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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.

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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

Fig. 2. Proposed amendments to the traditional SCP paradigm.

gas sector goals, or by a mix of the two? How are the government's regulatory measures in gas and power affecting the industry agents? What implications could they have on sector planning and short-term operations?

3. Framework presentation

The presentation of the SCPR framework is outlined in Fig. 3. A stylized energy balance diagram is used to illustrate the energy supply chain segments to which this framework is applied (see Fig. 4). The blocks in the extended supply chain diagrams represent the infrastructure that is required to enable the flow of energy from the supply-end to the demand-end. It can be seen from Fig. 4 that both industries (gas and power) are capital intensive and dependent upon transmission and distribution networks to bridge supply with demand.

Fig. 3. Proposed SCPR framework outline.

3.1. Structure archetypes

A structure archetype, akin to Platonic ideals, is an idealized representation of the two divergent trends in the organization of gas and power supply chain ownerships: complete centralization and complete decentralization. These serve the purpose of anchoring the spectrum of possible structures that might exist in particular countries, rather than representing the most common models. As a matter of fact, a structure that does exist in a particular country is more likely to be a hybrid of both centralized and decentralized archetypes.

3.1.1. Complete centralization

In this archetype, state-owner vertically integrated companies/utilities are the owners of all infrastructure (apart from that associated with energy consumption), and act to advance the interest of the national government (see Fig. 5). Due to their co-occurrence, the production of natural gas and oil are often tied, as is the ownership of their production assets – in the form of a national petroleum company which controls all upstream gas production and export. The downstream processing and distribution of natural gas, once it has been produced, is handled by a separate state-owned utility. Similarly, a vertically integrated utility for the power sector is in control of its upstream generation assets and all network infrastructure.

Each integrated company/utility is the sole owner of all supply assets within its scope of control; investment in each segment is determined on the basis of an integrated resources plan for all of its holdings. The upstream petroleum company is responsible for the co-planning of (oil and) gas production and exports; the downstream gas utility is responsible for the co-planning of gas import, storage, and distribution; and the integrated power utility is responsible for the co-planning of generation and network expansion.

3.1.2. Complete decentralization

In this archetype, the ownership of the particular segments of the supply chain are divided and this division is mandated by the national legislation (see Fig. 6).

All non-network segments including gas production, import/

Fig. 4. An energy balance-based view of the gas-to-power supply chain.

Fig. 5. Centralized archetype for the gas-to-power supply chain.

export, gas storage, and power generation have multiple owner participants. Competition in these segments is possible; it is adopted to improve the performance of industry agents active in these segments. Private ownership in the competitive segments is more likely, even encouraged by liberalization legislations, but it is not mandatory because public ownership does not necessarily harm competition.

On the other hand, power and gas networks (transmission and distribution, or T&D) are owned by regulated monopolies (one national monopoly or multiple regional monopolies), due to their natural monopoly properties. The ownership of non-competitive segments is unbundled from the other segments of the supply chain to limit the reach of monopoly power.

The coordination of long-term infrastructure between the unbundled segments is achieved mainly through market-based signals, chiefly as price movements. New supply-chain participants who do not own any infrastructure assets – gas shippers and power/gas suppliers, who arrange for the transportation of gas from producers to retailers and mediate between the supply chain and the end-users, respectively – emerge to facilitate coordination across segments. The varied ownership across the supply chain means that the considerations for investment in each segment are also varied, as documented in the segment-by-segment discussion below.

3.1.3. *Between the archetypes*

In the early days of the power and gas industries, the structure of the supply was much closer to the fully centralized archetype. Since the 1990s, a number of 'push' and 'pull' factors driving the developing world towards power sector privatization and

Fig. 6. Decentralized archetype for the gas-to-power supply chain.

liberalization have been identified [35]. Among developed countries, the EU directives 2009/72/EC for power and 2003/55/EC for gas have set the legal framework for the liberalization of these sectors in the entire European Union. However, due to the complexity of the restructuring process, making changes to the regulatory regime overseeing the industry's structure is an incremental process and is path dependent: the initial conditions in place in a country matter; different institutional traditions, historical and cultural experiences, and political priorities may all affect the process of liberalization within a particular country [38]. The varying efforts towards liberalization and, by extension, decentralization, have resulted in the manifestation of a wide range of hybrid structures in different countries [3,13].

