CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976149

Gas Networks, Energy Storage and Renewable Power Generation

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With an increase in variable and sometimes uncertain renewable generation coming on-line, there is an associated increase in the importance of energy storage to balance supply and demand. The gas network already stores and transports energy, and it has the potential to play a significant role for longer term energy storage. In addition, gas and electrical grids are becoming more integrated with fast responding gas-fired power stations, providing the main source of back up for renewable electricity in many systems. In 2017, Ireland's renewable generation accounted for 19 % of electricity generated and was the second largest source of electricity generation after natural gas and coal with 51 % and 18 % respectively. The percentage of renewable electricity is rising and there is a 40 % target to be met by 2020. Using a simplified version of Ireland's gas network, with 14 nodes and 15 pipes, the objective of this paper is to investigate how hydrogen, generated through power-to-gas (P2G) from curtailed wind power, impacts the operation of the gas network system. A quasi-transient model was constructed in MATLAB to calculate the main characteristics of the gas network. The results show, with an increasing mass fraction of hydrogen in the gas network, that the pipeline flow rate needs to be increased to compensate for reduced energy quality due to the lower energy density of the blended gas. There is significant potential for the gas network to store and transport excess and/or otherwise non-transportable renewable electricity to maximize renewable energy utilization.

1. Introduction

In many regions through-out the world with limited fossil energy resources, there is huge potential for renewable energy generation (Knezović et al., 2017), but the availability of the renewable power does not always match demand. For the island of Ireland, approximately 50 % of the natural gas (NG) supply is imported and this is expected to increase as indigenous production falls (Network, 2016). 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 upto 80 % of peak power demand (Network, 2016). Furthermore, wind power is the main renewable energy resource in Ireland, which is highly variable (Soroudi, 2019), although the gas network can provide longer term storage and transport of the excess wind power (non-transportable renewable electricity) through the use of technologies such as P2G.

Currently, fossil fuels are still the main source of global energy, so, reducing reliance on fossil fuels and the associated CO_2 emissions, means finding an alternative economic source of energy to replace them (Hansen et al., 2000), with one of these ways being to make better use of renewable energy sources (RES). Based on REN 21 annual report (REN 21, 2018), RES has provided 10.4 % of global final energy consumption with 1.7 % from wind, solar, biomass and geothermal, and 4.1 % from biomass, 3.7 % from hydro-power and 0.9 % bio-fuel for transport (REN 21, 2018). Security of energy supply plays a key role in energy policies (Pambour et al., 2018). Fossil fuels are still widely available, and while society might want to weaken dependency due to environmental concerns (MacKay, 2008), significant investments in fossil fuels are still occurring and a rapid transition away would undoubtedly make societies vulnerable (MacKay, 2008). One of the major shortcomings of is its variability, which makes the balancing of energy supply from a wide range of sources with end users with different behaviours challenging, especially with very large interconnected infrastructure, such as the gas and power networks (Ekhtiari et al., 2019). Traditionally, the interconnections between the gas network and the

Paper Received: 15/03/2019; Revised: 15/05/2019; Accepted: 22/05/2019
Please cite this article as: Ekhtiari A., Flynn D., Syron E., 2019, Gas Networks, Energy Storage and Renewable Power Generation, Chemical Engineering Transactions, 76, 889-894 DOI:10.3303/CET1976149

electrical grid have been compressor stations and power plants (Pambour et al., 2017). However, the number and variety of these inter-connections is increasing, for example, when a choice of energy can be used for heating or cooling purposes. The gas network can play a key role in energy storage, storing the fuel for the fast-responding gas power stations, which provide back up for the renewable electricity supply (Ekhtiari, 2018). In addition, the gas network can store non-transportable renewable electricity through the use of technologies, such as power to gas. A P2G system converts electricity into hydrogen using an electrolyser or synthetic natural gas by a reactor (Pambour et al., 2018), (Götz et al., 2016) which can be stored by injection into the pipelines and mixing with NG (Qadrdan et al., 2017) Figure 1. If hydrogen is injected directly into the natural gas network, then care must be taken regarding the permissible upper hydrogen limit. Hydrogen is lighter than air and due to its small molecules size may increase leaks from the network (Gondal, 2016). Additionally, there is concern about the structural integrity of metal pipes and the risk of hydrogen fracture at elevated hydrogen concentrations (Hafsi, 2018).

