Integrated modelling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks

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Abstract **— Power-to-gas (P2G) is the process whereby electricity is used to produce hydrogen or synthetic natural gas. The electricity for the P2G process could, for instance, come from renewable energy which would otherwise be curtailed due to system or line constraints. The existing natural gas network could then potentially be used as a means to store, transport and reutilize this energy, thus preventing its waste. While there are several ongoing discussions on P2G in different countries, these are generally not backed by quantitative studies on its potential network implications and benefits. To bridge this gap, this paper introduces an original methodology to analyze different P2G processes and assess their operational impacts on both electricity and gas transmission networks. This is carried out by using a novel integrated model specifically developed for the simulation of operational interdependences between the two networks considering P2G. To demonstrate the several innovative features of the proposed model, technical, environmental, and economic operational aspects of P2G and its potential benefits are analyzed on the case of the Great Britain's system, also providing insights into relief of gas and electrical transmission network constraints.**

Index Terms**—Power-to-gas; Natural gas networks; Optimal power flow; Integrated energy systems; Multi-energy systems; Hydrogen production.**

I. INTRODUCTION

WITH the continuing increase in the installed capacity of renewable energy sources, it is likely that more and more generation will have to be curtailed to maintain certain levels of system reliability [1]. Much research is therefore being carried out as to what practical means there are to make beneficial usage of this potentially unutilized energy. In this context, there has been widespread discussion of the power-to-gas (P2G) process whereby electrical energy is converted to hydrogen (H_2) or synthetic natural gas (SNG), stored and recovered at a later time through combustion to generate low-carbon electricity and/or heat [2] [3]. An additional benefit of this is the practical possibility of using existing natural gas (NG) networks for storing and transporting this energy. This is also very attractive to maintain high gas asset utilization even in future scenarios with reduced gas based energy supply [4].

Academic studies into the P2G process have primarily been considered in combination with other hydrogen producing technologies as part of a greater hydrogen economy (e.g., [3][5][6]). In this line, references [7] and [8] consider introducing alternative gases as part of a program ultimately aiming at the conversion of the NG network into a hydrogen network. On the other hand, industrial reports on P2G have focused on technological development and safety implications. For example, in [9] a comprehensive review is given of the characteristics of the technologies involved for both H_2 and SNG production. In [8] and [10] the authors elaborate on the factors limiting the amount of H_2 that may be blended with NG, including H_2 embrittlement of steel pipes and change in the gas flame characteristics on combustion.

From a system perspective, previous studies that have discussed the use of P2G as a mechanism to reduce the levels of curtailment in renewable energy sources [4] do not model the levels of gas production with consideration of power system requirements through the use of an optimal power flow (OPF). On the other hand, studies which integrate the electrical and gas transmission network models, for example, [11][12][13], do not consider the effects of P2G. To the authors' knowledge, this work is the first to model P2G with power system requirements and integration with gas network modelling.

On the above premises, the aim of this paper is to model and assess the possibility of integrating the P2G process into an existing energy system, with focus on modelling the impact on the gas and electrical transmission infrastructure. Specific stress is put on P2G where the electricity curtailed from variable energy sources (in particular wind, in the application studies performed here) is converted into H_2 or SNG which are consequently injected into the gas transmission network. The primary novelty of this work lies in addressing the gas and electrical network implications of the P2G process, for which an integrated electricity-and-gas network analysis model has been specifically developed. In particular, an original two-stage DC OPF model coupled to a gas network transient analysis model has been specifically developed to quantify the levels of wind curtailment, the P2G transformation of electricity into different forms of gas, the utilization of gas from power generators, and changes in power flows caused by transfer of power due to P2G facilities.

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The developed transient analysis model, [14] [15], is able to highlight gas network flexibility characteristics and possible shortcomings. In particular, by explicitly considering gas pipeline storage ("linepack") characteristics throughout the network, the model is capable of showing the impact P2G facilities will have on the gas flows from both a temporal and geographical point of view. The physical interface between the two networks takes place through P2G facilities and gas-fired power plants. In this respect, P2G facilities are specifically modelled to account for the constraints in the capability to integrate the produced gas, e.g., due to network storage limitations or the limits to use the existing gas infrastructure with H_2. Allowance for H_2 storage facilities, is also considered. The benefits of P2G are investigated in terms of wind curtailment and carbon emissions displacement, economic cost saving associated with natural gas production, and congestion relief in both the gas and electrical networks. All these are unique and novel contributions to understanding the implications of P2G considering realistic network operation and constraints.

In the rest of the paper, Section II discusses the fundamentals of the P2G process. Section III outlines the integrated gas and electricity network model proposed, including the modelling of the P2G facilities. Section IV exemplifies the application of the model through case studies on the Great Britain (GB)'s gas and electricity transmission networks in the Gone Green scenario put forward by National Grid [16]. Section V contains the concluding remarks. Details on the gas network analysis model are in the Appendix.

II. Power-to-gas modelling

A. *Operation and location of the power-to-gas facilities*

Different types of P2G facilities can be considered which depend on the end-use of the gas produced as well as its locality and reason for the curtailment of the renewable sources. More specifically, there are three sets of P2G facilities considered here at three respective sets of locations, namely, at gas terminals, at congested gas nodes, and at congested electrical nodes. Without loss of generality, so as to prevent an overconcentration of H_2 in the gas network (see Section II.C) the placement of facilities which produce H_2 will be associated to the gas terminals. On the other hand, SNG facilities can be placed away from gas terminals and their utilization as a means of relieving gas network congestion by altering the gas flows will also be assessed as a potential application. Besides for system stability requirements, curtailment may also occur due to transmission line constraints. In this situation, the P2G process is required to occur at the locality of curtailment. When this is away from gas terminals, an SNG facility will be considered in the scenarios analyzed; on the other hand, if the curtailment occurs at a gas terminal, then both H_2 and SNG will be considered. In the modelling and the studies carried out below, it is assumed that the locations and sizes of the three sets of P2G facilities are assigned based on prior electrical and gas network analysis that identify the relevant requirements. More details are given in Section III.D.

B. *Power-to-gas processes*

In the first type of P2G process, gaseous hydrogen is formed by the process of electrolysis whereby water is split into hydrogen and oxygen. This process is described by $2H_2O \longrightarrow 2H_2 + O_2$. The technology may be alkaline electrolysis or proton exchange membrane (PEM). Owing to its potential faster adaptation to wind fluctuations thanks to its quicker ramp rates, PEM appears to be the favorable technology for the P2G process [9]. Facilities of this type are currently employed in P2G for gas distribution networks [17] [18].

As a second P2G process, the production of the SNG gas methane is considered. The methane forming process, *methanation*, is a secondary process which requires H_2 resulting from electrolysis along with carbon dioxide: $CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$. This process may be either chemical or biological [9]. Although the technologies in each are different, at a system level the overall process is similar and, for the purposes of this work, no distinction will be made between the two. As methanation is a secondary process using the H_2, its efficiency will always be less than that of the hydrogen forming process.

C. *Modelling of the injection of H_2 in the gas network*

There are technical and legislative restrictions on the quantity of H_2 that may be blended into the NG network. The legislative limits vary widely for different regions and gas networks [19]. For example, the UK has, historically, set a comparatively small limit of 0.1% by volume (%vol.) on the content of the H_2 in the NG network. In this work, the amount of gas entering the network is considered in terms of its energy content. Hence, if $\bar{L}_{H_2,\mathrm{Vol}}$ is the maximum volume level of H_2 allowed in the network, then its maximum energy level is

$$\bar{L}_{H_2,\mathrm{Energy}} = \frac{\bar{L}_{H_2,\mathrm{Vol}} \times HHV_{H_2}}{\left(1 - \bar{L}_{H_2,\mathrm{Vol}}\right) \times HHV_{NG} + \bar{L}_{H_2,\mathrm{Vol}} \times HHV_{H_2}} \quad (1)$$

where HHV_{H_2} and HHV_{NG} (in MJ/m^3) are the higher heating values (HHV) of H_2 and NG, respectively. As mentioned earlier, it is assumed that the H_2 will be blended with NG and/or SNG at the gas terminals up to the predefined limit. When doing so, it is also realistically assumed that the gas energy demand levels for each node are not affected by the H_2 content of the gas. Since the HHV of H_2, by volume, is approximately a third of that of NG, the H_2-NG mix will have a smaller HHV than NG. Therefore, the volumetric gas demand requirements will change with the introduction of H_2. The change in the HHV of the network gas will be determined at a system level. As such, it is assumed that, on introduction to the network, H_2 is fully dissipated throughout the network. Then, if H_2 makes up ϕ_{H_2} (measured in per unit) of the total energy which enters the gas network, then the HHV of the resulting blended gas is given by

$$HHV_{net} = \left(\frac{\phi_{H_2}}{HHV_{H_2}} + \frac{1-\phi_{H_2}}{HHV_{NG}}\right)^{-1} \quad (2)$$