3.2. Infrastructure investment by segment

This section provides information to be considered when surveying the established gas-to-power supply chain infrastructure in place in a given country. The supply chain is retraced from the downstream, contrasting comparable segments in the power and gas supply chains.

3.2.1. Power and gas consumption devices

Regardless of upstream industry organizational structure, devices which consume electricity and gas are mostly privately owned and are dispersed among companies, households, and other organizations. The owners are responsible for operating their equipment and for making decisions to acquire them (Table 1).

Table 1
Ownership and investment for power and gas consumption devices.

	Power and gas consumption devices
Ownership	Independent owners
Proposal of investment	Independent owners
Approval of investment	N/A
Operation	Independent owners
Investment remuneration scheme	Fulfilment of new needs or cost savings

From the perspective of the owners, the energy consuming devices/installations are acquired to deliver energy services such as heat, power, transport, and light. To estimate the potential for power and gas demand in a country of interest, it is necessary to understand the current and future needs for energy services in the country and to take inventory of the technologies (in the form of devices/installations) that are used or can be used to deliver them.

Table 2 can be used to guide the process to take inventory of the stock of electricity and natural gas consuming devices in a country. Currently, natural gas is capable of directly fulfilling the following energy services: space and process heating, cooling, and transport. In comparison, electricity is capable of directly fulfilling a wider range of energy services: outdoor and indoor lighting, space heating and cooling, process heating and cooling, transport, and stationary power.

The development potential of natural gas and electricity demand in a country can also be gauged using Table 2, in order to evaluate the demand increase associated with technology diffusion (in the case that some energy services listed are not yet fulfilled by devices existing in the country) and to evaluate the demand change associated with technology substitution (as technologies become more efficient and/or less expensive).

An important departure from the private ownership of power and gas consuming devices is the centrally planned collective energy consumption in space heating, seen in the form of the extensive district heating systems that were common in the former Eastern Bloc countries. These have not continued or been developed in post-communist years [5]. District heating and cooling have been regaining popularity as a more efficient path towards the provision of energy services in recent years, in conjunction with the use of combined heat and power technologies; however, its deployment has been generally slow [17].

3.2.2. Power and gas transmission & distribution networks

The flow of natural gas and electricity in pipelines and wires have close physical analogies (Table 3), They allow us to compare the two types of network.

The boundary between transmission and distribution network

Table 2
Energy services fulfilled by power and gas consuming devices.

	Energy service	Natural gas	Electricity	Other energy inputs
Residential	Lighting		Incandescent, halogen lightbulbs, LED, CFL	
	Space heating	NG boiler, gas-driven heat pumps	Resistive heaters, electric heat pumps	Coal, fuel oil, and biomass furnace
	Space cooling	Gas chiller, absorption refrigerator	Electric chiller	
	Stationary power		Various home appliances	
Commercial and Public Services	Lighting		Incandescent, halogen lightbulbs, LED, CFL, sodium vapour lamp	
	Space heating	NG boiler, gas-driven heat pumps	Resistive heaters, electric heat pumps	Coal, fuel oil, and biomass furnace
	Space cooling	Gas chiller, absorption refrigerator	Electric chiller	
	Stationary power		Various office appliances	
Industrial	Process heating	NG boiler	Electric arc furnace	Coal, fuel oil, or biomass furnace
	Process cooling	Gas chiller	Electric chiller	
	Stationary power	Gas-driven compressors	Various manufacturing and processing equipment	
	Non-energy use	Ammonia, methanol, and hydrogen manufacturing facility, electric arc furnace for direct reduction of iron ore	Aluminium smelting and chloralkali process facility[a]	Coke-based reduction of iron ore
Transport		NG vehicles	Electric and hybrid vehicles	Hybrid, fuel cell vehicles, internal combustion engine vehicles

[a] In electrochemical manufacturing processes, electricity (in the form of electrons) should be considered as a reactant instead of as a source of energy, since it cannot be substituted by any other form of energy.

is amorphous. Transmission networks typically have fewer interconnections; they are operated at high pressure/voltage to connect generation/production facilities with load centres. Distribution networks, which have radial configurations, are responsible for distributing gas/electricity to the decentralized consumption devices situated within businesses, households, and industries.

