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A multi vector energy analysis for interconnected power and gas systems

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HIGHLIGHTS

- The first multi vector energy system analysis for Britain and Ireland is performed.
- Extreme weather driven gas demands were utilised to increase gas system stress.
- GB gas system is capable of satisfying demand but restricts gas generator ramping.
- Irish gas system congestion causes a 40% increase in gas generator short run cost.
- Gas storage in Ireland relieved congestion reduced operational costs by 14%.

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ABSTRACT

This paper presents the first multi vector energy analysis for the interconnected energy systems of Great Britain (GB) and Ireland. Both systems share a common high penetration of wind power, but significantly different security of supply outlooks. Ireland is heavily dependent on gas imports from GB, giving significance to the interconnected aspect of the methodology in addition to the gas and power interactions analysed. A fully realistic unit commitment and economic dispatch model coupled to an energy flow model of the gas supply network is developed. Extreme weather events driving increased domestic gas demand and low wind power output were utilised to increase gas supply network stress. Decreased wind profiles had a larger impact on system security than high domestic gas demand. However, the GB energy system was resilient during high demand periods but gas network stress limited the ramping capability of localised generating units. Additionally, gas system entry node congestion in the Irish system was shown to deliver a 40% increase in short run costs for generators. Gas storage was shown to reduce the impact of high demand driven congestion delivering a reduction in total generation costs of 14% in the period studied and reducing electricity imports from GB, significantly contributing to security of supply.

1. Introduction

Previously, the interactions between energy supply vectors such as power and gas were relatively unexplored [1]. The continual increase in renewable energy penetration requires a pressing need to understand the interaction between energy system supply networks. By 2030, installed wind and gas generation capacity in Irish and British power systems will be 78% [2] and 67% [3] respectively. The reliance on both generation technologies results in an implicit relationship between power and gas systems as fast ramping gas generators are frequently utilised in the supply of residual load, adding flexibility to the power system and facilitating the adoption of renewable energy [4]. In the case of power systems with high penetrations of wind power and a reliance on gas fired generation, the stochastic nature of wind power is transmitted onto gas fired units and thus the gas transmission infrastructure.

The importance of considering the wider, multi vector energy system has been highlighted in [5] where the demand driven gas price had an impact on the ability of gas generators to be competitive in the power market. Significant work has been conducted regarding the ability of one energy system to cope with failures in another. The requirement of gas system operators to consider the impacts on power system operation when dealing with outages over a short time frame was highlighted in [6]. Both [7,8] show how power system security is negatively affected due to outages on the gas transmission network. As power systems continue to integrate high penetrations of renewable energy, the increased flexibility and variable output provided by gas units [9] will

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continue to couple the gas and power energy vectors closely. A modelling approach for system operators to co-ordinate demand response in both power and gas vectors considering wind power uncertainty was described in [10] and applied to an IEEE test system. The approach highlighted how supply companies could reduce system operating costs by incentivising demand response participation and optimising peak energy system loads. A model investigating the dynamic interaction between power and gas systems at the micro grid scale was developed in [11]. It was found that single shaft micro turbines insulate both power and gas systems from each other, whereas a split shaft turbine increases interaction between both vectors allowing faults to be distributed.

Unit commitment models relating to short term security constrained operation and long term planning of combined power and gas test systems were developed in [12,13] respectively. The long term model highlighted the ability of gas transmission constraints to impact combined system expansion planning schedules, due to the dependency of natural gas units on gas transmission infrastructure. However, short term operational impacts due to natural gas transmission constraints were shown to impact on gas generators ability to contribute flexible generation, overall generation volumes and ultimately total system generation costs [14]. Similar work regarding short term power and gas interaction was performed in [15]. Similarly, a combined network expansion planning methodology applied to both an IEEE test system and the real gas and power system of Hainan province, China was presented in [16]. It was shown in this analysis that planning gas and power networks together in addition to optimising investment and production costs delivered higher social welfare than planning of individual networks. However, it was shown that high levels of wind power have the potential to increase cost despite multi vector expansion planning.

