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A holistic framework for the study of interdependence between electricity and gas sectors

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ABSTRACT

The increasing global use of natural gas for power generation has begun a period of interdependence between two important energy industries. Understanding of the extended gas-to-power supply chain is important for power and gas system operators, integrated utilities, regulators, and government bodies responsible for overall energy policy. This paper seeks to align the study of gas and power industries by providing a holistic framework for the thorough identification and discussion of power and gas sector structure, infrastructure, market, and regulatory drivers. Additionally, it offers a simulation model as an example of applying the analytical framework to study gas and power interdependence in the UK.

1. Introduction

In the last two decades, there has been important convergence between the previously parallel electricity and natural gas industries in a number of countries – the key connector between the industries being the use of gas-fired generators for power generation. The amount of natural gas used for power generation globally has increased steadily since 1973, from 212 to 1167 Mtoe in 2012 [16]. This represents 21.8% and 41.5% of world gas production, respectively. As the cleanest-burning fossil fuel, natural gas is often portrayed as the transition fuel that will bridge the fossil fuels dominated present to a future powered by renewable forms of energy. Also, natural gas-fired generators have favourable modular investment costs and are flexible to operate. Therefore, the global volume of natural gas used is expected to increase in the mid-term, and its role in power generation is expected to persist [18]. As this convergence continues, the power industry effectively becomes the downstream industry of the natural gas sector, and coordination across this extended supply chain becomes important [42]. Hence, it becomes important to understand the new risks to which the power sector is exposed via its use of natural gas, and the challenges that the gas sector needs to overcome in supplying the extremely dynamic power industry.

The extended gas-to-power supply chain is a complex socio-technical system with physical, commercial, regulatory, and policy dimensions. The behaviour of the system is dependent on the interaction of industry agents active throughout the supply chain, across different dimensions. Given this, the question is how to systematically think about such a complex system in order to explain, anticipate, or even guide its behaviour?

The study of interdependence between electricity and gas sectors is of interest to, power and gas system operators or integrated utilities, regulators, and government bodies responsible for overall energy policy. A better understanding of such interdependencies will allow these stakeholders to evaluate the effect of technical, commercial, and regulatory decisions on the short-term and long-term performance of the joint power and gas system.

The contribution of this paper is two folded. First, it provides a holistic framework which allows for the thorough identification and discussion of multidimensional drivers for dynamic behaviour in the gas-to-power supply chain, surveying industry structure, infrastructure, market, and regulatory drivers. The analytical framework proposed is based on the established Structure–Conduct–Performance (SCP) paradigm commonly used in industrial organization. In order to account for the dynamic nature of

List of abbreviation: SCP, Structure-conduct-performance; SCPR, Structure-conduct-performance-regulation; T&D, Transmission & distribution; PHES, Pumped hydro energy storage; LNG, Liquefied natural gas; EU-ETS, EU emission trading scheme; AC, Alternating current; DC, Direct current; FACT, Flexible alternating current transmission system.

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industry agents' behaviour and its effects on the gas-to-power supply chain, highlighting the effect of informational and material feedback, accumulation, and delays, the framework is integrated with principles of System Dynamics. More specifically, the role of governmental and industrial (self) regulation and the difference between investment decisions and operational decisions, are both highlighted. Secondly, this paper provides an example for the application of the holistic framework proposed to a specific case: gas and power interdependence in the UK.

With the exception of a few (for example, see [43]), most previous studies in this area have focused on the physical interdependency such as the effect of the network congestion, outage, or fuel supply in one industry (e.g., gas) on the other industry (see [44,1]). We argue that the current performance and future evolution of the extended gas-to-power supply chain is dependent on drivers that span physical, commercial, and regulatory dimensions. Therefore, research on gas and power interdependence should be aware of the larger context in which specific interdependencies, physical or otherwise, unfold. The holistic framework that is introduced in this paper can be used to guide the development of studies with more narrow scope; it also provides a systematic way of relating gas and power sector issues.

In section two, the intellectual roots of the SCPR (Structure–Conduct–Performance–Regulation) analytical framework and the questions it seeks to address are presented. In section three, the components of this framework, as it is applied to the gas-to-power supply chain, is narrated in four parts. Section four illustrates a possible use of the framework, by presenting a simulation model developed based on the dynamic principles outlined by the framework. Section four provides concluding remarks.