Under the centralized archetype, the power T&D network is solely owned by the vertically integrated utility (see Table 4). The utility is thus responsible for planning new grid investments (given known generation expansion plans and demand growth), building the new facilities, and operating them. The planning of grid expansion is done within a framework of integrated resource planning to minimize the costs of providing electricity while meeting certain reliability criteria [33]. For most integrated utilities, the approval of the national regulator is needed before proceeding with the planned investments; depending on the country, this process can be substantive or mainly formal. Cost recovery for network investment is integrated into the overall electricity tariff, payable by end-users. The gas T&D network is owned and operated similarly.

Network industries are natural monopolies because of their physical characteristics: they have large economies of scale relative to the size of market, thus efficiency is lowered through duplication or multiplication of the power/gas grid [30]. Due to this special characteristic, under the decentralized archetype the network segment is unbundled from the rest of the supply chain, ensuring that the monopoly effect is contained. After unbundling in all transmission and distribution segments other than power transmission, ownership can be dispersed between a number of companies licensed to own and operate the infrastructure. The owners' plans for network expansion need to be approved by the regulator; the value of the investment is recovered via regulated network tariffs, payable by users of the network, that take the investment costs into consideration. The power transmission segment is distinct from other segments in that it requires second-to-second balancing of system parameters (frequency and voltage) due to the physical nature of power flows. The stability of a power grid is only achievable if control of the entire network is placed under a single system operator, licensed by the regulator, who might or might not own part of the transmission network. Natural gas transmission pipelines, on the other hand, only need to be balanced in terms of their pressure, and can be balanced locally by pipeline owners/operators, except for hubs located at the junction of multiple pipelines. Some differences also exist in the regulation of transmission versus distribution networks: due to the number of components involved, investments made by a distribution company cannot be controlled and evaluated to the same extent as transmission investments, which are evaluated on a line-by-line basis. Therefore, a more aggregated evaluation mechanism is used by the regulator to evaluate the adequacy of distribution investments [12].

In the case that ownership of the supply chain is decentralized, the model in Table 4 is only one among many possible regulatory models for the transmission and distribution segments. It can be more centralized, having the system operator (rather than independent owners) propose investment. Alternatively, investment proposals could be initiated by network users via capacity auctions, or by merchant investors who, once authorized by the regulator, finance a transmission facility and then charge their users according to pre-established contributions, or per actual use of the facility [30].

Table 3
Examples of similar concepts in fluidic and electric flows.

Type	Fluidic	Electric
Quantity	Molecule	Electron
Potential	Pressure	Voltage
Flux	Volumetric flow rate	Current
Flux density	Velocity	Current density

3.2.3. Gas and power storage facilities

Any energy storage option can be described via two parameters: the quantity of energy that can be stored, and the rate at which energy can be stored/withdrawn. Together, they determine the roles that storage facilities play in the wider supply chain. Dedicated storage is the gas and power industries' equivalent of inventory – the stock of energy commodity that buffers imbalances in gas/electricity supply and demand. Facilities that can deliver energy for many days at rated output capacity are commonly used to balance supply–demand imbalance over weeks or months. Facilities that have large output capacity but low storage capacity are used to balance supply–demand imbalance within a day (peak demand shaving).

In practice, natural gas has been stored in solution-mined salt

Table 4
Ownership structures for power and gas network infrastructure.

	Power and gas T&D	Power transmission	All other
	Complete centralization	Complete decentralization	Complete decentralization
Ownership	Integrated utility	Independent owners	Independent owners
Plan of investment	Integrated utility	Owners	Owners
Approval of investment	Various	Independent regulator	Independent regulator
Operation	Integrated utility	Licensed system operator	Owners
Investment remuneration scheme	Integrated into the cost-based tariff approved by regulator	Integrated into the cost-based tariff approved by regulator, with added conditions concerning performance and access	Integrated into the cost-based tariff approved by regulator, with added conditions concerning performance and access

caverns, depleted gas fields, and aquifers. Natural gas can also be stored in the form of liquefied natural gas in containers located above ground – although with much smaller storage capacity than the underground alternatives.

In the power sector the energy commodity that is delivered through the supply chain cannot be directly stored; it must be converted to another form of energy (such as kinetic, potential, or electrostatic). The most common types of technology employed for utility-scale energy storage are: pumped hydro installations, batteries, and flywheels. Others remain at the concept-proving stage [45,9]. An overall comparison of gas and electricity storage options is presented in Table 5.