This HHV value will be used to convert energy gas demand into volumetric gas demand. More specifically, if $E_k(t)$ is the energy content of the gas from P2G which is introduced at gas node k at the time t, from either SNG installations or a H_2-NG blend, then the volumetric quantity of gas is

$$Q_{P2G,k}(t) = HHV_{net} \cdot E_k(t) \tag{3}$$

D. *Modelling of the CO_2 emission reduction*

The P2G process, as well as offering cost benefits while it uses otherwise unutilized energy, also offers benefits in the reduction of the system carbon emissions. In fact, combustion of H_2 does not produce any of the greenhouse gases associated with the use of fossil fuels. In this work, the CO_2 emission reduction due to the introduction of H_2 is calculated in terms of the NG displaced (CO_2 emission factor of 185 kg/MWh, [20]). The SNG production process also allows for carbon benefits as atmospheric CO_2 can be used in its production. The CO_2 benefits from the production of SNG are taken as the quantity of CO_2 removed from the atmosphere. With respect to the energy content of the SNG produced, the CO_2 saving in kg/MWh is given by

$$\mathrm{CS_{SNG}} = \frac{\text{molecular mass of } \mathrm{CO_2}}{\text{molecular mass of } \mathrm{CH_4}} \times \frac{1}{HHV_{\mathrm{CH_4}}^{\mathrm{mass}}} \tag{4}$$

where $HHV_{\mathrm{CH_4}}^{\mathrm{mass}}$ is the HHV of methane with respect to its mass, taken as 0.0153 MWh/kg, and the molecular mass of CO_2 and CH_4 is 44 and 16, respectively. The resulting CO_2 emission reduction from SNG production is 180 kg/MWh.

III. Integrated Network Modelling and Simulation

A. *Overall network modelling and simulation methodology*

The overall integrated network modelling process is formed of fours steps (Fig. 1), namely, a two-stage DC OPF alternated with gas network transient analysis. The first OPF (Section III.B) determines the dispatch levels of conventional generators and the renewable energy to be potentially curtailed due to system and line constraints. Using the gas demand requirements for electrical generation, a transient gas flow (the general model is described in Section III.E and in the Appendix) is conducted to determine the modelling parameters of the P2G operation. These are used in the second OPF (Section III.C) which determines the level of power injected into P2G facilities to maximize renewable integration while taking into account the renewable curtailment and the location and type of P2G facilities. The power to each P2G facility is then transformed into H_2 (to be blended with NG) or SNG, as discussed in Section II, and injected into the gas network. All gas supplies and demands are considered in terms of the energy content of the gas, and are then transformed into volumetric units (Eq. (3)) for the purposes of a second transient gas-flow analysis to assess the impact on the gas network at the considered time interval, which is equal to 30 minutes. The process is then repeated for the next time interval and so on. In addition, in order to realistically represent the within-day linepack variations and the demand-supply mismatch, a gas supply-demand balancing across 24 hours has been considered, as currently done by the GB system operator [21]. The gas system imbalance introduced by the P2G facilities in a 24-h balancing period is resolved in terms of a reduction of conventional gas supply in the next balancing period. The integrated network model has been implemented and solved in MATLAB [22]. The OPFs have been implemented with the support of MATPOWER [23]. Details of the gas flow equation solutions are given later.

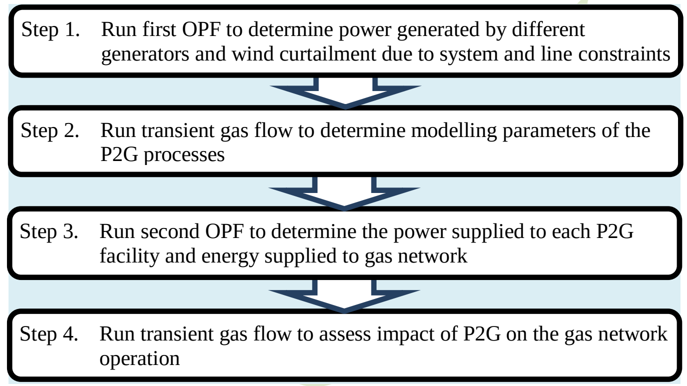


Fig. 1. Outline of the overall integrated network analysis methodology.

B. *First stage OPF*

Starting from classical DC OPF formulation [24], the first stage OPF (Step 1 in Fig. 1) determines the dispatch $P_{\mathrm{CG}_i}^1$ of each generating unit CG_i. This OPF is formulated as follows:

$$\text{minimize} \quad f^1(\mathbf{P}_{\mathrm{CG}}^1, \mathbf{P}_{\mathrm{RG}}^1) = \sum_{\mathrm{CG}_i} c_{\mathrm{CG}_i} \cdot P_{\mathrm{CG}_i}^1(t) + \sum_{\mathrm{RG}_r} c_{\mathrm{RG}_r} \cdot P_{\mathrm{RG}_r}^1(t) \tag{5}$$

$$\text{subject to} \quad \mathbf{Y}^1(t) = \mathbf{X}^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{U}^1(t) \tag{6}$$

$$U_z^1(t) = \sum_{\mathrm{CG}_i \in \mathrm{CGENS}_z} P_{\mathrm{CG}_i}^1(t) + \sum_{\mathrm{RG}_r \in \mathrm{RGENS}_z} P_{\mathrm{RG}_r}^1(t) - D_z \tag{7}$$

$$\left|Y_{Jl}^1(t)\right| \le \overline{Y_{Jl}} \tag{8}$$

$$s_{\mathrm{CG}_i}(t) \in \{0,1\} \tag{9}$$

$$\underline{P_{CG_i}} \le P_{\mathrm{CG}_i}^1(t) \le \overline{P_{\mathrm{CG}_i}} \quad \text{if} \quad s_{\mathrm{CG}_i}(t) = 1 \tag{10a}$$

$$P_{\mathrm{CG}_i}^1(t) = 0 \quad \text{if} \quad s_{\mathrm{CG}_i}(t) = 0 \tag{10b}$$

$$0 \le P_{\mathrm{RG}_r}^1(t) \le \overline{P_{\mathrm{RG}_r}(t)} \tag{11}$$

$$\sum_{\mathrm{CG}_i} R_{\mathrm{CG}_i}(t) \ge SR(t) \tag{12}$$

$$R_{\mathrm{CG}_i}(t) = s_{\mathrm{CG}_i}(t) \cdot \min\{\overline{R_{\mathrm{CG}_i}}, \overline{P_{\mathrm{CG}_i}} - P_{\mathrm{CG}_i}(t)\} \tag{13}$$

$$s_{\mathrm{CG}_i}(t) - s_{\mathrm{CG}_i}(t-1) - s_{\mathrm{CG}_i}(t+n) \le 0, \quad n = 1, \dots, MUT_{\mathrm{CG}_i} - 1 \tag{14}$$

$$s_{\mathrm{CG}_i}(t-1) - s_{\mathrm{CG}_i}(t) - s_{\mathrm{CG}_i}(t+n) \le 1, \quad n = 1, \dots, MDT_{\mathrm{CG}_i} - 1 \tag{15}$$

