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# Gas generation and wind power: A review of unlikely allies in the United Kingdom and Ireland

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ABSTRACT

No single solution currently exists to achieve the utopian desire of zero fossil fuel electricity generation. Until such time, it is evident that the energy mix will contain a large variation in stochastic and intermittent sources of renewable energy such as wind power. The increasing prominence of wind power in pursuit of legally binding European energy targets enables policy makers and conventional generating companies to plan for the unique challenges such a natural resource presents. This drive for wind has been highly beneficial in terms of security of energy supply and reducing greenhouse gas emissions. However, it has created an unusual ally in natural gas. This paper outlines the suitability and challenges faced by gas generating units in their utilisation as key assets for renewable energy integration and the transition to a low carbon future. The Single Electricity Market of the Republic of Ireland and Northern Ireland and the British Electricity Transmission Trading Agreement Market are the backdrop to this analysis. Both of these energy markets have a reliance on gas generation matching the proliferation of wind power. The unlikely and mostly ignored relationship between natural gas generation and wind power due to policy decisions and market forces is the necessity of gas to act as a bridging fuel. This review finds gas generation to be crucially important to the continued growth of renewable energy. Additionally, it is suggested that power market design should adequately reward the flexibility required to securely operate a power system with high penetrations of renewable energy, which in most cases is provided by gas generation.

## 1. Introduction

As the public and political conscience continues to focus on greenhouse gas emissions and clean energy, the power sector is enhancing its green credentials in order to achieve the binding European Union (EU) 2020 targets. Increased penetration of renewable energy, particularly wind power, is apparent. Great Britain (GB) has recently emerged as a global leader in offshore wind installation, with over 1200 MW installed by 2012 [1]. In Ireland, the lack of indigenous fossil fuel production, favourable domestic policy landscape and geographical suitability for wind energy have encouraged development [2]. As of 2015, there has been over 2800 MW of wind capacity installed, with a further 2000 MW planned for installation by 2020 [3].

However, both the Single Electricity Market (SEM) of Northern Ireland (NI) the Republic of Ireland (ROI) and the British Electricity Trading and Transmission Arrangements (BETTA) market in Great Britain (GB) have high installed capacities of gas fired generation. Output from these gas units contributed 42% and 30% of total electricity production in 2014 respectively [4,5]. Gas fired generation in the BETTA market has a lower share in overall production than in the SEM since the BETTA is a much larger system with increased scope for inflexible base load coal and nuclear generation. As increasingly stringent European legislation restricting the operation of coal plants comes into force [6], the importance of gas fired generation for system security and integrating renewable energy will continue to increase.

Gas fired power stations are much more adept at adjusting output based on residual demand resulting from wind power variation than more inflexible units such as coal [7], hence the power industry's favouring of the use of natural gas in its electricity generating operations as the penetration of renewable energy continues to increase. This natural gas generation also emits much less Green House Gas (GHG) emissions than coal and oil fired power stations [8]. From the outset it is clear that gas fired generation in the SEM and BETTA can contribute to the savings required to achieve the legally binding 2020 targets [9] on two fronts, by reducing overall emissions and supporting the increase of renewable electricity.

However, the intersection of relatively dependable high installed capacities of gas generators and the stochastic nature of high levels of wind penetration provide an extremely interesting set of issues for system operators and energy market participants. The status of wind

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energy and its barriers to market entry in SEM have been well documented by Foley et al. in [10]. The paper concludes that an interaction analysis of the SEM and the BETTA markets is necessary for future development regarding market design, operation and energy mix. Both jurisdictions geographical proximity and interconnection provide a suitable scenario for comparison.

Similarly, both the SEM and BETTA are heavily reliant on imported fossil fuels [11]. Domestic oil and gas production in the United Kingdom Continental Shelf (UKCS) is declining rapidly [12] further increasing the dependence of the UK on energy imports. This has a direct effect on Ireland, since 95% of natural gas demand in 2013/14 was imported via a single interconnection point from the GB system [13]. By harnessing the natural resources which are freely available, both the UK and Ireland can reduce their exposure to volatile international energy markets and the effects of geopolitical events.

Analysis of the relatively unexplored relationship between wind and gas generation [10] in an effort to establish a sustainable energy generating future is the central aim of this paper. Despite numerous other developments in the power system such as decentralisation and the electrification of transport and heating systems, this work focuses on the transition to a time when these technologies are widespread. This bridging period is the backdrop for the analysis and considers the impact wind power has on gas generation and the operation of the conventional power system. Wind energy due to its non-synchronous low inertia characteristics, poses significant challenges to frequency control and overall power system operation [14]. This, coupled with the inherent stochastic nature of the resource, requires conventional generation to satisfy residual demand and provide auxiliary services such as reserves and frequency response regulation [15]. Section 2 documents and analyses current policy decisions and their effects on technology development. The technical impact of integrating large penetrations of renewable energy is discussed in Section 3. Economic factors relating to the change in operational profile of gas units are discussed in Section 4, accompanied by a detailed discussion. Concluding remarks are given in Section 5.

## 2. Policy impact

Policy decisions are one of the largest contributory factors towards emission reduction [16]. Policy also has the ability to affect energy prices and the distribution of wealth between consumers and generators [17]. The EU 2020 targets and Emissions Trading Scheme (EU ETS) are prime examples of the ability to directly impact the fuel mix. Future commitment to a revamped EU ETS and carbon taxes will constrain base load coal generation, since gas fired units require 50% less allowance [18]. However, the adoption of the initial EU ETS triggered innovation mostly in coal fired power generation via the development of carbon capture and storage [19]. The price of carbon in the first two allocations of credits did not sufficiently penalise the adoption of coal fired generation [20], resulting in no shift in the merit order with respect to gas. The direct capability of policy to affect generation technology must be fully realised. Technology advancement benefits from long term legislative goals, providing the policy decisions are time specific and flexible [21]. It has been found that technology advances relating to climate change mitigation only occur at sufficient levels if there is an incentive to do so, i.e. supported by policy developments [22]. The policy implemented accelerates the rate of development, but it is imperative that policy is clear in direction. Industry is made up of many stakeholders who all interpret decisions differently, limiting the effectiveness of overall change [23]. It is imperative that sensible policy decisions are made in order to drive the future technology required to achieve a high renewable penetration energy system.

In the case of gas generation, increases in efficiency both overall and in cycling operation could mitigate the exposure to fuel price uncertainty. Cementing of plant flexibility from an operational, economic and environmental view point would ensure the support capabilities of gas are fully realised in high wind penetration markets. Supporting policy is integral to these developments, and the European Union has been instrumental in achieving a single internal energy market with sustainability as the overarching aim.

### 2.1. European drivers

European level legislation is adopted in GB, NI and ROI. From an energy perspective the most notable are the 2020 energy targets and the "Third Energy Package". These two main pillars of energy policy aim to reduce the rate of climate change experienced by member states and encourage the development of a competitive single energy market.