The global installed natural gas storage capacity is 270 bcm, almost 8% of the world's annual natural gas consumption of 3497 bcm; the estimated total peak output capacity for all of these facilities is 5333 mcm/day, or 56% of the world's average daily natural gas demand [19]. For comparison, pumped hydro energy storage (PHES), currently the only commercially proven large-scale energy storage technology, has 127 GW installed (pumping/generating) capacity, or 0.25% of the world's average daily demand of 51.8 TW [9].

The ownership structure and operation of gas and power storage facilities differ (Table 6). Within the centralized archetype, the requirement for gas storage is planned as part of the overall system design process by the integrated utility, along with other sources of flexibility. The costs of storage investment and operations are embedded within the overall system costs, then passed on to the consumers through regulated tariffs. Within the decentralized archetype, physical storage assets are owned and operated independently, and need to compete for remuneration with other sources of flexibility in the market for flexibility services [24]. The regulation of gas storage facilities bears many similarities to that of the transmission network, frequently requiring third-party access, tariff regulation, and legal/functional unbundling.

Under the centralized archetype, PHES facilities are also developed by power sector integrated utilities to balance system supply and demand, receiving compensation through approved tariffs. Under the decentralized paradigm, they are developed and operated by private generation companies: although PHES provides energy storage capacity, it is still primarily considered as another generation facility; no special regulation is dedicated to it [28]. Therefore, the ownership and operation of PHES is strongly integrated with upstream generation of electricity within the owner's portfolio. This has limited the presence of independent electricity storage owners/operators.

3.2.4. Power interconnectors, gas import and export infrastructure

In terms of their physical characteristics, power interconnectors and gas pipelines for international trade are extremely similar to their domestic counterparts. However, because their operation involves more than one country, issues relating to ownership and operations become more complex than those involving intra-national power interconnectors or gas pipelines. As there is often no supra-national regulatory entity to oversee the operation of interconnectors, differences in the institutional, administrative, and technical features of the energy systems involved need to be resolved.

In the natural gas sector, import/export pipelines that stretch over vast distances, crossing multiple countries (importer, exporter, and transit countries), are rather common, while power interconnectors mainly connect two neighbouring countries. One explanation for this difference is the distributions of energy resources: on average, the self-sufficiency of countries in electricity generation and consumption is higher than that in gas production and consumption, so more countries are capable of exporting electricity than exporting gas, and trades between neighbouring countries are more common than those between distant countries. Also, transporting electricity across long distances remains expensive despite technological development. Furthermore, harmonized national power sector structures and coordinated operation are seen to be of great importance to the development of trade via interconnectors [46].

The ownership structure for the most common power interconnector structure archetypes ('both centralized' and 'both decentralized') is presented in Table 7. In general, it has been observed that, in the electricity sector, most countries value meeting local demand, diversifying supply, and building a local industry that generates revenues and employment as much, or

Table 5
Comparison of natural gas and electricity storage options.

Storage option	Natural gas		Power		
	Sub-surface reservoirs	LNG	Pumped-hydro	Batteries	Flywheels
Energy stored	Natural gas	Liquefied natural gas	Potential energy	Chemical energy	Kinetic energy
Rate of conversion, or injection/withdrawal	Reservoir injectability/deliverability	Liquefaction/regasification capacity	Pumping/generating capacity	Battery chemistry and charging capacity	Charging capacity
Storage limit	Reservoir volume and integrity	LNG tank capacity	Reservoir capacity	Mass of active material	Flywheel geometry and material

Table 6
Ownership structures for power and gas storage facilities.

	Gas storage facilities		Electricity storage facilities	
	Complete centralization	Complete decentralization	Complete centralization	Complete decentralization
Ownership	Integrated utilities	Independent owners	Integrated utilities	Independent owners/generation owners
Proposal of investment	Integrated utilities	Owners	Integrated utilities	Owners
Approval of investment	Various	Independent regulator	Various	Independent regulator
Operation	Integrated utilities	Owners	Integrated utilities	Owners
Investment remuneration scheme	Integrated into the approved tariffs	Tolling, exemption from open access possible	Integrated into the approved tariffs	Integrated upstream

more, than seeking the profits which could be obtained from electricity exports [4]. This has limited the development of interconnections between countries with centralized power sector structures. Recently, a number of interconnector projects among countries with heterogeneous industry structures and historically diverging interests have been proposed (Desertec, Medgrid, North-East Asian Super Grid); the resolution of past and present geopolitical disputes will also become important for the power sector [26].