In (5), the vectors $\mathbf{P}_{\mathrm{CG}}^{\mathbf{1}}$ and $\mathbf{P}_{\mathrm{RG}}^{\mathbf{1}}$ of conventional and renewable generation's power outputs are determined so as to minimize the cost of generation. For a conventional generator CG_i a constant marginal generation cost, c_{CG_i}, is used for the non-gas generators (must-run generators are modelled with cost zero), while the cost of gas technologies (Combined Cycle Gas Turbines – CCGT, Combined Heat and Power – CHP, and Open Cycle Gas Turbines – OCGT) depends on their efficiency and the price of NG. Each of the renewable generators, RG_r, are assumed at zero marginal cost c_{RG_r} in the rest of the paper. The vector $\mathbf{Y}^1$ of the power flows $Y^1_{J_l}$ is described by (6), in which $\mathbf{U}^1$ is the vector of power injections $U^1_z(t)$ at each bus z, $\mathbf{B}$ the admittance matrix, $\mathbf{A}$ the line-bus incidence matrix, and $\mathbf{X}$ the diagonal matrix with the line impedances as entries [24]. The power injections $U^1_z(t)$ are described in (7) by the demand D_z and the sum of the real power generation $P^1_{\mathrm{CG}_i}$ (resp. $P^1_{\mathrm{RG}_r}$) for each conventional (resp. renewable) generator CG_i (resp. RG_r) in the set of generators CGENS_z (resp. RGENS_z) at each bus z. The power output $P^1_{\mathrm{CG}_i}$ is restricted to a range defined by the minimum stable generation (MSG) $\underline{P_{\mathrm{CG}_i}}$ and maximum generation $\overline{P_{\mathrm{CG}_i}}$ when the generator is online, as from (10a), or is equal to 0, as from, (10b), while the binary variable $s_{\mathrm{CG}_i}(t)$ defined in (9) denotes whether the generator is online at time t. The renewable generators RG_r have power output $P^1_{\mathrm{RG}_r}(t)$ between a lower bound of zero and upper bound $\overline{P_{\mathrm{RG}_r}(t)}$ in (11). The line constraints $\overline{Y_{J_l}}$ for each line J_l are observed by limiting the magnitude of the real power flows $Y^1_{J_l}(t)$ in (8). The system's reserve requirement $SR(t)$ in (12) accounts for uncertainty in demand, outage of conventional generators, and wind forecast uncertainty [25]. Reserve is fulfilled by conventional generation and characterized by the generator's upward ramp capability $R_{\mathrm{CG}_i}(t)$, which is determined by the generator's maximal ramp $\overline{R_{\mathrm{CG}_i}}$ and the availability of upward generation, as in (13). Finally, relations (14) and (15) describe the minimum up and down times MUT_{CG_i} and MDT_{CG_i} requirements of generator CG_i.

C. Gas network transient analysis and second stage OPF

The modelling of the operation of the P2G facility at a given time t depends on a number of parameters determined by the gas and electrical system states. More specifically, results from the first OPF are used to determine the level and location of the curtailed wind. The gas generation fuel requirements are used to conduct a preliminary gas flow analysis (as generally described in Section III.E) to determine, at each time t, areas of gas congestion, the gas throughput at each terminal (Step 2 in Fig. 1).

A second OPF is then run to model the operation of P2G facilities starting from the dispatch levels of the conventional generating units resulting from (5)–(15) (which are now fixed) and the gas network parameters as from Step 2. The objective is to maximize the system benefit of the otherwise curtailed renewables as determined in the first OPF. At this stage, the P2G facilities are modelled as equivalent generating units $\mathrm{P2G}_z$, $\mathrm{P2G}_k$, $\mathrm{P2G}_{T_k,\mathrm{H2}}$, $\mathrm{P2G}_{T_k,\mathrm{SNG}}$, with output $P_{\mathrm{P2G}_z}(t)$, $P_{\mathrm{P2G}_k}(t)$, $P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t)$, $P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t)$ and "negative" costs c_{P2G_z}, c_{P2G_k}, $c_{\mathrm{P2G}_{T_k,\mathrm{H2}}}$, $c_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}$, respectively. These costs depend on the relevant conversion efficiencies of the different facilities so that higher efficiency conversion is favored. Moreover, when there is curtailed wind generation, and there is demand for gas network congestion relief, these P2G facilities are given operational priority over other P2G installations. This allows for power from the renewable generation sources to be transported to the areas of gas network congestion, instead of being allocated to nearby P2G facilities. Details are given in Section III.D.

Denoting the curtailed power (from the first OPF) at the renewable generator RG_r by $\Delta P_{\mathrm{RG}_r}(\mathrm{t}) = \overline{P_{\mathrm{RG}_r}(t)} - P^1_{\mathrm{RG}_r}(t)$, then, at a given time t, the second OPF is described by:

$$\text{minimize } f(\mathbf{P}_{\mathrm{P2G}}) = \sum_{\mathrm{P2G}_z} c_{\mathrm{P2G}_z} \cdot P_{\mathrm{P2G}_z}(t) + \sum_{\mathrm{P2G}_k} c_{\mathrm{P2G}_k} \cdot P_{\mathrm{P2G}_k}(t) + \sum_{\mathrm{P2G}_{T_i,\mathrm{H2}}} c_{\mathrm{P2G}_{T_k,\mathrm{H2}}} \cdot P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) + \sum_{\mathrm{P2G}_{T_k,\mathrm{SNG}}} c_{\mathrm{P2G}_{T_k,\mathrm{SNG}}} \cdot P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t) \quad (16)$$

subject to

$$0 \le P_{\mathrm{RG}_r}(t) \le \Delta P_{\mathrm{RG}_r}(\mathrm{t}) \quad (17)$$

$$0 \le P_{\mathrm{P2G}_z}(t) \le \overline{P_{\mathrm{P2G}_z}(t)} \quad (18a)$$

$$0 \le P_{\mathrm{P2G}_k}(t) \le \overline{P_{\mathrm{P2G}_k}(t)} \quad (18b)$$

$$0 \le P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) \le \overline{P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t)} \quad (18c)$$

$$0 \le P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t) \le \overline{P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t)} \quad (18d)$$

$$\mathbf{Y}(t) = \mathbf{X}^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{B}^{-1}\mathbf{U}(t) \quad (19)$$

$$U_z(t) = \sum_{\mathrm{CG}_i \in \mathrm{CGENS}_z} P^1_{\mathrm{CG}_i}(t) + \sum_{\mathrm{RG}_r \in \mathrm{RGENS}_z} \left(P^1_{\mathrm{RG}_r}(t) + P_{\mathrm{RG}_r}(t)\right) - \sum_{\mathrm{P2G}_z \in \mathrm{P2GE}_z} P_{\mathrm{P2G}_z}(t) - \sum_{\mathrm{P2G}_k \in \mathrm{P2GG}_z} P_{\mathrm{P2G}_k}(t) - \sum_{\mathrm{P2G}_{T_k,\mathrm{H2}} \in \mathrm{P2GH}_z} P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) - \sum_{\mathrm{P2G}_{T_k,\mathrm{SNG}} \in \mathrm{P2GS}_z} P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t) - D_z \quad (20)$$

$$\left|Y_{J_l}(t)\right| \le \overline{Y_{J_l}} \quad (21)$$

The results of the preliminary OPF define the generation levels $P^1_{\mathrm{CG}_i}(t)$ and $P^1_{\mathrm{RG}_r}(t)$ in (20). The introduction of P2G facilities will change the power injections U_z in (20) which now includes the otherwise curtailed generation $P_{\mathrm{RG}_r}(t)$ as well as the powers P_{P2G_z}, P_{P2G_k}, $P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}$, and $P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}$ respectively supplied to the P2G facilities $\mathrm{P2GE}_z$, $\mathrm{P2GG}_z$, $\mathrm{P2GH}_z$, $\mathrm{P2GS}_z$ of each type at the bus z. Upper power bounds to the different P2G facilities are applied in (18a)–(18d) (see Section III.D). Equation (19), describes the relation between the changed vector of power injections $\mathbf{U}(t)$ and the vector of transmission line real power flows $\mathbf{Y}(t)$ using the same matrices $\mathbf{X}$, $\mathbf{A}$, and $\mathbf{B}$ as in (6) since the characteristics of the network remain unchanged. The power flows $Y_{J_l}(t)$ along the lines must continue to satisfy the line constraints $\overline{Y_{J_l}}$ as in (21). Other relevant constraints and relations are explained next.

D. P2G operation modelling

As mentioned in Section II.A, there are three sets of P2G facilities that have been considered in the model:

P2G facilities at congested electrical nodes: this first set is composed of P2G units $\mathrm{P2G}_z$ that could generate SNG from (otherwise) curtailed wind due to electrical line constraints. They are thus located at buses z at which curtailment may occur due to line constraints. If the level of curtailment due to line constraints returned by the first OPF is given by $\Delta P_z(\mathrm{t}) = \sum_{\mathrm{RG}_r \in \mathrm{RGENS}_z} P_{\mathrm{RG}_r}(t)$, then the P2G facility at the relevant bus will operate to relieve this constraint by utilizing this power up to its capacity. The constraints to its power output $P_{\mathrm{P2G}_z}(t)$ is thus modelled in (18a) as

$$\overline{P_{\mathrm{P2G}_z}(t)} = \min(\Delta P_z(\mathrm{t}), \overline{P_{\mathrm{P2G}_z}}) \tag{22}$$

The cost associated to the facilities is $c_{\mathrm{P2G}_z} = -c_{\mathrm{gas}}/\eta_S$ where c_{gas} is the cost of natural gas and η_S is the efficiency of SNG production.