#### 2.1.1. 2020 energy targets

The 2020 targets offer a three pronged, legally binding target scenario which aims to mitigate climate change over the entire EU by the year 2020 [9]:

- A reduction in greenhouse gas emissions by 20% from 1990 levels;
- Total energy demand is to be met with 20% renewable energy;
- An increase of 20% in energy efficiency.

This analysis relates to the first two targets listed above. By increasing the amount of renewable energy, the need for fossil fuel electricity generation shows an overall decline, thereby assisting in the reduction of GHG emissions. In 2011, power generation accounted for 33% of total EU greenhouse gas emissions [24].

Each member state sets out their own national renewable energy action plan (NREAP) detailing the steps they will take in order to achieve the 2020 goals. The individual targets when combined with the remainder of the EU, will achieve the required benchmark. In addition to the mandated NREAP, the UK published "UK Renewable Energy Roadmap" in July 2011, setting a GHG emissions reduction target of 16% and a renewable energy target of 15%. Since Northern Ireland is a devolved local government, there is no defined target at EU level. However, in the UK Energy Roadmap, Northern Ireland committed to a renewable electricity target of 40% and a 10% renewable heat target [25]. The GHG emissions target for Northern Ireland extends to 2025, when a reduction of 35% on 1990 levels is expected [26]. Similarly, ROI set out challenging targets in pursuit of 2020 compliance. The Irish NREAP sets out a target of 16% of energy from renewables [27]. GHG emissions are aimed to be reduced by 20%.

#### 2.1.2. Third energy package

The third package is a collection of legislation which aims to further the progress of creating a single EU wide market for gas and electricity [28]. By fostering a European wide energy network, policy and infrastructure can align across borders enabling significant potential for renewable integration. In the case of wind, the meteorological variability experienced by one area of can be offset by the conditions in another [29].

The main area of legislation in the Third package relates to the unbundling of the supply and transmission businesses for both electricity and gas systems. By ensuring these activities are completely separate, non-discriminatory access to pipelines and interconnectors can be achieved. Separating production and supply activities from transmission operation increases market transparency and removes conflicts of interest in the energy supply chain. Implementation of Directives 2009/72/EC [30] and 2009/72/EC [31] for electricity and gas markets respectively ensures unbundling is a requirement of Member States, and ultimately aims to promote efficient use of European wide energy infrastructure under common market rules. By utilising energy infrastructure across Member States in a more efficient, effective and transparent manner, the formation of a single internal energy market is expected to reduce energy prices for

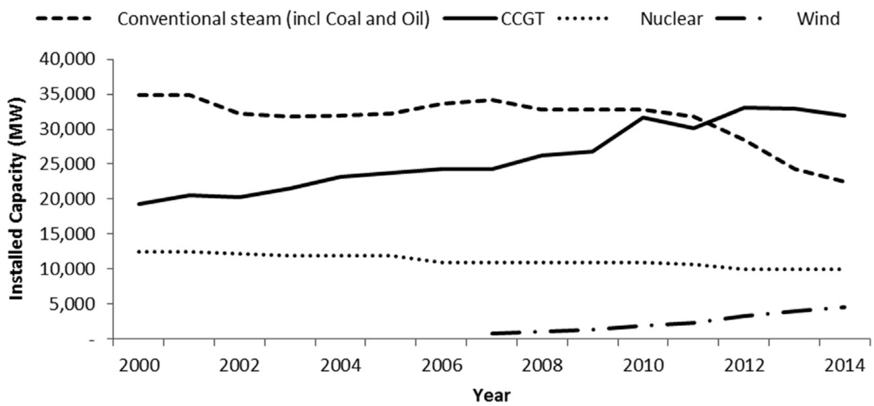


**Fig. 1.** BETTA installed capacity [5].

consumers and increase security of supply across the EU. The Third Energy Package also strengthens the statutory power of regulators by ensuring their independence from market forces and governments. This was achieved by establishing a central European regulation agency, Agency for the Cooperation of European Regulators (ACER). How this legislation is implemented in the UK after their decision to leave the EU remains to be seen.

### 2.2. Results of policy

The effects of policy implementation can often vary with the source reporting the results. In the case of renewable energy development, where as discussed above policy decisions are integral to the development environment, the definition of success in this work is aligned with capacity installed. The capacity of BETTA generating units is shown in Fig. 1. With the rise of wind power installation, although still dwarfed by conventional generation, has been accompanied by a rise in Combined Cycle Gas Turbine (CCGT) capacity. It is important to note that CCGT capacity has overtaken conventional steam plants (mostly including coal) in 2012. The decline of coal fired generation is mainly due to the EU wide Large Combustion Plant Directive (LPCD) which came into force in 2008. The directive aimed to reduce the amount of particulate, sulphur and nitrogen oxide pollution by restricting running hours of qualifying plant. From 2016, the LPCD was succeeded by the more stringent Industrial Emissions Directive (IED) [6].

In both the SEM and BETTA markets, wind has priority dispatch status in accordance with the EU Renewable Electricity Directive [32], resulting in displacement of thermal generation on the system. Since the SEM is a much smaller market than the BETTA, system security with high penetrations of wind is an issue. In an effort to protect system security from rapid changes in wind output, EirGrid (SEM system operator) set a limit on the amount of non-synchronous generation on the system at any given time (SNSP limit). This limit is calculated using (1) [33] and was initially set at 50%, but is set to increase to 75% pending successful completion of the "DS3 Programme" [34] which is discussed in Section 4.5.

By raising the SNSP limit to 75%, wind curtailment drops on average by between 14% and 7%, reducing the required level of installed wind power [35].

$$SNSP = \frac{Wind\ Generation + HVDC\ Imports}{Demand + HVDC\ Exports} \tag{1}$$

The SNSP limit imposed on the SEM highlights the operational challenges posed by a high penetration of wind power. Similar operational issues are apparent in the BETTA market. As the capacity of installed wind generation in the BETTA has increased significantly, the use of gas units as provider of residual demand in support of wind power is well illustrated in Fig. 2. As the volume of electricity generated from wind increases, the most negatively affected fossil fuelled generator is gas. This suggests that gas generation is falling out of favour in the merit order, with the cheaper to run fuel coal plants gaining. However, it is necessary to consider the manner in which gas plant are utilised in the face of high penetrations of wind energy. By monitoring the recent trends in the dispatch of generators in the BETTA market, it can be seen that the capacity factor for gas plants has decreased significantly. Gas is now used as the sacrificial fossil fuel in the presence of wind generation. The sharp decrease in both volume generated and capacity factor since 2010 shows that new gas plant installations are entering a market vastly different from the plants installed during the Dash for Gas during the 1990's.

