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An integrated gas and electricity model of the EU energy system to examine supply interruptions

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HIGHLIGHTS

- High temporal resolution analysis of a 28 country European power & gas systems.
- Identifies concerns for weak points and "bottlenecks" in the network.
- Publically available power and gas model of Europe.
- Impacts of several gas supply interruption scenarios on the power system described.

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ABSTRACT

The EU dependence on imported gas is increasing, rising to 67% in the year 2014 with 30% of total gas consumption used for electricity generation that year. With such a dependence on imported gas, gas supply interruptions can have significant impacts on the EU energy system and economy. This points to the need for integrated electricity and gas modelling tools to fully explore the potential impacts of gas supply interruptions. This paper builds and applies a detailed publically available integrated electricity and gas model for the EU-28. We use this model to examine a number of hypothetical scenarios where gas supply routes are interrupted for yearly periods and the impacts on power system operation and gas flow in Europe observed. Model results show that interruption of Russian gas supply to the EU could lead to a rise in average gas prices of 28% and 12% in electricity prices. When supply from North Africa was removed all Southern European states were affected heavily, Spain in particular saw large increases of 30% in gas prices with a corresponding rise of 18% in electricity prices as a result. In addition to supply interruptions, all gas storages were removed from the model to examine the importance of gas storage infrastructure. This resulted in an average increase in power prices of 6% across Europe. These additional insights offer an increased understanding of the interplay between the gas and power systems and identify challenges which may arise when seeking to understand energy systems as a whole.

1. Introduction

The current global energy system is almost entirely dependent on hydrocarbons [5,33,56]. In the coming decades, global energy markets will face many challenges, such as emission restrictions, infrastructure restructuring and supporting renewable technologies in addition to maintaining reliability and security of supply [25]. The planned deployment of renewable electricity generation represents a significant change in electricity system operation. The impact of variable renewables on the electrical power system is well documented and researched [8,14,34,53,54]. The output from variable renewables such as wind, wave, and solar PV are variable with associated uncertainty in forecasting. While variability and uncertainty in electricity systems are not a recent phenomenon, their impact on the associated gas infrastructure is generally not well examined. The inherent variability of a renewable resource like wind requires a power system to be sufficiently flexible to cope with the changes in production. Both Open Cycle and Closed Cycle gas plants (CCGT and OCGT) have to cycle on and off and may have to ramp sharply over various timescales to accommodate this variability [32]. Depending on the specific power system portfolio this variability can be passed to the gas system and its associated infrastructure i.e. electric-driven compressors.

It is important to understand and quantify these associated impacts on the gas system in order to assess its resilience. Most gas infrastructure was built and deployed in times with low levels of variable renewables and will need to be expanded to deal with

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large temporal fluctuations in demand/generation [26]. While this has issue has been raised in the existing literature [16,40], the model presented here aims to analysis the impact of supply shortages on a large scale system with high levels of renewables. The work presented here provides a platform to analyse the interaction between gas and power across the EU for the year 2030 under a variety of scenarios effecting the gas system. The model has been constructed to highlight the interplay between the power and gas systems and examine the added value of such an approach. The model determines gas and power prices endogenously as well as the least cost generation and production mix to meet exogenous power and gas demands. The model developed is for the snapshot year of 2030 and results are not intended to be forecasts or predictions but instead are used to gauge the value of an integrated approach.

Following a summary of the relevant literature on this topic the methodology used is detailed, as well as the key findings from various scenarios that were applied to the model. In all scenarios, only the gas portion of the model was altered and the impact on the power sector studied, each variation highlighting the cascading effect that the operation of the gas network has on the power system in terms of cost, fuel mix, and operational flexibility.

The model, associated data and select hourly results have been made freely available for academic research and are online at link https://www.dropbox.com/sh/sfbc2tde6xi3cwe/AAA5KSTAcmGm-TIvCHT2cCoTQa?dl=0.

2. Existing literature

Interest in integrated modelling has been growing over time with the challenges associated with a non-integrated approach being highlighted in literature [37,38]. From a research perspective, the interplay between the power and gas systems is important so as to understand how operational limitations on one system affects the other. Natural gas and electricity systems have certain similarities in terms of their topology, as both systems have transmission and distribution networks. Both networks are subject to physical laws that can limit the energy transmitted (electrical current or gas flows) and cause losses (electrical losses or pressure decreases). The systems, however, are very different in term of timeframes; power systems dynamics after a fault can travel much faster through the electrical system while disturbances are generally much slower in the gas system. The ability to store gas in linepack or conventional gas storages is also a major difference and in general, the gas system is thought to be a more ‘forgiving’ system in terms of balancing.