If we consider the gas nodes k_z associated with the locality of these P2G units, the quantity of SNG injected at these nodes is given by $E_{k_z}(t) = \eta_{\mathrm{S}} \times P_{P2G_z}(t)$.

P2G facilities at congested gas nodes: the second set of P2G units $\mathrm{P2G_k}$ to be considered are those which can be used as a means of relieving congestions in the gas network due to excessive gas load. The preliminary gas flow highlights areas in the gas network where there are reduced pressures. When there is low pressure and curtailed wind, a P2G facility may introduce gas into the network to alleviate the congestion. If the results of the preliminary gas flow indicate network vulnerability at an extremity node k, where the pressure p_k is less than a threshold $p_{k,thres}$ which is caused by a gas demand $GD_k(t)$ in excess of a threshold $GD_{k,thres}$, then the congestion will be relieved by a P2G facility $\mathrm{P2G}_k$ with power $P_{\mathrm{P2G}_k}(t)$ whose operation is limited in (18b) as

$$\overline{P_{\mathrm{P2G}_k}(t)} = \begin{cases} \min\left(\overline{P_{\mathrm{P2G}_k}},\ (GD_k(t) - GD_{k,thres})/\eta_S\right) \\ \qquad\qquad\qquad \text{if } p_k(t) < p_{k,thres} \\ 0 \qquad\qquad \text{otherwise} \end{cases} \tag{23}$$

It is assumed that this rule as to the operational conditions for congestion relief as well as suitable facilities' placement are obtained from prior gas network operational analysis.

As mentioned earlier, it is desirable that these P2G facilities have operational priority over other P2G installations. In the modelling, this is achieved by reducing the cost so that $c_{\mathrm{P2G}_k} = -c_{\mathrm{gas}}/\eta_S - c_{rel}$ where c_{rel} is an additional cost benefit employed to assign this priority.

As above, if we take the gas nodes k associated with the locality of these P2G units, the energy quantity of SNG injected at these nodes is given by $E_{\mathrm{P2G_k}}(t) = \eta_{\mathrm{S}} \times P_{\mathrm{P2G_k}}(t)$.

P2G facilities at gas terminals: At the gas terminals the model considers two types of P2G facilitates. The first are H_2 producing facilities which have an associated capability for H_2 storage; the second are SNG production facilitates. On introduction to the network, H_2 should be blended with NG. When its production is above that which can be blended with the NG, this excess may be placed into storage; on the other hand, when there is reduced H_2 production, then H_2 from storage can be used to supplement the quantity blended. For a gas terminal T_k, the H_2 which may be produced is limited by that which may be introduced into the network and that which may be placed into storage. If $NG_{T_k}(t)$ is the natural gas throughput, the maximum level of H_2 which may be blended is $\overline{L_{T_k}(t)} = \bar{L}_{H_2,\mathrm{Energy}} \cdot NG_{T_k}(t)$. While for a H_2 facility $\mathrm{P2G}_{T_k,\mathrm{H2}}$ with associated H_2 storage of capacity C_{T_k}, the quantity of H_2 which may be injected depends on the current level of storage $V_{T_k}(t)$, which defines its spare capacity $C_{T_k} - V_{T_k}(t)$. As such, in (18c) the facility's power is limited by

$$\overline{P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t)} = \min(\overline{P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}}, \\ (\overline{L_{T_k}(t)} + C_{T_k} - V_{T_k}(t))/\eta_H) \tag{24}$$

For the SNG producing facility $\mathrm{P2G}_{T_k,\mathrm{SNG}}$, its power $P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t)$ is limited in (18d) by its installed capacity

$$\overline{P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t)} = \overline{P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}} \tag{25}$$

The costs associated to the H_2 and SNG producing facilities are $c_{\mathrm{P2G}_{T_k,\mathrm{H2}}} = -c_{\mathrm{gas}}/\eta_H$ and $c_{\mathrm{P2G}_{T_k,\mathrm{SNG}}} = -c_{\mathrm{gas}}/\eta_S$, respectively. As the efficiency of H_2 production is greater than that of SNG production, the cost benefit of H_2 production will be greater than that of SNG production and so, at a given terminal, H_2 production will be prioritized over that of SNG.

The SNG produced is introduced directly into the gas network; hence, the energy content injected at the terminal T_k is

$$E_{T_k,\mathrm{SNG}}(t) = \eta_{\mathrm{S}} \times P_{\mathrm{P2G}_{T_k,\mathrm{SNG}}}(t) \tag{26}$$

The quantity of H_2 introduced, meanwhile, is also impacted by the injection/withdrawal operation of the storage facilities. More specifically, when the H_2 production is less than the limit for H_2 blending (i.e., $P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) \cdot \eta_H < \overline{L_{T_k}(t)}$) then, where possible, the shortfall will be made up by the gas in storage so the quantity introduced into the network is

$$E_{T_k,\mathrm{H2}}(t) = \min\left(P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) \cdot \eta_H + V_{T_k}(t), \overline{L_{T_k}(t)}\right) \tag{27}$$

While the resulting level of H_2 in storage, which is used as a parameter in the next iteration of (16)–(21) at $t + 1$, is

$$V_{T_k}(t+1) = \max(0, \\ V_{T_k}(t) - (\overline{L_{T_k}(t)} - P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) \cdot \eta_H)) \tag{28}$$

Alternatively, if the H_2 production is greater than the limit for H_2 blending then H_2 is introduced at its maximum capacity

$$E_{T_k,\mathrm{H2}}(t) = \overline{L_{T_k}(t)} \tag{29}$$

and additional H_2 is placed into storage so the resulting level of storage is

$$V_{T_k}(t+1) = V_{T_k}(t) + (P_{\mathrm{P2G}_{T_k,\mathrm{H2}}}(t) \cdot \eta_H - \overline{L_{T_k}(t)}) \tag{30}$$

The total energy content of the gas from P2G introduced at the terminal T_k is therefore given by $E_{T_k}(t) = E_{T_k,\mathrm{SNG}}(t) + E_{T_k,\mathrm{H2}}(t)$.

E. Gas network transient flow analysis model

Gas network studies at Step 2 and Step 4 of Fig. 1 are conducted via a transient gas flow analysis model. Transient gas flow in a section of pipeline is characterized by three relations, namely, the equation of state and the continuity and motion equations (see equations (34), (35) and (36), in the Appendix) [14]. These expressions relate the pressure and flow rates across a pipeline and over time and are solved via a finite difference scheme starting from the flows and pressures at a given time t_0 and determining the pressures and flows at $t_0 + \Delta t$ across the pipe's length (see Appendix).

For network studies, further relations are needed that define the boundary conditions as to how pressures and flows of different pipes interact throughout the network so that overall pressure and flow balance is achieved. More specifically, at an intersection point (gas node) k, the conservation of mass equates the flows into and out of the point, and these flows may have a number of sources. The point k may include a terminal or storage facility, T_k, with supply/injection rate Q_{T_k}, a gas demand GD_k, a compressor station with inlet flow CI_k or outlet flow CO_k, or a point of P2G injection $Q_{P2G,k}$[1].These are combined with the pipe flows so that if at node k there are N_k adjacent pipe sections S_c^k each with a flow rate of $Q'_{S_c^k,a}$, the conservation of mass at the node is then described by

$$Q_{T_k} - GD_k + CO_k - CI_k + Q_{P2G,k} + \sum_{c=1}^{N_k} Q'_{S_c^k,a} = 0 \qquad (31)$$

This relation includes the point of coupling between the gas network and the P2G facilities, via $Q_{P2G,k}$, and the electrical generators, via the overall gas demand GD_k.

If $N_k > 1$ then the ends of the pipes at k must be set to equal pressure. Hence, for the pressure p'_k of k at $t_0 + \Delta t$, if the pipes adjacent to k are S_c^k, $c = 1, \ldots, N_k$, the equality of the gas pressures $p'_{S_c^k,a}$ at the end of each pipe is expressed by

$$p'_{S_c^k,a} = p'_k \qquad (32)$$

As a further study element, the power requirements of the compressor stations to overcome transportation pressure drops are modelled as in [26]. More specifically, compressor stations are modelled by either fixed outlet pressure or fixed compression ratio. For each compressor CP having inlet and outlet pipe sections S_{CP}^{in} and S_{CP}^{out} and associated pressures $p'_{S_{CP}^{\text{in}},a}$, $p'_{S_{CP}^{\text{out}},a}$, the compressor stations are modelled as

$$\begin{cases} p'_{S_{CP}^{\text{out}},a} = \alpha_{CP} p'_{S_{CP}^{\text{in}},a} & \text{if } CP \text{ defined by compression ratio} \\ p'_{S_{CP}^{\text{out}},a} = CP_{\text{out}} & \text{if } CP \text{ defined by outlet pressure} \end{cases} \qquad (33)$$

where α_{CP} defines the fixed compression ratio and CP_{out} defines the fixed outlet pressure.