The aforementioned work considers idealised test systems. The following references consider the Great Britain (GB) power and gas network utilising a DC load flow model for the power system and a representative hydraulic model for the gas network. The model is initially presented [17] and developed to consider the impacts large penetrations of wind have on the gas network [18], then utilised to investigate operating strategies to account for wind forecast error [19] and influence expansion planning respectively [20]. More recently, the work has been used to outline the benefits of power to gas technology with respect to wind curtailment and system operational costs, reducing both [21]. Similar work on the GB network has been conducted by [22], where changes in domestic heating technology are implemented to quantify the changes in flexibility afforded to the power system by the gas network. Work undertaken by [23] quantified the impacts gas system outage events had on power market prices in the Hellenic power and gas system. By installing gas storage, gas network failures are mitigated and result in only a small increase in system cost. The importance of combined energy system operation is further highlighted in [24], where an optimal control model of the Illinois power and gas system is developed. It was found that gas unit dispatch considering only the power system decreased the flexibility of the gas system. However, when both energy vectors were operated in tandem gas units were shown to offer demand response capability to gas pipeline operators and assisted to increase gas supply ability.

The above work, whilst focusing on the interaction between power and gas supply networks, is performed using either a test system or a representation of a real power system. The work conducted in this analysis utilises a fully realistic unit commitment and economic dispatch model (UCED) which considers the technical characteristics of every unit in the power system. An energy flow model of the gas network is included, respecting pressure constraints via line pack limitations and interfacing with the UCED model in a spatially accurate manner. Additionally, multiple energy systems are considered. The integrated energy systems model is developed for GB and the island of Ireland, which to the author's knowledge is the first multi vector, multi-jurisdictional energy flow model for large scale interconnected power and gas systems. This facet of the analysis is extremely valuable since secure operation of the gas network in Ireland is almost exclusively dependant on imports from GB [25]. In turn, it has been shown that gas system operation is fundamentally important for the secure operation of the power system in Ireland. The methodology and analysis presented here is envisaged to contribute to high level understanding of the interactions between interconnected power and gas systems where one system is dependent on another, in line with EU progress towards a single European internal energy market [26].

2. Methodology

The overarching aim of the methodology employed in this work is to investigate the interaction between power and gas vectors when operation of both systems is co-optimised, rather than the separate operation which is historically the case. The work presented is an energy flow analysis, performed using a fully realistic unit commitment and economic dispatch model of the power systems of the UK and Ireland coupled with a representative gas model for each system. The objective function is shown in (1) and described in [27,28,7,29]. It is tasked with supplying both gas and power demands at least production cost, solved by Fico's Xpress Optimisation Suite [30] and built using Energy Exemplar's Plexos Integrated Energy Model 6.4 [31].

$$\min\ \Sigma_{t\epsilon T}\Sigma_{j\epsilon J}\Sigma_{i\epsilon I}\Sigma_{k\epsilon K} \times \left(\underbrace{\begin{bmatrix} SC_j \cdot US_{jt} + NLC_j \cdot UG_{jt} \\ +(VOM_j + UoS_j)\cdot P_{jt} \\ +PC_j \cdot P_{jt} \\ +PenLLE \cdot UEE_t + PenLLE \cdot RES_{jt} \\ +PDE \cdot ExE_t \end{bmatrix}}_{\text{Power System Component}} \underbrace{+[GPC_{it} + GTC_{kt} + PenLLG \cdot UGD_t]}_{\text{Gas System Component}} \right) \tag{1}$$

where SC_j and NLC_j are start costs and no load costs of each generator j at each time step from t to T. US_{jt} and UG_{jt} belong to set 0 or 1 determining the unit commitment state of each unit, if started or generating respectively. Variable operation and maintenance charges, VOM_j and use of service charges UoS_j are variable with the level of output from each unit, P_{jt} as is total production cost PC_j. Unserved energy UEE_t and insufficient reserve provision RES_{jt} are penalised the cost of loss of electrical load $PenLLE$. Excess energy ExE_t is priced at the dumped energy price PDE which is an arbitrary high price to ensure generation does not exceed demand at each node. The base price of gas in the model is set at the production cost of the individual supply source field GPC_{it} located at gas node i. Gas pipeline transportation tariffs for pipeline k are represented by GTC_{kt}. Loss of gas load is handled similarly to the electrical load counterpart, with unserved gas demand UGD_t penalised at the loss of load price $PenLLG$.

This work builds on the models presented in [7,32]. The key part of the methodology is focused on the interaction between power and gas vectors and is achieved by gas generators. Gas generators are present in both UCED and gas models, thus enable the co-optimisation of both systems to occur. Gas generators attached to a gas node are fuelled by the gas model and produce electricity in the UCED model. These gas nodes all receive a shadow price which is the value the energy system places on the next unit of gas supply at that node. Any scarcity pricing due to congestion, linepack limitations (where the volume of gas in a pipeline reaches