that when an 11.6% hydrogen content is injected, there is a 12% rise in pressure drop and 15% increase in flow rate, which indicates that the operational variables will not encounter significant changes and remain within limits. In addition, there is a reduction in natural gas requirements up to 2%, which is approximately 200,000 Sm^3 daily natural gas reduction and consequently a decrease of CO_2 nearly 432 metric tonnes during the specific day. The gas network has the potential to play an increasingly important role in the low carbon energy system due to using its capacity for renewable energy storage. Consequently, gas and electricity networks require a resilient multi-energy system as a large, interconnected infrastructure.

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Abbreviations

The following abbreviations are used in this manuscript:

A	Cross Sectional area of pipe (m^2)
V	volume (m^3)
D	pipe inner diameter (m)
x	pipeline coordinate
E	Energy (J)
X_i	volumetric fraction of components
f	friction factor
f_t	theoretical friction factor
z	elevation (m)
g	gravitational acceleration (m^2/s)
Z	compressibility factor
i	sender node
θ	inclination (rad)
j	receiver node
ρ_n	normal density (kg/m^3)
$\mathcal{L}_d$	set of nodal load (demand, m^3/s)
ρ	density (kg/m^3)
$\mathcal{L}_{ij}$	set of pipe$_{ij}$ from the branch list
τ	shear stress (Pa)
l	pipe length (m)
T	time span
$\mathcal{NG}_{composition(i)}$	set of natural gas compositions
CW	Curtailed Wind
p	nodal pressure (Pa)
HHV	Higher Heating Value
p_c	critical pressure (Pa)
IC	Industrial/Commercial
Δ p	pressure drop (Pa)
NG	Natural Gas
Q	flow rate (m^3/s)
ODE	Ordinary Differential Equation
R	gas constant (kJ/kg^oK)
P2G	Power-to-Gas
SG	specific gravity (kg/m^3)
P2H	Power-to-Hydrogen
T	Temperature (K)
PDE	Partial Differential Equation
T_c	Critical temperature (K)
PEM	Polymer electrolyte membrane

Appendix A

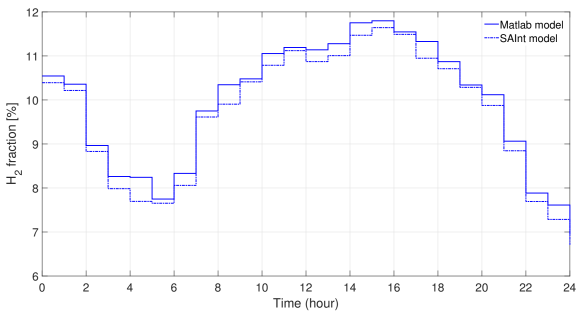

Figure A1. Hydrogen concentration variation from SAInt and Matlab models.

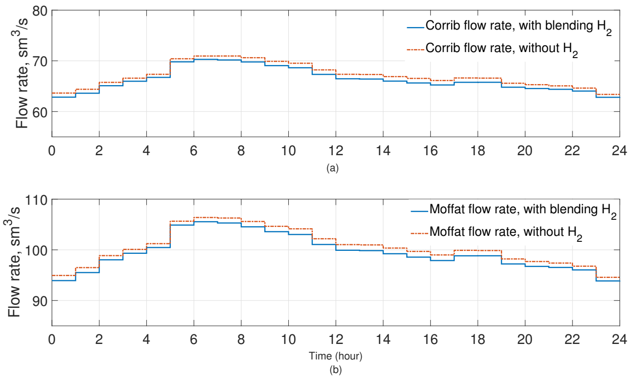

Figure A2. Corrib (**a**) and Moffat (**b**) flow rate reduction after injecting hydrogen.

Table A1. Gas network pipes and nodes.