As mentioned above, the transient gas flow equations have been implemented in MATLAB and solved via a finite difference scheme by using the Newton-Raphson solution method (see Appendix for further details).

[1] The energy content $E_k(t) = E_{k_z}(t) + E_{P2G_k}(t) + E_{T_k}(t)$ of the gas introduced into the network at node k is transformed into the volumetric quantity of gas $Q_{P2G,k}$, as from Eq. (3) in Section II.C.

IV. Case Study Applications

A. Case study description

The model developed has been applied to the GB gas and electricity transmission networks in five case studies:

- *Case 1*. P2G operational cost and environmental benefits.
- *Case 2*. Benefits of using hydrogen storage facilities.
- *Case 3*. Effects of P2G on the gas network.
- *Case 4*. Use of P2G to relieve electrical congestions.
- *Case 5*. Use of P2G to relieve gas congestions.

Before analyzing the case study results below, there is a description of the electrical, gas, and P2G facility data used.

B. Electrical network data

The GB electrical transmission network is modelled by an equivalent 29-busbar system [27], as depicted in Fig. 2(a). The installed generation are those predicted by National Grid's 'Gone Green' scenario in 2030 [16], where wind generation accounts for 40% (48GW) of the total installed capacity of 120GW, and there might therefore be large amounts of curtailment (peak demand is 63GW [16]). Table I gives the types of generation installed along with the share of the total capacity and relevant costs for OPF analysis. The electrical efficiencies of the gas-fuelled power stations relate the HHV of the gas consumed to the electrical output. The CCGTs and OCGTs are assumed to have electrical efficiencies of 50% and 32%, respectively. The gas price is set at 2.4 pence/kWh [16].

Historical wind speed data from December 2012 was combined with turbine output characteristics and installed wind capacity to determine the wind generation for each time period. The total wind generation capability, i.e., the maximum possible without system constraints, is given in Fig. 3. The figure also shows the actual output and curtailed wind (without P2G) due to stability reasons and line constraints.

The electrical load for each bus in the electrical network is considered as a fraction of the total electrical load. The historical national load of December 2012 is used (Fig. 3).

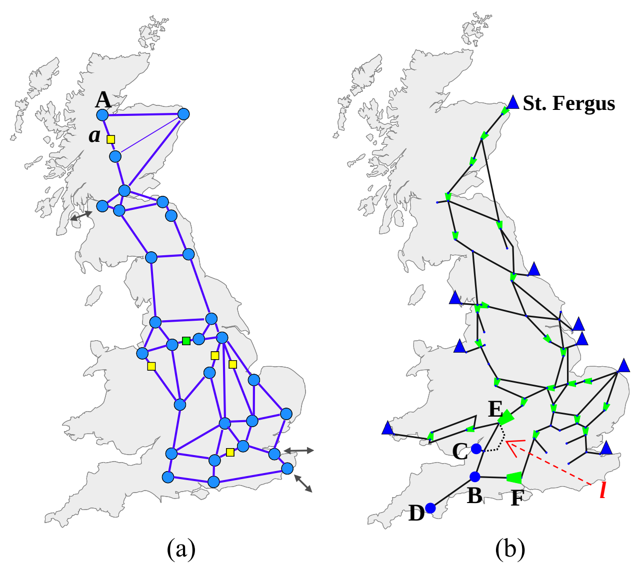


Fig. 2. 29 busbar electricity (elaborated from [27]) (a) and 79 node gas (b) models of the GB transmission networks.

TABLE I
GENERATION TECHNOLOGY AND RESPECTIVE INSTALLED CAPACITY, COST, MSG AND 30-MIN RAMP RATES [28].

Technology	Installed capacity	Cost (£/MWh$_e$)	MSG	30 min ramp rate
CCGT	28.3%	*f*(gas price)	50%	25%
CHP	1.4%	Must run	-	-
Coal	8.6%	46	50%	25%
Hydro	0.9%	0	-	-
Nuclear	14.1%	Must run	-	-
OCGT	0.5%	*f*(gas price)	10%	50%
Other Renewables	3.9%	70	-	-
Marine	2.3%	0	-	-
Wind	40%	0	-	-

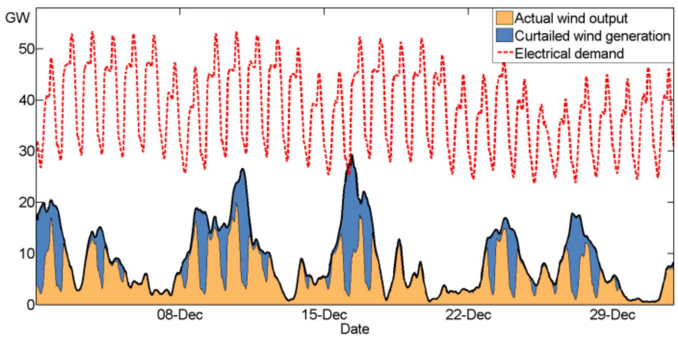


Fig. 3. Electrical demand and wind output and curtailment without P2G.

The system reserve considers the capacity of the largest generator, taken as $R_{\text{Gen}} = 1.8$ GW for 2030 [29], plus reserves for uncertainty in load and wind generation forecast, as in [25]. For each time period the reserve requirement for uncertainty in wind generation forecast is modelled considering a 4-hour persistence approach, [25], with forecasted mean square error (MSE) assumed to be equal to 10% [30]. The predicted load for each time period is taken as the historical load for the same period, its MSE being 1%. Reserve is supposed to be provided by CCGT, coal and OCGT, with MSG and 30-minute ramp rate data (as a fraction of the generating capacity) as from Table I. The resulting levels of wind generation and wind curtailment over a month as from the 30-min OPF are shown in Fig. 3.

C. Gas network data

A simplified version of the GB Gas National Transmission System with 79 nodes has been used to conduct the analysis of the gas flows and pressures across the network, as shown in Fig. 2(b). This simplified model has been derived from the full GB gas network while preserving a number of features so as to enable fruitful and realistic modelling. All gas terminals and compressor stations have been preserved. The network extremities (points of the network with lowest pressures), are essential for investigating any points of weakness and so have also been preserved. Pipes' flow characteristics and volumes have been preserved when amalgamating pipes in series and parallel into single pipelines. In fact, the flow characteristics of the pipe define the relation between the flows and pressures in the network. These, in turn, define the throughput capacity and identify areas of congestion. Meanwhile, the pipes' volumes relate the pressures of a given pipe to its linepack, a defining feature in the gas network's operation and flexibility.

The ability of this simplified network to realistically model the pipe flows, pressures and linepack has been verified by comparison with historical gas flows provided by National Grid Gas. The terminal flows are constant for each balancing period (that is, the period of which gas shippers must equate their gas network entry/offtake flows) and are determined using historic entry flow data from winter 2012. The compressor stations have been modelled by a fixed outlet pressure of 65 bar.

Historical daily gas demands from December 2012 have been used for network offtakes excluding the large industrial and interconnector demands, taken as 7.8GW and 5.0GW, respectively. These are historical averages for the demand from December 2012 [31]. The demands have been combined with an intraday demand profile to produce half-hourly non-generation gas demand, [28].

As an illustration as to the computational resource requirements for the modelling for a monthly timeframe, the run-time for the first OPF is about 140mins, for the OPF determining the P2G power is about 5mins, and for each gas flow analysis is about 100 minutes.

D. Power-to-gas facilities data

The following P2G facilities have been considered. Each gas terminal has a 1GW SNG facility and a 1GW H_2 facility with an associated H_2 storage capacity of 1GWh. At bus A (Fig. 2(a)) where wind is curtailed due to line constraints, a 1GW SNG facility is installed. In the study of the alleviation of gas network constraints of Section IV.I, an additional 2GW SNG facility is considered at node B (Fig. 2(b)).

The efficiencies for the P2G producing process is taken as 73% for H_2 production and 64% for SNG production [32]. These efficiencies also include the energy required to compress the gas to 80bar, a pressure suitable for the gases' consequent introduction into the gas network.

The maximal level of H_2 in the GB gas network is currently restricted to 0.1%vol. However, this level is under review with industry petitioning for it to be raised to 3%vol. [19]. For the case studies, the limit of H_2 in the gas network will be set to 3%vol. The mean HHV of the NG entering the network is $HHV_{NG} = 39.5\ \text{MJ/m}^3$ while the HHV of H_2 is $HHV_{H_2} = 12.75\ \text{MJ/m}^3$. It follows from (1) that the maximal level of H_2 content of the gas in the network is 1% in terms of energy content.