Despite this large decrease in capacity factor, the quantity of electricity produced by gas generators is still significant in both the SEM and BETTA markets, at 42% and 30% of total production in 2014 respectively [4,5]. A low capacity factor and large volume, as a result of wind power, serves to transfer the stochastic nature of wind onto the gas infrastructure. Large swings in demand are a cause for concern not only for power plant operators, but for pipeline infrastructure investment and add a multi vector energy system dimension to the integration issue. The radically new operating profile of gas generators in support of high penetrations of renewable energy, mainly wind power, illustrates the ability of policy decisions made at the domestic and European level to influence the current and future fuel mix. In order to achieve the power system with sustainability at its centre, the numerous technical challenges of intermittency and variability are required to be managed.

## 3. Technical impact

Both the SEM and BETTA are power systems with high wind power penetrations, the installed capacity of which are forecast to continually increase. The changing generation system paradigm presents a multitude of challenges for system operators and existing thermal generation plant owners ranging from provision of system inertia to system balancing and cycling of thermal units. From a gas generation perspective, the technical characteristics of the generating technology are well suited to supporting system operators in maintaining system security whilst facilitating high penetrations of renewable energy and are outlined below.

### 3.1. Wind forecast error

The main challenge for wind power integration is its stochastic nature and its effects on economic dispatch in the short term operation of power systems. This challenge is currently being mitigated due to developments in wind forecasting [36] and the reduction of errors [37]. Improvements in wind forecasting enable more efficient unit commitment and economic dispatch decisions to be made by system operators and reduces the volume risk to other market participants [38]. With an

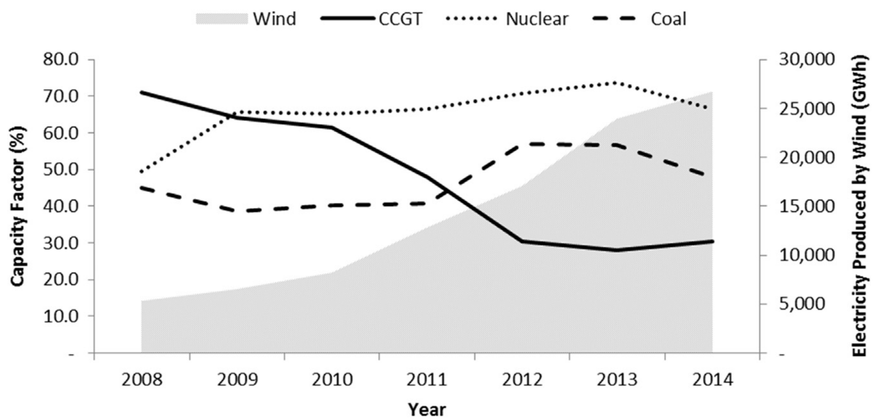


**Fig. 2.** BETTA generation capacity factor v wind generation [5].

accurate picture of the day ahead wind case, increased levels of planning could result in the decrease of plant cycling. In the case of gas fired generation, a decrease in cycling (transitioning from a cold or hot state to full load) would minimise the amount of carbon dioxide and nitrogen oxide air pollution emitted [39].

Wind forecast error has been shown to have substantial negative effects on a generators profit in the medium term [40] and results in increased system marginal prices [41]. Increasing wind forecast accuracy in the SEM has been shown to decrease system costs by up to 1.6% and reduce the level of wind curtailment, but improvements beyond mean absolute errors of 2–4% are unlikely [42]. Furthermore, the use of stochastic unit commitment methodologies accounting for wind forecast uncertainties and variability can reduce system operational costs more than deterministic unit commitment, delivering savings comparable to a 4% improvement in forecast error [42]. These results are in agreement with [43] where it has been shown that stochastic operating strategies have the potential to reduce the BETTA operational costs by 1%. However, the fact remains that no matter the improvement in wind power forecasting and the sophisticated unit commitment methods applied, the inherent variability of renewable sources of energy such as wind power are required to be accommodated in the current thermal generation dominant energy systems of the UK and Ireland.

### 3.2. System flexibility

System operators now face uncertainty on both the demand and supply side of network balancing which will need to be satisfied by flexible dispatch [39]. Fully dispatchable generating plant is required to provide the residual demand when wind and other renewable sources do not have the instantaneous capacity to do so. The need for this power system flexibility continues to increase as the penetrations of wind power continue to increase and is a necessity going forward [44]. Several methodologies have been developed to assess the flexibility of power systems with high penetrations of renewable energy. An attempt to create a standard for flexibility assessment was presented in [45] and flexibility aggregation and visualisation was outlined in [44]. Several metrics for flexibility assessment in long term generation planning applications have been developed. Work carried out in [46] established an “insufficient ramping resource expectation (IRRE)” to highlight times of inadequate system flexibility provision and monitor how the situation changes with respect to installed capacity and operating regimes. Further work incorporating IRRE and an additional “periods of flexibility deficit (PFD)” metric considering transmission constraints was presented in [47]. It was found that transmission constraints exert considerable pressure on the ability to realise flexibility, correlating strongly with the variability in residual system load. Similar work considering planning and transmission constraints for system flexibility assessment is presented in [48]. The framework presented considers time, cost, action and uncertainty and aims to assist operators in gaining visibility into flexibility shortage and zonal requirements based on the ISO New England power system. Further flexibility centric planning via a unit construction and commitment model was presented in [49]. Market design was shown to have a significant impact on the installation and profitability of flexible plant.

However, most applicable to the SEM and BETTA power systems was the integration of flexibility concerns outlined in [50] where it was noted that as wind generation increased, baseload generation decreased in favour of mid merit and peaking plant. This was attributed to an overall decrease in residual load volume accompanied by an increase in variability. Meeting this load was economically and technically best suited to the installation of mid merit and peaking plant capacity. In the SEM and BETTA, as the future of coal plants is uncertain due to the stringent IED, it logically follows that gas units will be integral to this provision of flexibility enabling large penetrations of variable renewable energy to be achieved.

### 3.3. Operational impact of flexibility provision

System flexibility is the overall ability of a power system to respond to changes in demand and online generation. At the generator level, flexibility is governed mainly by:

- Ramp up and down rates;
- Start Time;
- Minimum Stable Generation Level (MSL).