Pipes					Nodes	
Pipe No.	**Sender Node**	**Receiver Node**	**Diameter, m**	**Length, km**	**Node No.**	**Node Type**
Pipe 1	1	19	0.76	280	1	Supplier (NG)
Pipe 2	2	10	0.6	300	2	Supplier (NG)
Pipe 3	3	9	0.6	70	3	Supplier (NG)
Pipe 4	9	6	0.6	15	4	Power plant
Pipe 5	7	6	0.6	15	5	Power plant
Pipe 6	8	7	0.6	15	6	Non-Power
Pipe 7	9	8	0.6	7	7	Non-Power
Pipe 8	3	5	0.6	15	8	Non-Power
Pipe 9	5	14	0.6	70	9	Non-Power
Pipe 10	5	11	0.6	35	10	Power plant
Pipe 11	4	5	0.6	130	11	Power plant
Pipe 12	2	4	0.6	113	12	Non-Power
Pipe 13	11	12	0.6	15	13	Non-Power
Pipe 14	11	13	0.6	13	14	Connector
Pipe 15	14	16	0.6	20	15	Connector
Pipe 16	15	17	0.6	20	16	Power plant
Pipe 17	14	15	0.6	30	17	Non-Power
Pipe 18	15	6	0.6	30	18	Non-Power
Pipe 19	4	18	0.6	100	19	Connector
Pipe 20	18	10	0.6	65	20	Power plant
Pipe 21	19	10	0.6	5	21	Power plant
Pipe 22	20	19	0.6	160	22	Power plant
Pipe 23	1	20	0.6	180	23	P2H
Pipe 24	20	21	0.6	100		
Pipe 25	4	22	0.6	5		
Pipe 26	23	5	0.6	20		

References

1. Gautam, P.; Kumar, S.; Lokhandwala, S. Energy-Aware Intelligence in Megacities. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 211–238.
2. Smil, V. *Energy in World History*; Routledge: London, UK, 2019.
3. MacKay, D. *Sustainable Energy-Without the Hot Air*; UIT Cambridge: Cambridge, UK, 2008.
4. Hansen, A.B.; Nybroe, M.H. Future possibilities—The gas system as flexibility provider for wind power production. In Proceedings of the Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–8.
5. Knezović, K.; Soroudi, A.; Keane, A.; Marinelli, M. Robust multi-objective PQ scheduling for electric vehicles in flexible unbalanced distribution grids. *IET Gener. Transm. Distrib.* **2017**, *11*, 4031–4040. [CrossRef]
6. Ekhtiari, A.; Dassios, I.; Liu, M.; Syron, E. A Novel Approach to Model a Gas Network System. *Appl. Sci.* **2019**, *9*, 1047. [CrossRef]
7. GasNetworksIreland. Delivering a Reliable and Secure Gas Supply. Gas Networks Ireland em. 2020. Available online: https://www.gasnetworks.ie/corporate/company/our-network/18048_GNI_GasNetwork_ReliabilityCapacity_Doc_Update.pdf.html (accessed on 23 August 2022).
8. Pambour, K.A.; Cakir Erdener, B.; Bolado-Lavin, R.; Dijkema, G.P. Development of a simulation framework for analyzing security of supply in integrated gas and electric power systems. *Appl. Sci.* **2017**, *7*, 47. [CrossRef]