The calculated gas demand for electrical generation is shown in Fig. 4 alongside the non-generation gas demand.

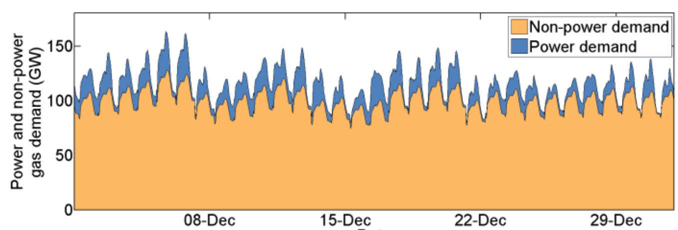


Fig. 4. System gas demand for non-power and power generation.

E. Case 1. P2G operational cost and environmental benefits

With the introduction of the P2G installations described in Section IV.D, the cost benefits of the P2G process for the gas which is introduced into the gas network will be evaluated in terms of the cost of the NG which it displaces, i.e., if $E(t)$ is the energy content of the gas from the P2G process which is introduced into the network, then the cost benefit to the system is given by $E(t) \cdot c_{\text{gas}}$ where c_{gas} is the system NG cost. The cost benefit of the P2G process, for each half-hour, is shown in Fig. 5. The P2G process produces a total of £53M of gas for the considered monthly period. The systems emission reduction is measured at the time at which the H_2 or SNG enters the gas network (also shown in Fig. 5). The total CO_2 emission reduction for the month is 250 kilotonnes.

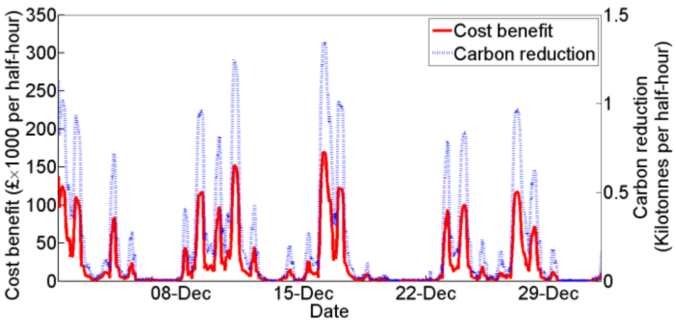


Fig. 5. System cost benefit and emission reduction from power-to-gas.

F. Case 2. Benefits of using hydrogen storage facilities

When the level of wind curtailment is greater than that sufficient to produce the maximum levels of H_2 permissible to be blended into the gas network, H_2 may be put into storage, if available. For illustrative purposes, wind curtailment is compared against that required to meet the maximal level of H_2 content of the gas network for an average winter day. This is shown in Fig. 6 where it can be seen that, without H_2 storage, there is a large unutilized H_2 content capacity of the gas network as well as curtailed wind which could have been converted into H_2 for successive injection into the gas network. Therefore, storage facilities could allow for greater and safe use of the H_2 capacity of the gas network.

The benefits of including H_2 storage have been evaluated by considering the installed P2G facilities described in Section IV.D with and without the H_2 storage installation of 1GWh. The energy saved by the introduction of storage facilities, over the monthly time frame considered, is 18GWh, corresponding to £430,000 at the considered gas price.

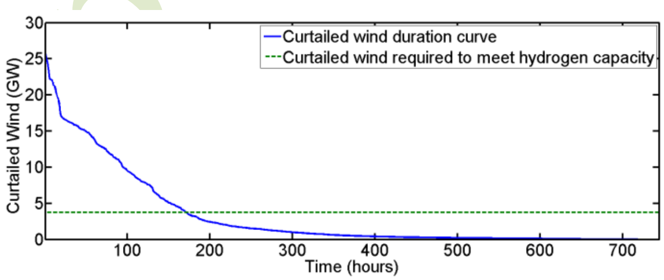


Fig. 6. Curtailed wind duration curve and energy required to meet the network's mean monthly hydrogen capacity.

G. Case 3. Effects of P2G on the gas network

The P2G process will have a number of effects on the gas network. For example, the addition of large SNG facilities away from terminals will alter the network flow patterns while the introduction of H_2 will reduce the HHV of the gas and increase the volume of gas necessary to satisfy the demand.

Considering the GB gas network as of 2014 (shown in Fig. 2(b), without the additional pipe labelled *l*), and the P2G installations described in IV.D, the injection of H_2 into the gas network decreases the HHV value by 1% and hence there is a 1% increase in the volumetric system demand. The gas system impact of P2G is shown in Fig. 7, where H_2 injection can be compared against the NG demand. The energy transportation capability of the GB gas transmission network far exceeds that of the installed wind generation. And, if the terminals are used for the large scale P2G facilities, then the inputted H_2 and SNG act to displace NG supplied through the terminals. There is minimal effect on the gas network flow characteristics. Therefore, for P2G facilities placed at terminal and H_2 blended with NG, the national transmission network seems a particularly apt option to help facilitate a P2G program.

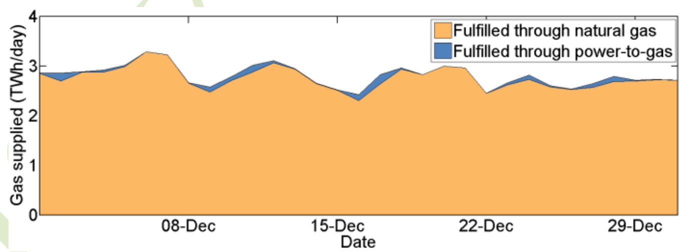


Fig. 7. Effect of P2G on gas supply at the system level.

H. Case 4. Use of P2G to reduce electrical congestions

Line constraints due to excessive wind generation occur on the electrical transmission line *a* (Fig. 2(a)). The P2G process can be used to relieve these line constraints by increasing the load at certain nodes by means of a P2G facility. In this respect, a 1GW SNG production facility is considered at bus A in the electrical network so as to use curtailed wind to form SNG. The resulting SNG production is shown in Fig. 8. Again, the value of the SNG produced can be considered based on the gas price. Over the simulation period 119 GWh of energy which would have been curtailed due to line constraints is converted into SNG resulting in £2.9M cost savings. By running this analysis over reference months, these savings could be compared with, for example, the cost of line reinforcements, so as to assess the feasibility of a P2G investment plan. This is the objective of work in progress.

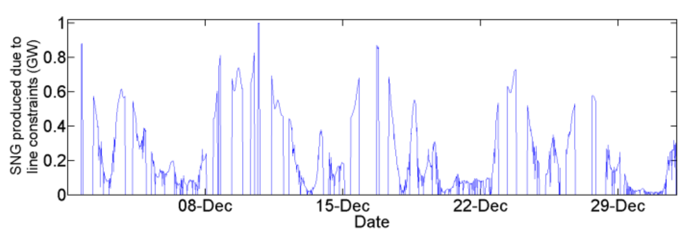


Fig. 8. SNG production following electrical transmission line constraints.

I. Case 5. Use of P2G to reduce gas congestions

The P2G concept can be used to reduce congestion in the gas network by introducing SNG production units at vulnerable areas in the gas network, for example, at network extremities, where the pressures will be least. In this respect, there has been the proposal for demand-side reinforcement in the gas network in the area in the south-west, near nodes B and C (Fig. 2(b)). This reinforcement would take the form of additional pipes built in parallel to existing lines so as to increase the overall capacity of this route. In fact, as an extremity of the network and a long distance from the major gas terminals, this area of the network is a place where the occurrence of vulnerabilities may arise. Further to this, the location C has 1200 MW of CCGT installed which may be expanded upon in a future power system. This would lead to the possibility for the need of further reinforcements. An alternative to pipeline reinforcements may be the installation of a P2G facility at a nearby location which would be able to inject gas into the network at times when flow problems may occur, for example, due to high demand or network failures.

To assess the possible benefits of using the P2G concept in this manner three situations have been considered. The first considers the case where an SNG facility has been installed as a means of congestion relief while the second considers an alternative form of network reinforcement which is the construction of an additional pipeline. These two reinforcement cases are finally compared against a third case in which there is no network reinforcement. Each scenario is modelled with the P2G installations of Section IV.D with the first scenario also including the additional 2GW SNG facility at node B. The second scenario is modelled on a network with an additional parallel pipeline (labelled *l* in Fig. 2(b)) of the same diameter (600mm) as its adjacent pipes and of length 79km.