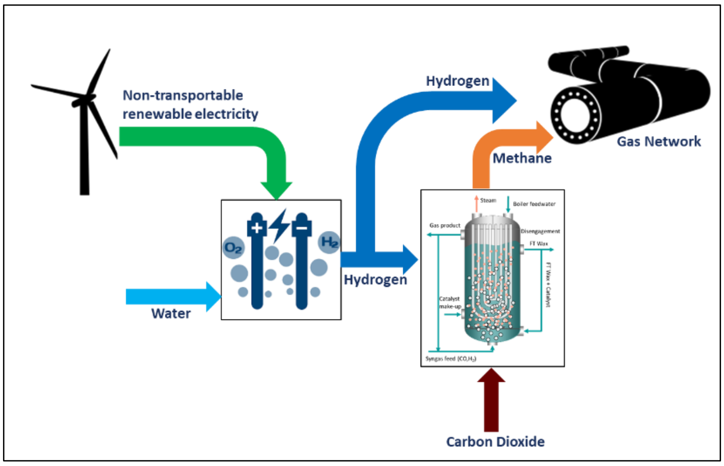


Figure 1. Power to Gas schematic process

Different modelling approaches have been proposed for investigating an integrated gas and power system. Some research has mainly focussed on modelling an integrated system to study the main physical interactions and analyse the impacts of both gas and power systems interactions e.g. gas compressor stations and power plants (Pambour et al., 2017). Other publications have centred on 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 synthetic natural gas into the gas network (Gahleitner, 2013).

Qadrdan et al. (2015), performed out a cost evaluation of P2G in an integrated gas and electricity system with varying levels of synthetic methane. Their major finding was that the overall operating cost of gas and electricity grids was reduced when using the surplus wind to generate methane from P2G. Ameli (2017), investigated the potential role of battery storage and P2G systems when power generation was made up of a large capacity of wind and solar sources. A combined gas and electricity network model was utilised for optimization of an integrated Great Brittan system over a predicted winter and summer of 2030. Abeysekera et al. (2016), concentrated 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. Long term P2G application has been discussed by Guandalini et al. (2017) with the study investigating P2G potential for storing energy on a national scale. Hydrogen generation from excess renewable electricity (from solar and wind) was determined, the outputs showed recovered curtailed electricity from RES equal to approximately 5 % of the NG consumption or, 7 % of national fuel consumption in Italy in 2016.

In the current study, a simplified model of the Ireland gas network is presented with a source node representing a P2G system which is producing hydrogen and injecting it into the natural gas transmission pipes. The model solves gas flow equations by calculating the compressibility factor, line pack capacity, the density of blended NG taking into account the gas quality due to the mass fraction of the different components a factor that is often neglected in previous work. The energy capacity of the NG before and after blending with hydrogen has also been calculated in order to investigate how the integrated gas network might perform in reality. This analysis is of particular interest to gas network operators that are intending to de-fossilize their gas network, even if it is only by a small fraction.

2. Integrated Gas Network and RES Model

In this case study, wind power which is the main source of renewable energy on the island of Ireland (with a 30 % share of Ireland's electricity in 2018 (Eirgrid-SONI 2018)) is taken as the primary RES source. Local limitations of the electrical network and stability considerations can lead to wind dispatch-down at certain time, which refers to the amount of wind power that cannot be transported to customers (Eirgrid-SONI 2018). On the island of Ireland (Republic of Ireland (ROI) and Northern Ireland (NI)) 9,280 GWh power from wind was generated in 2017 while 386 GWh of wind was dispatched-down, nearly 4 % of available wind (EirGrid-SONI, 2018), as seen by the monthly wind dispatch-down for Ireland in 2017.