As international natural gas pipelines connecting gas producers with gas consumers necessarily involve more countries (through transit), and countries with larger institutional differences, than power interconnectors; conflict can arise when profit and rent resulting from the project needs to be shared among many divergent parties. In consequence, except for cases in North America and Western Europe, where the gas industries are similarly structured (decentralized), the rules of the game are clearly defined and accepted, and a history of cooperation exists, cross-border pipelines have a long history of vulnerability to disruption and conflict [21]. The typical ownership structure of pipelines for the two scenarios, 'all decentralized' and 'mixed regimes', are shown in Table 7. It can be seen that in the case of pipelines operating across mixed regimes, there are many different ownership and operatorship arrangements. Compared to the 'all decentralized' scenario, the involvement of national governments and the use of long-term contracts tied to pipelines are common.

LNG terminals, an alternative to gas pipelines, can also be used to transport natural gas from production centres to demand centres. The full equivalent of a pipeline is the ensemble of the liquefaction terminal, LNG tankers, and a reception terminal with liquefied gas storage and regasification plants. The LNG transportation method is a capital intensive supply chain in itself. The economies of scale of the LNG value chain are such that it becomes more economical than a pipeline for transporting gas above distances of 700 miles offshore and 2200 miles onshore [47]. Compared to pipelines, the LNG value chain has less asset specificity. This means that a given liquefaction terminal can process natural gas and ship it to different regasification terminals. Among all possible ownership structures, the most centralized one for the LNG value chain exhibits upstream and downstream integration as shown in Fig. 7.

LNG liquefaction terminals are very commonly integrated with upstream production: gas producers become part of the ownership structure of the terminal to ensure the commercialization of their gas [20]. Integrated utilities, on the downstream end, can take ownership of the tankers and regasification terminals. On the other end of the spectrum, a completely decentralized ownership structure for the gas industry is shown in Fig. 8: the owners of LNG terminals do not take possession of the gas – the terminals operate as tolling facilities – and tankers are chartered out by independent owners. Because the gas exporting and importing countries do not necessarily share the same industry structure paradigm, mixed ownership structures for the LNG value chain are common.

3.2.5. Power generation and gas production

Located at the upstream of their respective supply chains, power generation and gas production are the most dissimilar parallel segments. Both of them are capital intensive, but in general, gas production, due to the uneven distribution of gas reserves across the globe, involves a higher degree of geological and political risk compared to power generation [2].

Power generation is an aggregate of a diverse range of technologies. Multiple categorizations are possible based on the nature of the energy source used for conversion into electricity, the emissions associated with generation, and the siting requirements for the generation plants (Table 8).

Within the centralized archetype, power generation facilities, like the rest of the centralized supply chain, are owned by the integrated utility, which also plans for investments and operates the installed facilities. The generation projects that can be achieved at

Table 7
Ownership structures for power interconnectors, gas pipelines and LNG terminals.

	Power interconnectors		Gas pipelines		LNG terminals	
	Both centralized	Both decentralized	Mixed regimes	All decentralized	Fully centralized	Fully decentralized
Ownership	Integrated utilities of the countries involved	Joint venture of companies, including system operators	Various	Independent owners	Gas producers/gas buyers	Independent owners
Proposal of investment	Integrated utilities of the countries involved	Owners	Owners or national governments involved	Independent owners	Owners	Owners
Approval of investment	National governments involved	Regulators of countries involved	National governments involved	Regulators of countries involved	Regulator	Regulator
Operation	Integrated utilities of the countries involved	Owners	Various	Independent owners	Owners	Owners
Investment remuneration scheme	Integrated into the approved tariffs	Integrated into the approved regulated tariffs, exemption from tariff and open access possible	Long-term purchase/supply contract associated with pipeline	Integrated into the approved tariffs	Integrated upstream or downstream	Tolling, exemption from open access possible

Fig. 7. Centralized ownership structure for LNG value chains.

the lowest costs, while providing an adequate level of reliability, are chosen based on evaluation conducted. Other selection criteria are also possible, examples are: job creation and the use of domestic fuels. Once a project proposal is approved by the regulator and completed, the utility recovers its costs through the regulated tariff, which also includes a fixed profit margin deemed appropriate by the regulator [25]. In a decentralized environment, decisions on the development of generation infrastructure are made by for-profit generating companies that construct, own, and operate them, motivated by estimates of perceived revenue from market operations and available policy incentives. Investment decisions need to be approved by the local planning authority responsible for the area in which the site of generation is located.