2. Analytical framework for gas-to-power interdependence

The inspiration for the proposed framework is based on: (i) the Structure–Conduct–Performance (SCP) paradigm, a foundation of industrial organization theory, and (ii) System Dynamics, an interdisciplinary approach for analysing and designing decision-making principles that seeks to enhance the understanding of complex dynamic systems.

The SCP paradigm postulates that causal relationships exist between the structure of a market, the conduct of firms in that market, and economic performance; it has been used to provide the theoretical justification for competition policy [10] (see Fig. 1). The SCP approach argues that industry performance is determined by the conduct of firms, which is in turn determined by the structural characteristics of the market. Revisions to the theory suggest that industry structure is not purely exogenously determined [10]. Firms' conduct can also affect industry structure through mergers or innovation (changing product and technology characteristics), among other actions. Moreover, firms may adapt their behaviour to alter their performance.

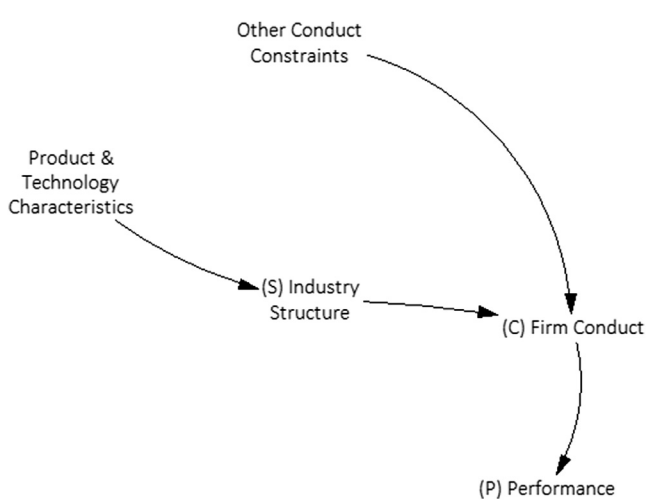

Fig. 1. Traditional Structure–Conduct–Performance paradigm.

On the other hand, the central principle of System Dynamics theory is the identification of endogenous feedback loops, postulating that real systems are rarely sequential and open-loop [37]. It focuses on how systems react to current situation, making decisions which then define future situations. It also focuses on the effect of delay and accumulation of informational and physical flows.

Combining the two views, the System Dynamics-inspired framework proposed in this paper for the identification of gas and power sector interdependence amends the traditional SCP paradigm in the following ways (see Fig. 2):

1. Differentiating industry agent conduct into two types: long-term investment/retirement decisions related to the accumulation of infrastructure (stock-based) and short-term decisions related to the use of installed infrastructure (flow-based),
2. Recognizing that long-term decisions influence short-term decisions: use of infrastructure cannot exceed the constraint of the infrastructure capacity in place. In other words, energy flowing through the infrastructure is limited by the infrastructure capacity available – a stock variable which changes, with a delay, after investment decisions have been made;
3. Recognizing the dynamic nature of all elements in the original SCP paradigm: the effects of industry and government regulation (feedback) are taken into account.
   a. Industry agents regulate their own conduct and structure, making decisions (among others) to invest or to merge, in order to fulfil their organizational objectives;
   b. The government constantly interacts with the conduct and, at times, the structure of industry, based on its evaluation of industry performance, in order to fulfil its own evolving energy agenda.

These amendments lead to an extension of SCP framework which we term as SCPR (Structure-Conduct-Performance-Regulation). The new framework (SCPR) is applicable to the gas-to-power supply chain, given its heavy dependence on infrastructure, the important lead time required in the setting up and retirement of infrastructure, and the increasingly complex regulatory measures in place in countries with developed mature gas and electricity industries. The potential gas and power sector interdependencies that this framework aims to elucidate are:

- Structural: To what extent does the ownership/operational control of the gas and power sectors experience overlap across different segments? And what could be the implications of any such overlap on the investment and operational decisions in the sector?
- Infrastructure: What is the state of the gas-to-power supply chain infrastructure? What is the state of the gas and power demand infrastructure? What could be the potential implications for the absolute and the relative use of gas and power, or on the substitution between gas and power?
- Operational (administrative or market): In the case that gas-to-power flow is important, what is its consequence on gas balancing? Is the existing gas sector coordination mechanism adequate to handle it?
- Regulatory: How does the government's energy policy relate to the gas and power sectors? Is it driven by power sector goals, by