The preliminary gas flow analysis (Step 2 of Fig. 1) indicates that, with the considered gas demands, node D (Fig. 2(b)) is vulnerable to low pressures. On occasions of high demand, the SNG facility at node B will produce SNG. A gas demand threshold of 1GW (see Eq. (23)) is considered here, above which the facility will supply, subject to the levels of curtailed wind and transmission line constraints, gas to help relieve congestion.

The effects of the three cases have been quantified by studying the pressures at the gas node D (Fig. 2(b)). The resulting pressures are shown in Fig. 9. For clarity, only one week's simulation period is shown. The figure demonstrates that an SNG facility can play a role in the reduction of network congestion. The introduction of the facility often raises pressures to above those after pipeline reinforcements. This allows for additional resilience in the network's ability to meet the minimum assured offtake pressure of 38bar [12] and the networks ability to adapt to unpredicted changes in demand. However, relying solely on curtailed wind for immediate SNG production may not suffice at the times of greatest demand, especially in areas with large installed capacity of gas turbines. In fact, at times of little wind (and therefore of little SNG production from little wind curtailment) the gas demand due to CCGT use is likely to be greater to fulfil the shortfall in wind generation. The model output would then suggest that a storage facility might have to be installed.

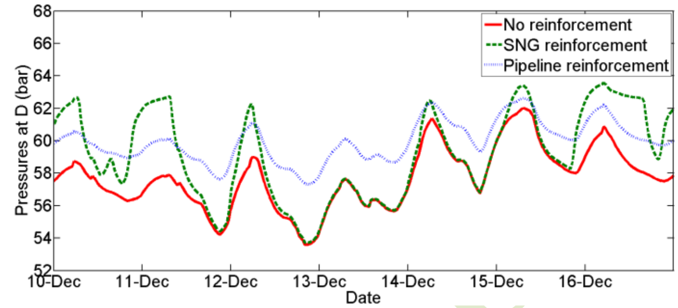


Fig. 9. Pressures at node D (Fig. 2(b)) for different cases.

The reduction in congestion can also be quantified by a reduction in the compressor usage requirements. In areas of the network where there is limitations in the flow capacities, compressor stations are used as a means to keep the pressures within required limits. The introduction of the SNG facility leads to a 9% reduction in the power requirements of compressors E and F (Fig. 2(b)). The reduction, due to the introduction of the SNG facility, in the power requirements for these compressors is shown, for each time period, in Fig. 10. Again, for clarity, only one week's simulation period has been presented. At the system level, this can be viewed as using the two integrated gas and electrical systems to find the most efficient means of transporting energy. More specifically, when there is spare electrical generation and transmission capacity then this can be used to transport energy and fulfil gas demand, whilst previously this energy would have to be transported via the gas network and would have contributed to compression costs.

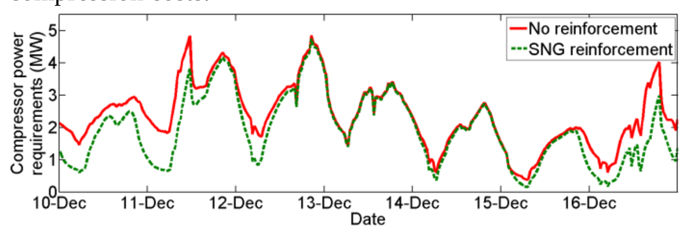


Fig. 10. Power consumption of compressors E and F (Fig. 2(b)) for different cases.

V. Concluding Remarks

In this work, a novel methodology, supported by a relevant computational model, has been specifically developed for investigating the impact of P2G technologies on electricity and gas networks. This includes P2G facilities which use electrical power to create H_2 and SNG as well as those which use the NG network as a means of storing and transporting the gas produced. The methodology, based on a novel integrated two-stage electrical DC OPF/gas transient flow model with coupling through P2G facilities and gas fired electrical generators, has been applied to a case study using the GB electrical and gas transmission networks. As a key contribution, the developed integrated model allows for the exploration of techno-economic, environmental and operational implications that P2G programs could have, including impact on both transmission networks. In particular, case study simulations have shown that, with the placement of the P2G units near gas network terminals, the benefits of using the curtailed wind to create H_2 for blending into the NG at the terminal, as well as SNG production, can be attained with little disruption to the operation of the gas network in terms of the flows of the gas. The benefits of including H_2 storage facilities as a means of capturing the curtailed winds spikes in the P2G process and reducing conversion losses have also been quantified, together with potential use of P2G facilities as a substitute to electrical and gas transmission line reinforcement. It has also been shown how strategically placed SNG facilities can be used as an alternative to compressor usage.

Work in progress aims at performing cost benefit analyses that take into account planning aspects of P2G as a measure to increase system flexibility and a substitute for network reinforcement. Further, the short-term storage investigated in this work will be extended to include the benefits of seasonal storage and the impacts on the gas network of transporting gas formed from the P2G process to the seasonal storage facilities. In addition, a full multi-energy system [34] model that integrates the electricity, heat and gas systems is under development.

REFERENCES

[1] P. Denholm and M. Hand, "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity," Energy Policy, vol. 39, no. 3, p. 1817–1830, 2011.

[2] Department of Energy and Climate Change, "The Future of Heating: Meeting the challenge," HM Government, London, March 2013.

[3] M. B. Ball and M. Wietschel, The Hydrogen Economy: Opportunities and Challenges, Cambridge University Press, 2009.

[4] P. E. Dodds and W. McDowall, "The future of the UK gas network," Energy Policy, vol. 60, p. 305–316, 2013.

[5] L. M. Gandía, G. Arzamendi and P. M. Diéguez, Eds., Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety, Elsevier B.V., 2013.

[6] International Energy Agency, Prospects for Hydrogen and Fuel Cells, Paris, 2005.

[7] P. E. Dodds and S. Demoullin, "Conversion of the UK gas system to transport hydrogen," International Journal of Hydrogen Energy, vol. 38, no. 10, p. 7189–7200, 2013.

[8] D. Haeseldonckx and W. D'haeseleer, "The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure," International Journal of Hydrogen Energy, vol. 32, no. 10–11, p. 1381–1386, 2007.

[9] L. Grond, P. Schulze and J. Holstein, "Systems Analyses Power to Gas: Technology Review," DNV KEMA Energy & Sustainability, Groningen, 2013.

[10] H. De Vries, O. Florisson and G. Tiekstra, "Safe Operation of natural gas appliances fueled with hydrogen/natural gas mixtures (progress obtained in the naturalhy-project)," in International Conference on Hydrogen Safety, San Sebastián, Spain, 2007.

[11] S. An, Q. Li and T. Gedra, "Natural Gas and Electricity Optimal Power Flow," in Proceedings of IEEE PES Transmission and Distribution Conference, Dallas, USA, 2003.

[12] M. Chaudry, N. Jenkins and G. Strbac, "Multi-time period combined gas and electricity network optimisation," Electric Power Systems Research, vol. 78, p. 1265–1279, 2008.

[13] C. Liu, M. Shahidehpour, Y. Fu and Z. Li, "Security-Constrained Unit Commitment With Natural Gas Transmission Constraints," IEEE Transactions on Power Systems, vol. 24, no. 3, p. 1523–1536, 2009.

[14] V. L. Streeter and E. B. Wylie, "Natural Gas Pipeline Transients," Society of Petroleum Engineers Journal, vol. 10, no. 4, 1970.

[15] I. Cameron, "Using an Excel-Based Model for Steady-State and Transient Simulation," in PSIG Annual Meeting, October 20 - 22, 1999, St Louis, Missouri.

[16] National Grid, "UK Future Energy Scenarios," 2013.

[17] "ITM electrolyser adds first P2G hydrogen to German gas grid," Fuel Cells Bulletin, no. 1, p. 8–9, January 2014.

[18] G. Gahleitner, "Hydrogen from renewable electricity: An international review of power-to-gas plants for stationary applications," International Journal of Hydrogen Energy, vol. 38, no. 5, p. 2039–2061, 2013.

[19] UK Hydrogen and Fuel Cell Association, Power to Gas: Energy Storage and Methanation Webinar, 2014.

[20] HM Government, "2050 Pathways Analysis," 2010.

[21] N. Keyearts, M. Hallack, J.-M. Glachant and W. D'haeseleer, "Gas market distorting effects of imbalanced gas balancing rules: Inefficient regulation of pipeline flexibility," Energy Policy, vol. 39, no. 2, p. 865–876, 2011.

[22] The MathWorks, Inc., "MATLAB," Natick, Massachusetts, United States.