9. Ekhtiari, A.; Syron, E. Moffat Constraints to supply Ireland's Gas Network. *Irel. Soc. Eng.* **2018**. Available online: https://www.engineersireland.ie/Brexit/irelands-future-natural-gas-supply-how-well-connected-is-the-island (accessed on 23 August 2022).
10. Götz, M.; Lefebvre, J.; Mörs, F.; Koch, A.M.; Graf, F.; Bajohr, S.; Reimert, R.; Kolb, T. Renewable Power-to-Gas: A technological and economic review. *Renew. Energy* **2016**, *85*, 1371–1390. [CrossRef]
11. Gahleitner, G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. *Int. J. Hydrogen Energy* **2013**, *38*, 2039–2061. [CrossRef]
12. Qadrdan, M.; Cheng, M.; Wu, J.; Jenkins, N. Benefits of demand-side response in combined gas and electricity networks. *Appl. Energy* **2017**, *192*, 360–369. [CrossRef]
13. Portarapillo, M.; Di Benedetto, A. Risk Assessment of the Large-Scale Hydrogen Storage in Salt Caverns. *Energies* **2021**, *14*, 2856. [CrossRef]
14. Gupta, R.B. *Hydrogen Fuel: Production, Transport, and Storage*; CRC Press: Boca Raton, FL, USA, 2008.
15. Hafsi, Z.; Mishra, M.; Elaoud, S. Hydrogen embrittlement of steel pipelines during transients. *Procedia Struct. Integr.* **2018**, *13*, 210–217. [CrossRef]
16. Ekhtiari, A. Academic Article: Ireland's Decarbonisation Target, Green Hydrogen and End-Users' Limits. Gas Networks Ireland em. 2022. Available online: https://www.gasnetworks.ie/corporate/news/active-news-articles/irelands-decarbonisation/ (accessed on 23 August 2022).
17. Gondal, I.A. Hydrogen integration in power-to-gas networks. *Int. J. Hydrogen Energy* **2019**, *44*, 1803–1815. [CrossRef]
18. 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. [CrossRef]
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. Hydrogen Energy* **2015**, *40*, 5763–5775. [CrossRef]
20. Ameli, H.; Qadrdan, M.; Strbac, G. Techno-economic assessment of battery storage and Power-to-Gas: A whole-system approach. *Energy Procedia* **2017**, *142*, 841–848. [CrossRef]
21. Afkousi-Paqaleh, M.; Rigoni, V.; Wilson, C.; Hewitt, N.; Flynn, D.; Keane, A. Network limits on residential heat pump capacity as an enabling technology towards renewables integration. In Proceedings of the The 9th Renewable Power Generation Conference (RPG Dublin Online 2021), Online, 1–2 March 2021; Volume 2021, pp. 265–270.
22. Guandalini, G.; Robinius, M.; Grube, T.; Campanari, S.; Stolten, D. Long-term power-to-gas potential from wind and solar power: A country analysis for Italy. *Int. J. Hydrogen Energy* **2017**, *42*, 13389–13406. [CrossRef]
23. 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. [CrossRef]
24. 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. [CrossRef]
25. 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.
26. Ordoudis, C.; Pinson, P.; Morales, J.M. An integrated market for electricity and natural gas systems with stochastic power producers. *Eur. J. Oper. Res.* **2019**, *272*, 642–654. [CrossRef]
27. 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* **2017**, *9*, 582–598. [CrossRef]
28. Clegg, S.; Mancarella, P. Integrated modeling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks. *IEEE Trans. Sustain. Energy* **2015**, *6*, 1234–1244. [CrossRef]
29. Ozturk, M.; Dincer, I. System development and assessment for green hydrogen generation and blending with natural gas. *Energy* **2022**, *261*, 125233. [CrossRef]
30. Smith, C.; Mouli-Castillo, J.; Van Der Horst, D.; Haszeldine, S.; Lane, M. Towards a 100% hydrogen domestic gas network: Regulatory and commercial barriers to the first demonstrator project in the United Kingdom. *Int. J. Hydrogen Energy* **2022**, *47*, 23071–23083. [CrossRef]
31. Eirgrid. Annual Renewable Energy Constraint and Curtailment. 2020. Available online: https://www.eirgridgroup.com/site-files/library/EirGrid/Annual-Renewable-Constraint-and-Curtailment-Report-2020.pdf (accessed on 23 August 2022).
32. Ekhtiari, A.; Flynn, D.; Syron, E. Gas Network, Storing Energy and Renewable Power Penetration. In Proceedings of the 22nd Conference on Process Integration. Modelling, and Optimisation for Energy Saving and Pollution Reduction, PRES'19, Crete, Greece, 20–23 October 2019; pp. 1–6.
33. Osiadacz, A. *Simulation and Analysis of Gas Networks*; Gulf Publishing Company: Houston, TX, USA, 1987.
34. Ekhtiari, A.; Flynn, D.; Syron, E. Investigation of the Multi-Point Injection of Green Hydrogen from Curtailed Renewable Power into a Gas Network. *Energies* **2020**, *13*, 6047. [CrossRef]
35. Pambour, K.A.; Bolado-Lavin, R.; Dijkema, G.P. An integrated transient model for simulating the operation of natural gas transport systems. *J. Nat. Gas Sci. Eng.* **2016**, *28*, 672–690. [CrossRef]
36. 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. [CrossRef]
37. Parra, D.; Zhang, X.; Bauer, C.; Patel, M.K. An integrated techno-economic and life cycle environmental assessment of power-to-gas systems. *Appl. Energy* **2017**, *193*, 440–454. [CrossRef]

38. Abdon, A.; Zhang, X.; Parra, D.; Patel, M.K.; Bauer, C.; Worlitschek, J. Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales. *Energy* **2017**, *139*, 1173–1187. [CrossRef]
39. Hafsi, Z.; Ekhtiari, A.; Ayed, L.; Elaoud, S. The linearization method for transient gas flows in pipeline systems revisited: Capabilities and limitations of the modelling approach. *J. Nat. Gas Sci. Eng.* **2022**, *101*, 104494. [CrossRef]