Natural gas power plants are ideally suited for providing the flexibility to fulfil residual demand as a result of wind penetration. The main reason for this is due to the unrivalled capacity of gas fired power plant to ramp up and down quickly as well as having fast start up and shut down times. Work conducted in [51] showed that as wind power penetration increased, CCGT plant in the SEM showed a dramatic increase in cycling which delivered a large decrease in capacity factor. The technical flexibility of gas units contributed to this dramatically inefficient operating profile, as coal units due to their limited ramping response and lower MSL were able to stay committed to provide system reserve. This increase in reserve provision from inflexible plant increased as wind penetration increased. The results of the work suggested flexible plant require incentive for investment, which is discussed in Section 4.5. When cycling costs were included in the unit commitment formulation, cycling operation decreased. Further work considered the operation of CCGT's in open cycle mode [52]. It was found that CCGT's in low position in the merit order used the open cycle more often in an attempt to be committed. Additionally, as wind penetration increased, so too did CCGT on CCGT competition

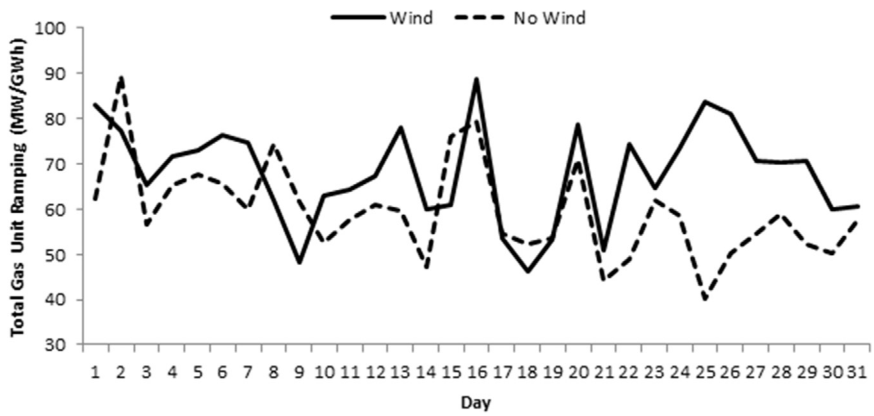


**Fig. 3.** Change in gas unit ramping due to wind power [89].

where utilisation of open cycle mode decreased. However, this multi-mode operation of CCGT's decreased the need for OCGT's possibly preventing such units from being commissioned in future. These findings are in agreement with those in [53] where the multi-mode operation of CCGT's was shown to be more suitable for wind power integration than coal or nuclear plant due to low fixed costs, quick start up times and high ramping capability. A back cast investigation into the impacts of wind power on the operation of gas units in the SEM during 2011 further highlights the increased ramping requirement from gas units to support wind [54]. Over a winter month in 2011, the level of ramping performed by all gas units in the SEM increased from 1845 MW in the no wind case to over 2100 MW in the presence of wind. Weighed by actual gas generation volume, the daily increase can be clearly seen in Fig. 3. The methodology used to produce this figure is published in [54].

The sub optimal dispatch of gas units incurs more than just the real time cost of fuel and start-ups/shutdown operation. Long term component degradation due to factors such as thermal shock, fatigue and general wear and tear costs are often not considered fully in integration analysis [55]. In [55], a model for start-up costs estimations derived from fatigue life considerations was developed. Hot, warm and cold start costs excluding fuel were presented for a sample unit. It is common to include a fixed and variable operation and maintenance cost to the short run marginal cost, however it has been shown that these simple approximations are not accurate for the new operational profile required from CCGT's [56]. The work models realistic operation and maintenance costs from long term service agreements and includes these costs in the unit commitment formulation, yielding CCGT dispatch profiles with higher firing hours per start.

### 3.4. Gas transmission infrastructure

As gas generation transitions to the role of residual demand support due to high penetrations of wind power, it is clear that power system flexibility is transferred onto the gas transmission infrastructure. This is a research area that has been traditionally overlooked from a renewable integration perspective [10]. However, consideration of multi vector energy systems has been increasing. The variable output from gas generators reduces the reliability of gas supply to the units providing power system flexibility and thus the overall safe operation of the gas transmission system [57]. Furthermore, gas system balancing is also significantly affected with the rise of renewable energy in Europe. Work conducted in [58] showed that the gas market ultimately pays the price for power system flexibility and wind forecast errors, with an increase in the expense of physical gas system balancing. The work recommends those who cause system imbalance should cover the majority of the cost.

However, consideration of multi vector energy systems has been increasing. The variable output from gas generators reduces the reliability of gas supply to the units providing power system flexibility and thus the overall safe operation of the gas transmission system [54]. This effect was well documented at the ends of pipelines, which could result in gas units shutting down to ensure security of the whole gas system. Such eventualities driven by pressure changes due to stochastic renewable power sources relate to the inherently different dynamics of power and gas systems, where the linepack storage ability of gas infrastructure can be used to manage power system flexibility requirements due to stochastic renewables, but at the expense of total gas system security due to the spatial and temporal swings in pressure across the network.

Work on multi vector energy system security was presented in [59], where gas system constraints faced by a generator could be submitted to the power system operator as energy constraints. Furthermore, gas unit fuel switching capability was shown to contribute to power system security at times of high demand. Findings presented in [60] highlighted the disparity between gas and power system outages on total energy system operation. It has been demonstrated that power system outages have a larger impact on the operation of the gas system due to the fast dynamics of the power system compared to relatively slow reaction time of the gas system. The differing dynamics of both vectors explains the reason for the limited impact gas system outages have on the power system. However, the analysis was conducted on a test system with multiple alterative supply routes for both power and gas.

The impact of gas infrastructure outages on energy systems with limited supply routes poses a significantly larger security of supply risk. Multi vector analysis for the Irish system was carried out in [61], where it was found that gas interconnector outages resulted in a significant decrease in power system security. The lack of storage infrastructure and alternative supply routes for the Irish system was the reason for such significant power price increases in the gas of outages of the single supply point.

Further modelling of real world energy systems with high penetrations of wind power and its impact on the GB gas transmission system was conducted in [62]. Times of low wind power were shown to limit the ability of the transmission system to supply gas generators in addition to the increased gas compressor use required on the network to handle the variability in flows required. This finding again highlights how two closely linked energy vectors with significantly different operating requirements and dynamics are required to work increasingly together to manage wind power. It is clear that in order to adopt high penetrations of renewable energy into the power system, significant levels of investment is also required in gas infrastructure. As previously discussed, the flexibility required by the power system is increasingly being sourced from the gas system. Gas storage is a significant provider of this flexibility, but requires significant investment and many such projects in GB are not being developed due to commercial risks such as low summer winter gas spreads and uncertainty over future energy policy [63].

However, in systems where long term energy security in the form of wind power is endangering short term gas system and thus power system security, investment in gas infrastructure is a necessity. This is especially true for the Irish energy system, as natural gas import reliance through a single entry node from GB was 95% in 2013/14 [13] and where wind power capacity is forecasted to be 32% of total installed generation capacity by 2020 [3]. Twinning of a section of the single import route for Ireland has been identified in order to reduce congestion on this vital piece of infrastructure [64]. Additionally, the development of a gas storage facility in NI is forecast to provide greater security of supply for the island of Ireland and explicitly for the GB system [65].

Lack of investment in this critical infrastructure would not only undermine the overall pursuit of renewable energy as a long term security of supply solution, but would actively contribute to the restriction of the gas system to accommodate high penetrations of wind power. It can be concluded that the sometimes overlooked dependency of power system flexibility on natural gas transmission infrastructure is increasingly important in power systems with high penetrations of wind power. As the penetration of wind power increases, the variability required to be accommodated by gas generation and its associated infrastructure will continue to increase. In turn, the value of multi vector energy analysis and the wide ranging system level impacts of high renewable energy penetrations will be vital for optimal adoption.