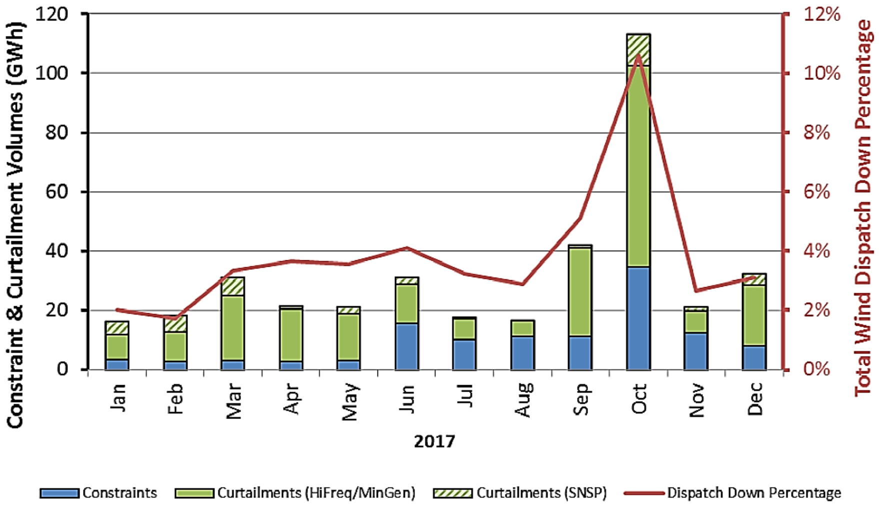


Figure 2. Wind dispatch-down for Ireland, divided into curtailments and constraints (EirGrid-SONI, 2018)

The simplified NG network includes 14 nodes including 3 supplier nodes of natural gas (1, 2, and 3 with 70 barg set point pressure) from Moffat (the gas terminal in Scotland), Corrib, and Inch-Kinsale which are local Ireland's gas fields (Ekhtiari, 2018) and a hydrogen supply node 14 from P2G with 225 MW, the capacity of electrolyser, from a wind farm in the southwest of the network (which is close to the wind farm). As shown in Figure 3a, hydrogen blended with NG is supplied at nodes 5 to 13 and only node 4 is being supplied by NG without hydrogen. Due to the nature and molecular flow in gas network pipelines a quasi-unsteady state model is sufficient for this study. The governing flow equations are presented in Eq(1) (Osiadacz 1987), while Eq(2) to Eq(4) (Ekhtiari et al. 2019) represent sub-parts integrating the main gas flow equation.

$$\left(\frac{\partial P}{dx} = \frac{16 f_t \rho_n^2 ZRT|Q|Q}{2\eta^2 DA^2 P} - \frac{g sin(\theta)}{ZRT} P\right)_{@\ hourly\ \Delta t} \tag{1}$$

$$P_i^2 - P_j^2 = a_{ij}|Q_{ij}|Q_{ij} + b_{ij}P_{ave}^2 \tag{2}$$

$$a_{ij} = \frac{16 f_{ij} \rho_n^2 ZRTl}{\pi^2 D^5} \tag{3}$$

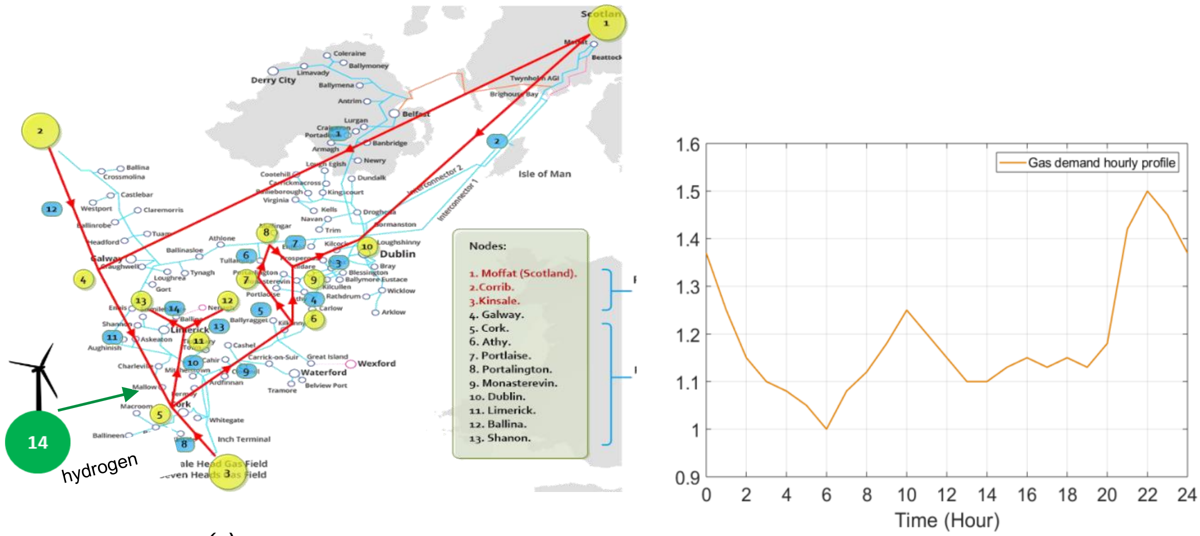
$$b_{ij} = \frac{2gl sin(\theta)}{ZRT} \tag{4}$$

