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The importance of gas infrastructure in power systems with high wind power penetrations

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HIGHLIGHTS

- The first multi-vector gas and power system analysis for Ireland is performed.
- Power system security is vulnerable to outages on the gas network.
- Economic operation of the power system is negatively affected by gas network outages.
- Excessive power system reserve allocation can occur over a transmission constraint.
- Wind forecast error results in large utilisation swings for importing gas pipelines.

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ABSTRACT

Gas fired generation currently plays an integral support role ensuring security of supply in power systems with high wind power penetrations due to its technical and economic attributes. However, the increase in variable wind power has affected the gas generation output profile and is pushing the boundaries of the design and operating envelope of gas infrastructure. This paper investigates the mutual dependence and interaction between electricity generation and gas systems through the first comprehensive joined-up, multi-vector energy system analysis for Ireland. Key findings reveal the high vulnerability of the Irish power system to outages on the Irish gas system. It has been shown that the economic operation of the power system can be severely impacted by gas infrastructure outages, resulting in an average system marginal price of up to €167/MW h from €67/MW h in the base case. It has also been shown that gas infrastructure outages pose problems for the location of power system reserve provision, with a 150% increase in provision across a power system transmission bottleneck. Wind forecast error was shown to be a significant cause for concern, resulting in large swings in gas demand requiring key gas infrastructure to operate at close to 100% capacity. These findings are thought to increase in prominence as the installation of wind capacity increases towards 2020, placing further stress on both power and gas systems to maintain security of supply.

1. Introduction

Due to the mass adoption of renewable energy, specifically wind in EU member states, the importance of gas fired generation is continually highlighted [1]. One of the driving factors behind large scale renewable integration is the pursuit of increased security of supply [2]. While the installation of renewables reduces reliance on imported fossil fuels in the long term, the high penetration of stochastic energy sources such as wind results in challenges for real time power system operation [3,4]. In markets with high penetrations of wind power, gas fired generation has been responsible for maintaining system supply and demand balance, accounting for the residual demand not fulfilled by wind and reacting to sudden changes in wind output. Wind power has been shown to gain fuel mix share at the expense of gas fired generation resulting in large decreases in gas unit capacity factors [5]. However, the resulting decline in capacity factor does not attribute less importance on gas plant, but signals a paradigm shift in electricity market operation [6].

The increasing support role fulfilled by gas and the uncertain supply profile required as a result of high penetrations of wind power are apparent in the flows of gas in pipeline infrastructure

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supplying gas units. It has been shown that variations in gas generator outputs are passed directly onto the existing gas infrastructure [7]. Uncertainty in the quantity of gas required to fuel a generator in order to participate in the electricity market poses a major problem for gas shippers by casting uncertainty over pipeline capacity nominations and re-nominations, as well as increasing their exposure to network balancing penalties [8]. Gas transmission system operators are also impacted, requiring to operate the system close to pressure margins in order to maintain adequate system pressure and ensure domestic customers are prioritised. Increased variability results in increased operational costs due to compressor usage in an effort to deliver gas where it is needed, since the transport time for gas in a pipeline is much longer than that of electricity over a transmission line [7].

In power systems with both high penetrations of gas fired generation and wind power, the importance of gas infrastructure (i.e. gas pipelines supplying power stations and compressor installations maintaining network pressure) for system security and operation is further heightened. This is especially true in the Single Electricity Market (SEM) of the Republic of Ireland (ROI) and Northern Ireland (NI). Analysis in [9] showed that gas supply interruptions to power generation on the island of Ireland ranging from 1 to 90 days could cost between 0.1 and 1 billion euro per day. Combined with domestic load losses, the cost of gas supply interruption was forecasted to be upwards of 80 billion euro.