### *3.5. Power system emissions*

It is clear that system flexibility is a pre-requisite for wind power penetration and the literature review discussed thus far is in strong agreement that gas generation is the integral provider of this commodity. However, emissions production is a key factor in the EU 2020 targets binding the UK and Ireland. Provision of flexibility via cycling and ramping is by definition dispatching gas units at sub optimal levels. Rapid ramping up and down of plant will often take a generator far outside its economic operation. However, despite this sub optimal operation, total emissions from gas generators in the BETTA since 2012 have been significantly lower than those from coal on a per GW h basis and can be seen in Table 1.

Coal generation emits large amounts of Carbon Dioxide (CO2) as well as particulate matter and other airborne pollutants such as sulphur oxides (SOx) and nitrogen oxides (NOx) [66]. The quantity of these pollutants are primarily dependant on the composition of the fuel and the operational conditions of the plant, with average CO2 emissions at 762 kg CO2/MW h [67]. Carbon capture and storage (CCS) is thought to be the solution to keep coal plant in the merit order by lowering emissions levels and obeying abatement thresholds in pursuit of the 2020 targets [68]. There is a large degree of uncertainty regarding CCS effectiveness and commercialisation, a review of which is given in [69], in addition to the UK government withdrawing £1 billion in funding for CCS development [70]. This instability and the fact that CCS technology remains in its early stages [71] further compliments the use of gas generation units in the energy mix until such time as lower emission coal is possible. Additionally, high carbon prices are required to develop the innovation in CCS field, restricting coal generation and further benefitting gas units due to significantly lower emissions per unit of electricity produced [72].

Natural gas combined cycle generation does not emit any $SO_x$ due to pre combustion processing. The level of $CO_2$ emitted is greatly reduced to 340–380 kg $CO_2$ per MW h of electricity produced [67]. The increased thermal efficiency of gas plant also contributes to the decrease in emissions. As for nuclear generation, severe environmental concerns due to safety as a result of waste storage and the events in Fukushima ensure that this option is not overly popular despite $CO_2$ emissions of 22.8 t-$CO_2$/GW h [73].

Emissions reduction targets are a key facet of EU legislation and are the driver for increased renewable energy penetration. Gas generation has been shown to be technically capable in assisting renewable energy integration into the power system and is the "least worst" fuel type from an emissions production perspective, cementing its status as the bridging fuel to a low carbon future. Technical and environmental concerns satisfy system operators and EU legislators, but economic concerns are of key importance to the private profit seeking entities who own and operate gas generation in the current liberalised electricity markets. It is these economic concerns that ultimately dictate the level of bridging capability gas generators can deliver.

**Table 1**
Emissions production [5].

| Fuel | Emissions (tonnes $CO_2$/GW h electricity generated) | | |
|---|---|---|---|
| | 2012 | 2013 | 2014 |
| **Gas** | 386 | 380 | 365 |
| **Coal** | 906 | 906 | 903 |

## 4. Economic impact

A competitive, reliable electricity market regardless of design and bidding arrangements will result in market participants bidding their short run marginal costs (SRMC) [74]. Fuel costs are a significant component of the cost to produce a unit of electricity. Therefore, power system flexibility concerns aside, the attractiveness of gas fired generation as a provider of energy is closely related to the price of the natural gas commodity. Domestic and European policy can penalise fossil fuel generation, but legislative powers do not translate into the global commodity markets. This results in external forces having a direct impact on the power system fuel mix, potentially altering the marginal supply source from gas to coal. However, the policy decisions made at a domestic and European level with respect to carbon taxation and the industrial emissions directive assist in limiting the share of coal in the fuel mix in favour of the less polluting gas generators. This section describes the operation of the GB gas market, gas price discovery and illustrates the supply and demand landscape. The economic challenges for gas generators are also described.

### *4.1. Operation of the GB gas market*

Throughout this section, reference to the GB gas market (covering England, Scotland and Wales) means trades carried out at the National Balancing Point (NBP). The NBP is a virtual trading hub where all gas is supplied to and taken from. Due to the disproportionate relationship between entry and exit points in the National Transmission System (NTS) and an effort to standardise trading, the NBP corresponds to all points inside the NTS, with transport costs charged separately [75]. Both Northern Ireland and the Republic of Ireland are outside the boundary of the NBP. Due to the heavy import reliance on GB, pricing and trends in the GB market are directly applicable to both Northern Ireland and the Republic of Ireland. Virtual reverse flow from the Irish system further couples both gas markets as this enables indigenous production to be sold in the highly liquid NBP.

There are two main methods of buying and selling gas in the GB gas market, over the counter and futures markets. The largest method of trading is performed via Over the counter (OTC) trades. Physical delivery of the contracted amount of gas occurs and it is via this method that all spot trading[1] is carried out. It is also possible to award forward contracts which establish physical gas delivery in the future. These can be a month ahead up to several years ahead in length. Both types of OTC trades are standardised, bilateral and not regulated [76].

[1] The spot market refers to actual, immediate delivery of a commodity.

Spot market trades and liquidity in this market are not only advantageous for shippers to manage changing positions, but are important for gas system security. One of the most important concerns during system operation is that the network remains in a balanced state, i.e. all gas demand is fully satisfied and operation is within safety limits. Within the GB system, network balancing is carried out by the TSO, National Grid. If the system is out of balance, National Grid will enter the spot market and either buy or sell gas in order to regain system balance.

Trading in the futures market involves agreeing to purchase gas at a set price at some time in the future. This differs from a forward contract since it is traded on an exchange and not done OTC. The futures market rarely results in actual delivery of natural gas due to many market participants entering from the financial world and using the commodities markets as part of a broad investment portfolio. Trading in the futures market can give insight into the global geopolitical situation affecting gas supply and demand dynamics. The record for largest amount of contracts traded in a day was set on March 4th, 2014 at 118,145 (3.65 billion therms) [77]. The increased futures market activity was due to political instability experienced in Ukraine putting pressure on market participants to minimise their exposure to high, volatile prices in the spot market.

### 4.2. Gas market pricing

The GB spot market is allowed to find its own price, directly related to supply and demand. This can only occur in fully liberalised, mature, highly liquid markets. A measure of this liquidity and maturity is the churn ratio, which defines the relationship between traded volume and actual consumption. Fig. 4 shows that the GB NBP is by far the most liquid market hub in Europe. A churn ratio of 15 and above demonstrates a well-functioning market [78]. As a result, the spot price of gas is generally lower than the prices paid in forward contracts [79] due to decreased demand and inflexible take or pay clauses [80]. Prior to GB market liberalisation, contract gas prices were indexed to oil and contained take or pay clauses. This required the buyer to commit to purchasing a set amount of gas over a set time frame no matter if they had demand to satisfy the contracted amount. If the gas was not used (taken), payment for the entire contract was required at pre agreed penalty prices, resulting in forced sale on the spot market [76].