$$Z = 1 - 3.52\left(\frac{P}{P_c}\right)\exp\left[-2.26\left(\frac{T}{T_c}\right)\right] + 0.274\left(\frac{P}{P_c}\right)^2 \exp\left[-1.878\left(\frac{T}{T_c}\right)\right] \tag{5}$$

Where "P" and "Q" represent pressure and flow rate, and compressibility factor, "Z", has been approximated by the Eq(5) (Papay equation) which is applicable for high pressure networks (Heidaryan, et al., 2010). Because of the diversity of components such as C1, C2, C3, N_2, and CO_2 in the gas network from P2G and NG suppliers, the density in each pipe is calculated by Eq(6) (Abeysekera et al. 2016), with consideration of the different mass fraction of individual components. Where "ρ" and "X" in Eq(7) represent flow density and mass fraction in a pipeline.

$$\rho_{out}^{node\ i} = \frac{\sum Q_{in}^{node\ i} \times \rho_{in}^{node\ i}}{\sum Q_{out}^{node\ i} + L_{Demand}^{node\ i}} \quad (6)$$

$$X_{out}^{H_2} = \frac{\rho_{out}^{NG} - \rho_{out}^{mixed\ gas}}{\rho_{out}^{NG} - \rho^{H_2}} \quad (7)$$

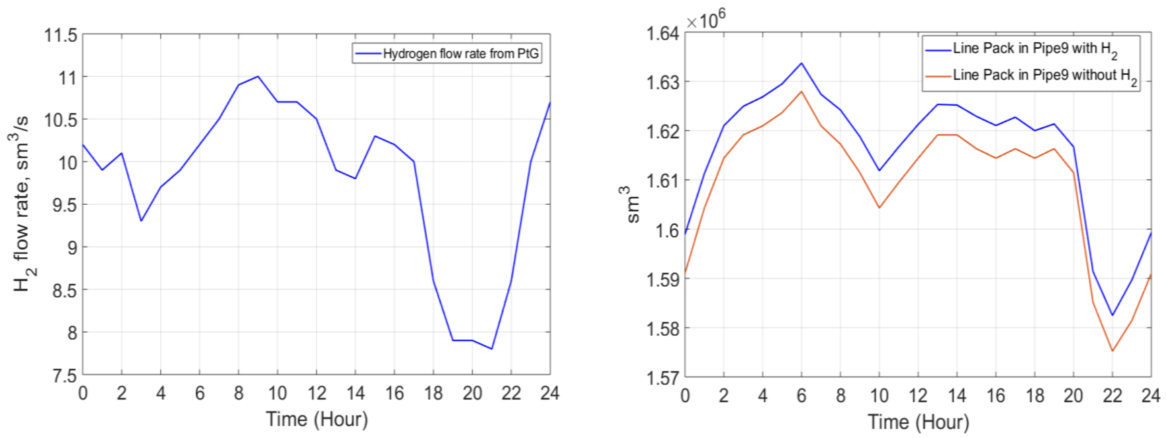


(a) (b)

Figure 3. (a) Simplified Ireland Gas Network, (b) the relative hourly gas consumption profile