The paper addresses a gap in the literature on the issue of integrated gas and electricity modelling at EU level and presents an applied methodology and model to examine natural gas supply interruptions and consequential impact on electricity impacts. Previous EU wide studies such as [30] use probabilistic Monte Carlo techniques to examine supply interruption from North Africa but do not examine the power system or associated impact on electricity prices. Similarly at EU wide level [51], examine the impact of disruption scenarios of Russian natural gas to Europe however the study is limited to the gas system impacts. Integrated power and gas models exist across the literature that look at different aspects of the European energy system. Abrell and Weigt [1] present an integrated mixed complementarity problem (MCP) model of the European region in 2005. This model is used to show how upstream loss of gas supply from Russia could propagate throughout Europe leading to higher electricity prices. Indeed the loss of supply from Russia has become a highly topical issue with many articles discussing its likelihood as well as its potential impact [29,36,46]. In a detailed report by Dickel et al. [18] an overview of the problem is presented with projections for those countries highly dependent on Russian gas, mainly Central & Eastern Europe, becoming even more so. This is compounded when considering projections for indigenous European supply [18,27].

From a European perspective, the importance of the gas system to the stability of the power system is a topic found frequently in literature [1,4,42]. For example, in [39,40] a least cost optimisation model of the European power and gas networks was built using PLEXOS. The PLEXOS software package allows for both gas and power objects within its framework. The model was then used to analyse the robustness of the European system for the base year 2013, with that system being stressed by an increasing share of variable renewables. Similarly, Ahern et al. [2] use another PLEXOS model to investigate the possible role of power to gas systems in the context of Ireland.

On an individual member state level, there are several models which consider in greater analytical detail the interplay between the gas & power networks. While the more regional issues of security of supply mentioned are still important, these models instead look at a more local picture with the specific topologies and characteristics dominating the analysis. A model of the UK power and gas system developed and presented by Chaudry et al. [7] considers the local importance of gas storages and their usage to maintain system pressure. The findings point to certain gas generation plants that depend on the injection from stores to operate. This demonstrates the importance of storages in the context of whole system stability and local linepack management. A similar approach was taken by Devlin et al. to investigate the impact of stochastic renewables on the Irish power and gas system [16]. Here the Irish Single Electricity Market (SEM) was modelled with a detailed representation of the gas network i.e. regional transmission lines and real geographic placement of power stations. Again, this methodology allows for analysis of localized linepack management under normal and stressed operation and allowed Devlin et al. to demonstrate the high dependency of the power system on gas supply to maintain prices.

This aforementioned model by Chaudry et al. is adapted [48] to determine the impact of large-scale renewables on the UK power system. As the UK government attempts to generate more of its electricity from renewable sources, the contribution of wind, both onshore and offshore, is going to increase if the mandatory target of 31% electricity from renewables [13] is to be met (see [12]. With both pressure and linepack being considered, this model was well suited to analysing this problem and indeed showed how curtailment of CCGT plants could occur due to lack of sufficient pressure in certain lines due to external stresses. In an extension of their previous work Devlin et al. include the UK and develop a larger context for the Irish systems findings [15]. The integrated power and gas model of the UK and Ireland presented by Devlin et al. points to an increase of 40% to the short run costs of generators during periods of congestion and further demonstrated the interplay of gas and power systems by showing that gas storages can mitigate the total generation cost increases by 14%.

A number of models reviewed have been developed for specific purposes such as wheeling charges. In [41] different approaches were used to include wheeling charges in an integrated gas and electricity model of Brazil. This detailed study examines options for modelling wheeling charges based on data availability and shows the impact each has when looking at the best location of a new gas generator. In [52] a model for the USA is introduced where different technical, economic and policy scenarios are presented. One of the case studies undertaken using the proposed model is the impact of gas prices on CCGT competitiveness. A result of the sensitivity analysis carried out was the susceptibility of CCGT plants to gas price volatility, even with such high efficiency. In [35] similar conclusions are drawn when examining the Chinese systems.