The ability of market forces to dictate the price of gas is a direct result of a liberalised and liquid market. The NBP is the reference price for spot market gas in Europe, due to the high liquidity and high liberalisation exhibited. This benchmarking is achievable due to the interconnection of the UK system with the continent via the Zeebrugge and Interconnector UK pipeline.

The discrepancy between oil indexed long term contracts and spot market prices has forced adoption of spot market prices in the long term gas price. Previously, the long term contracts were based entirely on oil price. This pricing formula is moving to include spot price considerations and renegotiation when set price divergence is reached [75]. By moving towards gas on gas competition, risk exposure to oil prices would be reduced for gas users. However, it has been proven by [81] that in the period between liberalisation of the UK market and opening of the Zeebrugge interconnector, gas prices were still coupled with oil prices and continue to exhibit this characteristic due to LTC contract influence in Europe. Results discussed in [82] also support the long term coupling of gas to oil prices, with market shocks evening out over time.

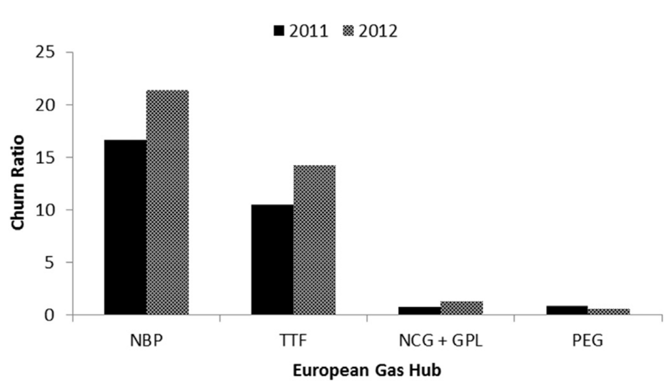


**Fig. 4.** European gas hub churn ratios [74].

With the onset of increased Liquefied Natural Gas (LNG) entering the global gas market as a result of American shale gas, it is predicted that the price difference in LTC and market based methods will increase due to oversupply of natural gas. However, specific analysis on this topic has been carried out in [80]. It is predicted that the gas market will experience a supply shock, but over time the price differential of spot market gas will reach the historical average. This is mainly due to the fact that end consumers are reliant on energy and are not generally worried about the source of this energy. However, the impact of shale gas could be larger than anticipated if gas demand remains sluggish, and this could force another round of LTC renegotiation in the near future. A detailed analysis in the relationship between UK OTC trades and the Average German Import Price (which reflects LTC pricing) taking into consideration high UK LNG and pipeline imports was documented in [83]. It was found that the relationship diminished over time, but further work is required when the data set increases.

In order to assist the role gas generation has in a market with high renewable penetration, increased gas on gas pricing would be advantageous. The positive effects of this trend, with respect to coal generation, would be further compounded in the UK due to the high liquidity exhibited in the NBP market. The highly successful NBP market continues to enable gas generation to remain high in the merit order in support of wind power. This then has a direct effect on the fuel mix used in the SEM, due to the high import reliance Ireland places on the GB gas market.

### 4.3. Supply

The top five natural gas producing countries by volume in 2014 is shown in Table 2. The US is the leader in supply of natural gas. This is attributed to the very recent discovery of large shale gas resources, which has completely transformed the energy outlook and import dependency for the US. As a result, it is estimated that the US will shift from being a net gas importer to a net gas exporter as soon as 2018 [85]. The UK, which reported a drop in production of nearly 15%, is expected to maintain this trend of decline in domestic supply according to data from the Department of Energy and Climate Change (DECC) [12]. The decline in production post 2019 is assumed to be 5% annually. This puts further pressure on security of supply and highlights the importance of investment in renewable energy. The future trend of UK domestic production can be seen in Fig. 5 [12].

From a European perspective, the most important natural gas suppliers are Norway and Russia. Norway is the sixth largest supplier

**Table 2**
Top natural gas producers [84].

| Country | Production 2014 (bcm) | Change from 2013 | Share of World Production |
|---|---|---|---|
| **US** | 728.27 | 6.1% | 21.4% |
| **Russian Federation** | 578.73 | −4.3% | 16.7% |
| **Qatar** | 177.23 | 0.4% | 5.1% |
| **Iran** | 172.59 | 5.2% | 5.0% |
| **Canada** | 162.04 | 3.8% | 4.7% |

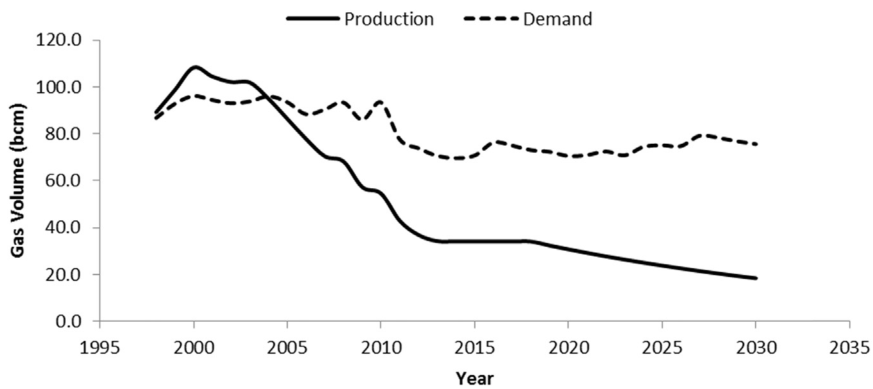


**Fig. 5.** UK natural gas production and demand [12].

of natural gas in the world, but only exports to the EU where it is responsible for 28% of total pipeline imports. This abundance of natural gas, its location in the North Sea and the political stability of Norway result in a relatively low risk trading partner for the UK. In 2012, the UK as the largest gas market in the EU imported 76% of its pipeline natural gas from Norway. Almost all (95%) of Ireland's 5.3 bcm gas demand was imported from the UK, linking all three countries very closely.

Gas demand is not satisfied completely by pipeline imports. The purchase of Liquified Natural Gas (LNG) from countries with abundant resources who are geographically much further away satisfy the residual demand. Iran and Qatar are large players in the LNG supply market. Qatar, due to its location, exports 85% of its natural gas in LNG form. The UK imported 13.3 bcm of LNG from Qatar, which corresponds to 97% of total LNG imports and 27% of total gas imports [85]. The importance of this trading partnership was highlighted when the state owned Qatargas company made a significant investment in the South Hook LNG terminal near Milford Haven [86], and by signing several long term gas supply agreements [87].

As can be seen from Table 3, the geopolitical climate of future supply countries varies extensively, with **former Soviet Union (**FSU) states accounting for the majority of world supply. Current supply routes of natural gas and LNG, with a focus on security of supply relating to geopolitical issues are discussed in [88,89]. Concerns about the possibility of energy shortages and pipeline failures are predicted to increase the demand for LNG, especially in import dependant countries.