3. System Outputs description

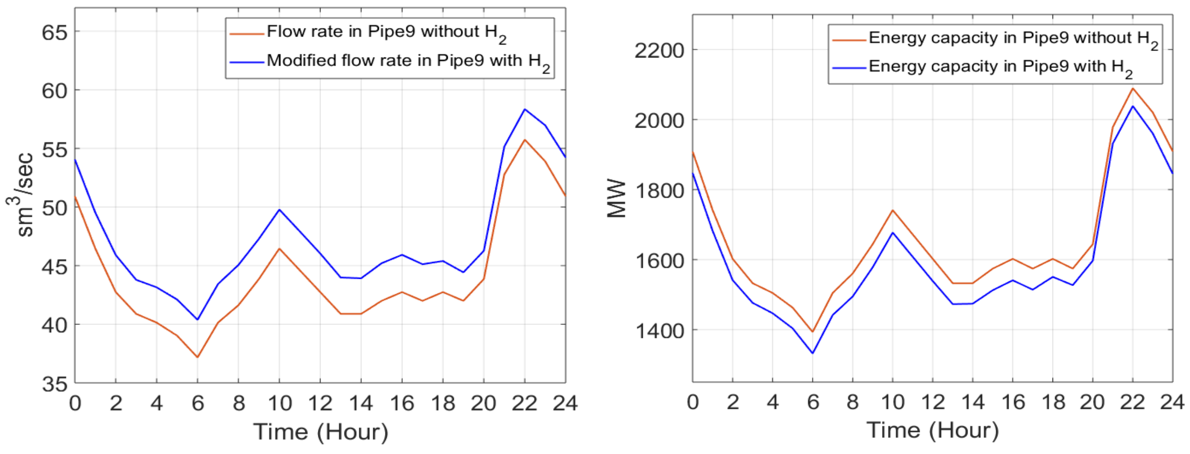
Nodes 1, 2, and 3 of the network are supplying NG at 70 barg pressure and hydrogen is injected at node 14 corresponding to an hourly profile of curtailed wind. Figure 4a shows the flow rate of hydrogen corresponding to the curtailed wind while Figure 4b shows the line-pack before and after injecting H_2 in pipe 9 (which is a connection between nodes 5 and 6). The hydrogen generation using P2G fluctuates between 7.8 and 11 sm^3/s due to intermittent-wind power during the day. The average line-pack during the day in pipe 9, before injecting H_2 is 1.609×10^6 sm^3 and after injecting is 1.616×10^6 sm^3, which is nearly 6600 sm^3 higher than the system without hydrogen. The average density of the mixed gas in pipe 9 is 55.6 kg/m^3 representing a reduction from 59 kg/m^3 before blending with hydrogen. The average pressure before and after mixing is 67 barg and 68 barg within pipe 9. Furthermore, if all annual curtailed wind injected into the gas network as hydrogen, reduces the natural gas consumed by 26 MSCM, offsetting 56,946 tones carbon dioxide.



(a) (b)

Figure 4. (a) hydrogen profile coming from P2G. (b) Line-pack in pipe 9 before and after injecting hydrogen

The results in Figure 4 and Figure 5 also show that injecting hydrogen to the network decreases the energy density of gas flow through the pipelines. It occurs because of lower volumetric energy of gas mixture; therefore, the average-daily flowrate will need to be increased by 3 sm^3/s to compensate for reduced energy quality.



(a) *(b)*

Figure 5. (a) Flow rate in pipe 9, (b) amount of energy through the pipe 9 before and after injecting hydrogen

The requirements for gas supply are variable with a unsteady state demand, and it can be difficult to predict how an unsteady supply will unfold, as it is effectively a function of the relative demand. The hourly gas consumption profile shown in Figure 3b is assigned to the gas demands goes to three main nodes (nodes 4, 5 and 10) which have the highest gas consumption during the period.

4. Conclusions

Understanding (gas and power) system behaviour is critical for managing an integrated energy system. This is becoming more challenging, with an increasing installed capacity of renewable energy sources reducing the CO_2 foot-print, but with a continued use of fossil fuel infrastructure to manage the security of supply. In this research, the impact of injecting hydrogen from a P2G electrolyser with 225 MW capacity but varying output with a varying natural gas demand was investigated. Results show an increase in the line-pack of interconnection pipelines with mixed natural gas and hydrogen. The flow rate through these pipes should be increased to maintain the supply of energy at the demand nodes. An integrated model combining electricity and gas is necessary to help energy system designers, researchers and policymakers make the combined system more resilient. Calculating the gas quality can provide more accurate results of the effect of hydrogen into a gas network and investigate its capacity to support the security of supply. Further research is required to understand how the gas and power systems can be co-optimised, while considering alternative options such as biomethane or Liquified Natural Gas (LNG) (weathering).

Acknowledgments

This work is supported by the Science Foundation Ireland, by funding Ali Ekhtiari, Damian Flynn and Eoin Syron under Strategic Partnership Programme Grant No. SFI/15/SPP/E3125.

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