[23] R. D. Zimmerman, C. E. Murillo-Sánchez and R. J. Thomas, "MATPOWER Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education," IEEE Transactions on Power Systems, vol. 26, no. 1, p. 12–19, 2011.

[24] A. J. Wood and B. F. Wollenberg, Power Generation, Operation, and Control, Wiley-Interscience, 1996.

[25] M. Black and G. Strbac, "Value of Bulk Energy Storage for Managing Wind Power Fluctuations," IEEE Transactions on Energy Conversion, vol. 22, no. 1, p. 197–205, 2007.

[26] A. J. Osiadacz, Simulation and analysis of gas networks, Gulf Publishing Co., 1987.

[27] K. R. W. Bell and A. N. D. Tleis, "Test system requirements for modelling future power systems," in IEEE Power and Energy Society General Meeting, 2012.

[28] S. Clegg and P. Mancarella, "Integrated electrical and gas network modelling for assessment of different power-and-heat options," in Power Systems Computation Conference, Wroclaw, 2014.

[29] M. Aunedi, P.-A. Kountouriotis, J. E. O. Calderon, D. Angeli and G. Strbac, "Economic and Environmental Benefits of Dynamic Demand in Providing Frequency Regulation," IEEE Transactions on Smart Grid, vol. 4, no. 4, pp. 2036 - 2048, 2013.

[30] G. Sinden, "Characteristics of the UK wind resource: Long-term patterns and relationship to electricity demand," Energy Policy, vol. 35, no. 1, p. 112–127, 2007.

[31] National Grid Gas, "Gas Transmission Operational Data," [Online]. Available: http://www2.nationalgrid.com/uk/industry-information/gas-transmission-operational-data/. [Accessed May 2014].

[32] M. Sterner, M. Jentsch and U. Holzhamme, "Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes," Fraunhofer IWES, Kassel, 2011.

[33] E. B. Wylie, M. A. Stoner and V. L. Streeter, "Network System Transient Calculations by Implicit Method," Society of Petroleum Engineers Journal, vol. 11, no. 4, p. 356–362, 1971.

[34] P. Mancarella, "MES (multi-energy systems): an overview of concepts and evaluation models", *Energy*, vol. 65, pp. 1–17, 2014.

APPENDIX: GAS FLOW TRANSIENT MODEL

As mentioned in Section III.E, transient gas flow in a section of pipeline is characterized by three relations, namely, the equation of state (34), and the continuity and motion equations (35) and (36), respectively [14][2].

$$\frac{p}{\rho} = ZR_{\text{spec}}\Theta = e^2 \tag{34}$$

$$\frac{e^2}{A} \cdot \frac{\partial M}{\partial x} + \frac{\partial p}{\partial t} = 0 \tag{35}$$

$$\frac{1}{2}\frac{\partial p^2}{\partial x}\left(1 - \frac{e^2 M^2}{A^2 p^2}\right) + \frac{2e^2 M|M|}{F^2 d A^2} +$$

[2] Without loss of generality, we adopted here the conventional assumptions of isothermal flow and horizontal pipe. In addition, for the sake of readability we are not explicitly writing the subscript indicating pipe index.

$$\frac{1}{A}\left(p\frac{\partial M}{\partial t}+\frac{e^2}{A}\frac{\partial M^2}{\partial x}\right)=0 \qquad (36)$$

where p is the pressure (Pa), Z is the compressibility factor, R_{spec} is the specific gas constant for natural gas (J/kg K), Θ is the absolute temperature (K), ρ is the density (kg/m^3), e is the speed of wave propogation in the gas (m/s), M is the pipe flow rate (kg/s), x is the distance along the pipeline (m), t is time (s), d is the pipe diameter (m), A is the pipe's cross-sectional area (m^2) and F is the Fanning transmission factor (dimensionless).

To study the effects on the network, the pressures and flows for each of the network's pipeline sections and for each time period are determined. As the transient gas flow equations are applied to transmission level gas networks, well-accepted simplification assumptions for higher-pressure ($p\frac{\partial M}{\partial t} \gg \frac{e^2}{A}\frac{\partial M^2}{\partial x}$) slow gas flow ($\frac{e^2 M^2}{A^2 p^2} \ll 1$) are used, [14].

The volumetric flow rate Q is related to the flow rate in terms of mass M by $Q = M/\rho_n$ where ρ_n is the density (kg/m^3) of natural gas at normal temperature and pressure. A given section of pipe, S, of length Δx has associated a pressure and flow rate to its beginning and end points. Let $p_{S,a}$ and $Q_{S,a}$ (resp. $p_{S,b}$ and $Q_{S,b}$) be the pressure and flow rate at the beginning (resp. end) point of the section at time t_0. Then at time $t_0+\Delta t$, a finite difference scheme can be used to resolve the respective values of pressures and flow rates $p'_{S,a}$, $Q'_{S,a}$, $p'_{S,b}$, $Q'_{S,b}$ (Fig. 11).

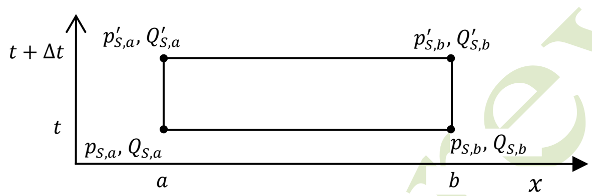


Fig. 11. Finite difference cell for determination of transient flow equations.

The pressures and flows at $t_0+\Delta t$ are determined as follows using an implicit finite difference scheme [15]. If there are N pipe sections, there will be $2(N+1)$ unknowns which will be determined by the solution of a set of $2(N+1)$ relations. As mentioned earlier, each pipe section has two relations defined by the continuity and motion equations. The continuity equation (35) is approximated by the difference equation

$$f_{S,\,\text{continuity}} = \frac{\rho_n R_{\text{spec}}\Theta}{A}\cdot\frac{\Delta t}{\Delta x}\left(Q'_{S,a}+Q'_{S,b}\right) + \frac{p'_{S,AV}}{Z'_S}-\frac{p_{S,AV}}{Z_S}=0 \qquad (37)$$

where $p_{S,AV}$ and Z_S are the average pressure and compressibility of the pipe section at t_0, and P'_{AV}, Z'_S are the respective values at $t_0+\Delta t$.

The motion equation (36) is approximated by

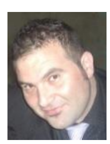
$$f_{S,\,\text{motion}} = \frac{\left(p'_{S,b}\right)^2-\left(p'_{S,a}\right)^2}{2\cdot\Delta x} + \frac{e^2}{F^2 dA^2}\cdot\frac{\rho_n^2\left(Q'_{S,a}+Q'_{S,b}\right)\left|Q'_{S,a}+Q'_{S,b}\right|}{2} + \frac{\rho_n\cdot p_{S,AV}}{A}\cdot\frac{Q'_{S,a}+Q'_{S,b}-Q_{S,a}-Q_{S,b}}{2\cdot\Delta t}=0 \qquad (38)$$

The remaining relations are described by the boundary conditions which are presented in (31)–(33) of Section III.E. To find the implicit finite difference scheme solution, the pressures and flows for $t_0+\Delta t$ are determined by solving (31)–(33) and (37)–(38) for $p'_{S,a}$, $Q'_{S,a}$, $p'_{S,b}$, $Q'_{S,b}$ by using the Newton-Raphson method.

The decision as to what time step Δt to use in the finite difference scheme must take into account a number of considerations, and, as in any numerical approximation, a balance should be made between computational time on the one hand and the accuracy, meaningfulness and purpose of the results on the other. Numerical analyses and assessments as to the effects of alternative Δt for the utilized finite difference scheme on the solution of the gas flow model are described in [33]. Taking into account these factors, and following [15], the conservative value of $\Delta t = 300$s has been chosen. This allows for the consideration of more abrupt changes which may, for example, arise due to a storage facility switching from injection to withdrawal within an hour.

BIOGRAPHIES

Stephen Clegg is at the University of Manchester where he is a research student in the Electrical Energy and Power Systems Group. His research includes the development of methods to study the interactions between the gas and electrical sectors and their applications to wider power systems contexts and integrated energy systems.



Pierluigi Mancarella (M'08, SM'14) received the Ph.D. degree in Electrical Engineering from Politecnico di Torino, Italy, in 2006. After working as a Research Associate at Imperial College London, UK, he is currently a Reader in Future Energy Networks at the University of Manchester, UK. His research interests include techno-economic and environmental analysis of multi-energy systems, business models for low carbon technologies, risk analysis of smart grid technologies, and infrastructure investment under uncertainty. He is an Associate Editor of the IEEE Systems Journal.