While the interaction of flexible generation capacity in support of renewable energy has been well studied [10,11], research on the effects and role of gas infrastructure on power systems with high renewable penetrations has been relatively limited. A review of the recent research in the field shows that much of the work has focused on developing new integrated gas and electricity models and applying the optimisation to test networks. In [12], a security constrained unit commitment (SCUC) model incorporating gas transmission constraints was developed and applied to a six bus power system and a seven node gas system. Several scenarios were analysed, including the impacts of gas transmission constraints, gas pipeline outages and varying natural gas loads. Further analysis of the SCUC model was conducted using a 118 bus power system and a 14 node gas system to show the effectiveness of the proposed model. It was found that gas transmission constraints resulted in higher daily operating costs than the case with no gas transmission constraints. In addition, variations in gas load as well as gas pipeline infrastructure failures negatively impact system security and results in large levels of load shedding. A similar SCUC model was presented in [13] to assess the relationship between gas pipeline outages and power system security. It was found that implementing a suitable fuel switching strategy in affected zones prevented some unit shutdowns. However, the overall system load shedding was directly related to the number of gas units unable to receive fuel. A co-optimisation planning model considering the relationship between gas and power infrastructure was presented in [14], where the ability of gas infrastructure expansion to transport the required fuel to the power system was considered in the iterative planning approach.

A comprehensive overview of gas and power system security dependence is given in [15]. Again, a SCUC model is used to illustrate the importance of gas infrastructure on a test system containing renewable sources. However, this is the only work to consider the impact gas pipeline outages have on the locational marginal price, noting a large increase due to congestion in affected zones as a result of gas generators being forced off. A pumped storage plant placed in the zone with highest demand was found to be a suitable alternative to load shedding in times of gas pipeline outages.

A fully representative model of the Great Britain (GB) gas and power system was developed and presented in [16]. Combined optimisation of both networks was conducted for a winter month. Outages of key pieces of gas infrastructure such as terminals and storage and their effects on compressor use, network line pack, gas shedding and generation by fuel type were illustrated. Low pressure on the gas network was shown to negatively affect the ability of gas generators to contribute electricity supply. Large levels of gas shedding were apparent, accounting for the large increase in combined system operation costs. The work highlighted the importance of multiple supply routes and the ability of gas storage to compensate for supply failures by reducing load shedding. Further development of the above model in order to consider the impacts of high wind power penetration on the Great British gas network in 2020 was presented in [7]. Low and high wind scenarios were compared to the 2009 base case, which resulted in higher and lower total operational costs respectively. It was shown that when high gas demand and low wind occurred together, the gas network was placed under stress and saw a rapid depletion in line pack which impacted on the ability of gas generators to run. These variations require more compressor use and thus result in increased system operational cost. Gas storage was offered as a solution, as well as hourly instead of daily line pack balancing.

Reliability of the combined GB gas and power system during a winter week in 2020 was investigated in [17]. The gas and power co-optimisation model presented in [16] was coupled with a Monte Carlo simulation to determine the reliability of the combined networks. Uncertainties regarding supply, demand and infrastructure for both power and gas networks were considered. The multi-vector energy system approach to reliability assessment was shown to be a possible asset when considering future investment decisions. A £900 million decrease in expected energy unserved as a result of a doubling gas storage capacity was illustrated. The impact of various deterministic and stochastic unit commitment and economic dispatch strategies to deal with uncertainties in wind power forecasts were analysed in [18]. The test system consisted of the GB gas and electricity networks. Day ahead and within day dispatch instructions resulting from stochastic methods are shown to deal with the variation in wind power better than the deterministic method, achieving a saving of 1% in total gas and power system operational costs.

All of the above work has developed an integrated gas and power model and applied it to either a test system or the GB system. Power system operational impacts have not been fully investigated as a result of gas infrastructure outages, with the above research focusing mainly on gas consumption, load shedding, fuel mix changes and stochastic methods not currently used by the system operators in Ireland. Instead, this research focuses on the impact gas infrastructure outages have on system operational metrics such as the price of electricity, capacity utilisation and gas pipeline flows in a high wind power system where gas supplies are mainly imported and the use of gas storage is limited. This paper is presented as follows. Section 1 introduces the subject matter and establishes the state-of-the-art. Section 2 describes the choice of the test system, modelling methodology and key assumptions utilised in the analysis. Section 3 provides results and discussions regarding key results including power system marginal price, unit commitment impacts, gas infrastructure flows and the effect wind forecast error has on gas infrastructure operation. Section 4 concludes the paper.

2. Methodology

Due to the high penetrations of natural gas fuelled generating units and installed wind capacity, the SEM was chosen as the test system. A winter week in 2011 was used since the available data from both gas and power system operators enabled clear validation