Ultimately, the security of supply can never be certain for a net importer of energy. By considering possible bottlenecks and hedging against inherently risky procurement processes, the likelihood of interruption and/or price volatility exposure can be greatly decreased. Geopolitical crises and re-routing of LNG cargo to the highest bidder will always leave natural gas vulnerable in the market place. The increased adoption of wind power not only mitigates climate change, but advances security of supply. Decreased reliance on gas in the future is the only certain hedging strategy against price volatility. However, until such times are reached, a diverse supply chain serves to minimise this price risk.

**Table 3**
Proved natural gas reserves [84].

| Country | Proven Reserves 2014 (tcm) | Share of World Reserves |
|---|---|---|
| **Iran** | 34.02 | 18.2% |
| **Russian Federation** | 32.64 | 17.4% |
| **Qatar** | 24.53 | 13.1% |
| **Turkmenistan** | 17.48 | 9.3% |
| **US** | 9.77 | 5.2% |

### 4.4. Gas demand

Gas demand in power generation is forecasted to change dramatically due to the increase in output from renewable sources and stringent emissions targets in the short to medium term. This is accompanied by significant decrease in non-power sector gas demand due to increasing energy efficiency gains and the drive for the electrification of heat. Fig. 6 shows the gone green scenario projections from [90], where the decrease in power gas demand is clear.

This is in direct contrast to predictions made in the US EIA International Energy Outlook 2013 [91], which estimates power generation gas demand will increase by 1.7% annually from 2020 to 2040. This uncertainty in future demand does not give rise to confidence in infrastructure investment. It is clear thus far that market liberalisation and environmentally oriented policy implementation at EU level has affected the attractiveness of gas as a generation fuel [92]. Uncertainty in the demand metrics can be offset by the historical tendency of policy making bodies to create an energy mix favouring gas.

The increased reliance on renewable generation will no doubt require an increase in the demand for natural gas fired power plant to account for the inherent stochastic nature of renewable energy. This is reflected in future adequacy assessments of the SEM conducted in [93] where conventional generation is responsible for a minimum of 96% of peak demand but only accounts for less than 60% of total energy output. The UK government outlined their gas generation strategy in 2012. This document declares that gas will continue to be a key player in the generation mix well into 2030. Depending on the legislative stance on carbon and the load factors relating to future electricity demand, the need for new gas capacity investment could range between 26 GW and 37 GW in 2030 [94].

The need for optimisation of the gas network and combined gas and electricity market modelling is relatively insular of total demand due to their inherent dependency. Unit commitment and economic dispatch is even more important in the SEM due to tight excess capacity [3]. The increased reliance on gas to smooth the large penetration of wind energy from 2015 onwards requires a more detailed understanding.

### 4.5. Economic challenges for gas considering wind integration

Natural gas fired generation has already been subject to a multitude of challenges due to the facilitation of renewable energy. The most pressing is the distinct decrease in revenue associated with wind energy penetration [95]. Due to the position of gas generators in the merit order and their dispatch flexibility, these units are the sacrificial fuel type. It has been shown that gas generation is the sacrificial fossil fuel in power systems with high penetrations of wind power, getting pushed out of the merit order by the zero SRMC renewable generators [54]. If a generator is not in merit and does not get dispatched, then the volume of energy sold into the market and thus the payment for this energy

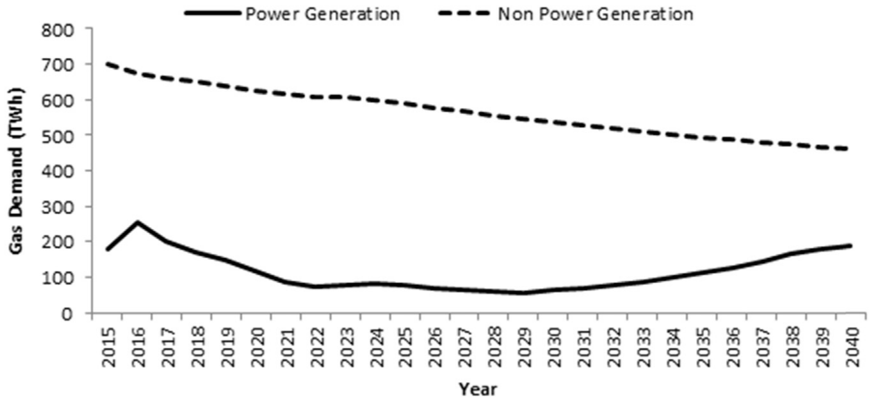


**Fig. 6.** Gas demand projections [90].

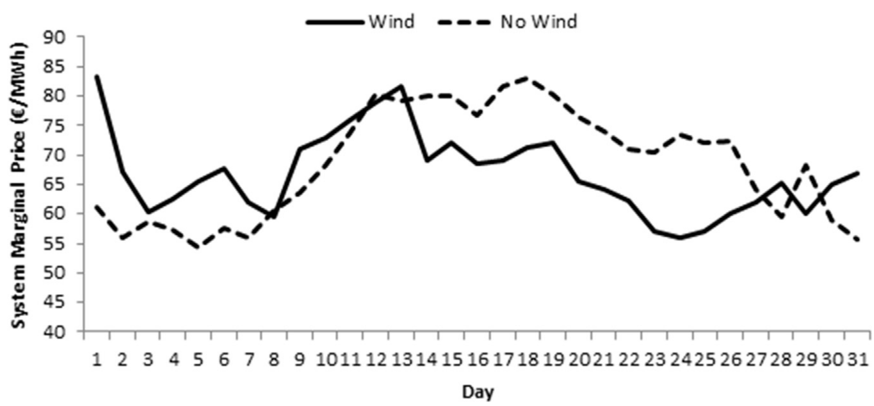


**Fig. 7.** Reduction in power price due to wind power [89].

decreases dramatically. This is a concern not only for owners of gas generators, but also system operators since liberalisation results in profit seeking entities building new capacity to assure system reliability. The volume risk placed on gas generators reduces the incentive for investing in gas plant as shown in [95], and therefore negatively impacts system reliability. Despite the preference for the EU in their target electricity model to operate as an energy only market, several countries are adopting capacity and ancillary service markets to maintain reliability and provide the necessary flexibility not currently rewarded by existing market arrangements. These have been termed the missing money and missing market problems respectively [96]. Examples of these capacity and ancillary services markets are present in the BETTA and SEM systems. Under electricity market reform in GB, a capacity auction was designed and implemented to ensure future power system reliability concerns were met [97]. By offering long term fixed capacity revenue to conventional plant the risk to profitability due to decreasing load factors in the energy market is minimised [98]. Capacity remuneration mechanisms like the auction offered in GB have been shown to increase system adequacy and decrease total generation costs [99]. However, it has been noted that those who design the capacity procurement process over value loss of load events leading to over procurement of capacity, increasing the missing money problem [96].

With variations on both the supply and demand sides of electricity markets, access to flexibility is integral to power system security in short term operation and is an increasingly important commodity for system operators dealing with high renewable energy penetrations [100]. It has been shown that system size is a key factor in the level of flexibility required, with large systems requiring significantly less flexibility at high penetrations of wind power [45]. The SEM is a relatively small system and has large thermal generation unit size compared to peak demand [96], therefore flexibility is of high importance. The SEM system operator EirGrid has identified the need to remunerate existing generation units in the provision of this flexibility and has introduced new system services to assist integration of renewable energy. Inertial response, fast frequency response and ramping products over one, three and eight hours are the additions to the existing reserve and reactive power products [101]. These products enable flexible generators, which in the SEM are mainly gas fired units, to be rewarded for their contribution to system security which otherwise would not be recognised. Additionally, generators providing these services will be able to recover some of the lost energy payments due to the increasing penetration of wind power.

It is clear that generators such as gas units are facing a radically new operational profile. Declining energy payments send negative signals for investment in these types of plant [102]. Utilising the same back cast methodology employed for Fig. 6, the presence of wind on the SEM in 2011 caused a decrease in price, decreasing the energy market revenue available to gas generators due to the shift in merit order. This decrease in power price is shown in Fig. 7.

However, from a system operators perceptive, the contribution to system security gas units offer is becoming increasingly important in order to realise a sustainable future power system. Electricity markets are in turn remunerating this contribution outside of the energy market where wind is exerting merit order superiority. The role of gas as a bridging fuel to this new renewable power system is therefore strengthened from an economic perspective with regards to reducing the missing money and missing market problem.

However, the ability of wind to provide spinning reserve is a growing research area. Previously, wind has been thought of as "negative load" (i.e. unable to be controlled and used for system services such as reserve and voltage regulation) in system operation methodologies [103]. It has been proven that wind power has the ability to participate in system balancing markets, providing up and down regulation [104]. Furthermore, reserve from wind has been shown to deliver a reduction in both wind curtailment and thermal unit ramping [105]. This results in the possibility of wind power not only reducing gas generation revenues in the energy markets, but also in the key system services market whilst minimising the cost of curtailment.

Another key technology minimising wind power variability, specifically in times of wind curtailment, is energy storage [106]. The ability to harness wind power at times of low demand or system stability limits (which is the case in Ireland due to the TSO's SNSP limit) for use at more appropriate times presents a challenge to gas. This is due to the fact that wind can be thought of as "always on", further displacing demand that would otherwise be fulfilled by gas generation. A study on the SEM showed that pumped storage would not be attractive in the Irish system until wind reached a penetration of 50%, with storage having the ability to replace 500 MW of conventional gas plant [107]. However, innovative asset owners have the potential to utilise storage technology to remove the negative operational profiles places on their gas units. In [108] a battery storage device was coupled to a gas generator, enabling a lower minimum stable generation level off peak and less peak time ramping in pursuit of a profit maximisation strategy by the merchant operator. Grid scale electricity storage is still in its infancy, but significant progress is being made in the field with a 100 MW battery device set to be operational in Northern Ireland by 2017 [109]. Ultimately, wide scale adoption of storage will significantly increase the ability of renewable energy to serve both energy demand and provide system services to system operators. In the short to medium term, however, storage technology is addressing its own missing market difficulties regarding the value the technology brings to power system operation [110,111]. Additionally, storage facilities continue to face a cost competitiveness barrier to wide scale adoption [112]. This barrier increases during times of low gas prices, where it has been shown that the attractiveness of energy storage decreases in both energy and system service markets [113].

External to the power system challenges discussed above, the volatility of gas prices is uncontrollable by a generation asset owner. Geopolitical events, such as the Russian and Ukrainian crisis (and the two week gas pipeline shut down in 2009) have a large effect on the market. A post event analysis of gas prices and pipeline flows was conducted in [114]. It was found that despite a serious disruption to supply, the majority of Western Europe were unaffected and the market reacted in the optimal manner. Analysis in [115] showed that the reasons for the ability of Western Europe to cope with this market shock was due to cross border market integration, high levels of storage and diverse supply portfolios. However, such events highlight the potential for geopolitical supply shortages, reducing the ability of gas fired generation to participate in the market and support renewable energy penetration.

Gas generation, although an integral part of the energy mix to support the adoption of renewables, faces a multitude of challenges both internal and external to the power system. Wind energy adoption isolates the UK and Ireland from external events uncontrollable by domestic policy. Increasing capacity of stochastic energy sources brings several unknowns to the power system. With increasing research and understanding, these unknowns can be mitigated, pathing the way for a vast reduction in power system emissions and greater security of energy supply. Until the current technical challenges regarding stochastic energy sources and storage are met, gas fired generation will continue to face operational challenges due to ramping and decreased capacity factors, but will nevertheless remain and integral part of the power system as a generator and guarantor of system stability.

## 5. Conclusion

This paper provides a comprehensive overview of the gas generation operating environment with regards to supporting renewable generation in the SEM and BETTA power markets. It is evident that the future energy mix will not resemble the fossil fuel dominated variant characteristic of previous decades. This paper has shown how European level policy decisions impact the technical operation of power systems and gas generating units in addition to the economic challenges facing gas generation in its support of renewable energy penetration. Policy makers and energy market regulators have the greatest ability to shape the future energy mix as proven with the 2020 energy targets. As a result, stochastic sources of renewable energy now dictate scheduling decisions in the power system. The integration of renewable energy into the power system from a technical perspective is well understood, however, the impacts of such decisions are relatively poorly understood from a gas infrastructure perspective. The importance of combined planning for gas and power has been realised due to the reliance of power system security on gas infrastructure. This is especially important for all power systems with high penetrations of gas generation and renewable energy, as evidenced by the SEM and BETTA.

However, the main risk from renewable energy integration is moving from a technical issue to an economic one driven chiefly by the new operating profile of gas generators. Decreasing capacity factors of gas plant and their increasingly variable dispatch profile as a result of renewable energy is decreasing the incentive to invest in such flexibility. This source of flexibility is an increasingly important commodity for power system operation as other sources of flexibility such as energy storage have yet to realise full commercial operation. It is recommended that power market design adequately rewards units for the valuable flexibility required to continually integrate renewable energy into the system. This change is required in order to bolster investor confidence in gas as a bridging fuel. Without this confidence, the required investment in critical infrastructure to mitigate climate change will not be implemented. Further investigation of the required infrastructure, the operational stresses on plant and the effects of carbon taxation are three starting points for further research. Central to these areas is the interaction between gas, wind and the power system. Integrated studies in these areas will help to plot the optimal energy policy and technical direction in pursuit of sustainability centred power systems. However, the bridging capability of natural gas in the transition period to a clean energy future must not be undervalued.

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