Currently, natural gas production is often divided into two types: conventional and unconventional (Table 9). Conventional gas production refers to the case where the natural gas comes from a commonly exploited type of geological reservoir. A number of sources of natural gas are regrouped under the heading of unconventional gas. They each require different extraction techniques and in the past they were considered uneconomical to produce because the required technology and market conditions were not available [31]. However, developments in horizontal drilling and hydraulic fracturing, during the last 15 years, pioneered by gas producers in the USA, have made the extraction of the American shale gas reserves economical, unleashing important production. However, the economic and political feasibility of shale gas production in other world regions remains unclear. Biogas can be perceived as an equivalent of distributed renewable generation for the gas sector: produced from non-depletable energy sources, close to load centres.

Due to the common origin of oil and gas (referred to together as petroleum), gas is commonly produced as a by-product of oil production (associated gas), or is produced from dry gas fields by firms whose primary business is oil. Thus, in addition to being correlated with gas reserve, natural gas production in a given country is also correlated with oil production (Fig. 9 and Fig. 10). The issue of ownership of gas production facilities is mingled with that of ownership of oil production assets, a highly political subject, since oil and gas are highly integrated upstream, especially in countries with mostly associated gas production (relatively high oil reserve with respect to gas reserve, see Fig. 11). Also, because gas production is an extractive activity, the issues of mineral rights and their transfer need to be considered when investments are motivated by potential revenues.

Table 10 presents the ownership structures for power generation and gas production facilities. Within the fully centralized

Fig. 8. Decentralized ownership structure for LNG value chains.

Table 8
Characteristics of groups of power generation technologies.

	Large-scale fossil fuels	Nuclear	Large-scale biomass	Hydro with reservoir	Offshore wind, wave, tidal, solar thermal	PVs, onshore wind
Energy source	Depletable, storable	Depletable, storable	Depletable if reforestation does not occur	Depletable if water reservoir not replenished	Renewable, intermittent	Renewable, intermittent
Emission from generation	Yes	No	Not carbon-neutral if reforestation does not occur	No	No	No
Siting requirements	Access to fuel supply	Access to fuel supply	Access to fuel supply	Geological constraint	Environmental requirements	Distributed
Conversion technology	Steam/gas turbine	Steam turbine	Steam turbine	Water turbine	Various	Various

Table 9
Characteristics of groups of gas extraction/production technologies.

	Conventional gas	Tight/shale gas	Coal bed methane	Methane hydrates	Biogas
Energy source	Depletable, storable	Depletable, storable	Depletable, storable	Depletable, storable	Renewable, limited storage
Emission from generation	Yes	Yes	Yes	Yes	Carbon neutral as gas is otherwise dissipated
Siting requirements	Access to reservoir	Access to shale	Access to coal seam	Access to deposit	Distributed
Extraction/production technology	Drilling and controlled reservoir depletion	Horizontal and directional drilling, hydraulic fracturing	Drilling and water pumping	Under development	Controlled anaerobic digestion/fermentation

archetype, which also coincides with full integration with upstream oil, rights to natural gas and the production facilities are entirely owned by the nationalized petroleum company. Decisions within the oil (and gas) industry (both investment and operation decisions) are part of an overall policy to maximize contributions to the national mission to ensure the popularity of the government, and to generate oil-related revenues, often an important portion of the government budget [40].

Fig. 9. Correlation between world country gas production and oil production ($R^2 = 0.66$) (2012 Data from Ref. [8].

Fig. 10. Correlation between world country gas production and gas reserve ($R^2 = 0.53$, 0.78 after excluding the USA) (2012 Data from Ref. [8].

Fig. 11. Correlation between world country gas reserve and oil reserve ($R^2 = 0.18$) (2012 Data from Ref. [8].

Within an entirely decentralized archetype, gas production facilities are owned by a variety of private companies, from vertically integrated international oil and gas companies to small-scale independent producers, seeking returns on their investments. Rights to minerals, including gas, are held by the owner of the surface; such rights can be transferred to gas producers through a lease.[1] Approval from the regulator is needed in the form of land use development permits and drilling permits.

For both scenarios, there are two pathways towards monetizing gas production: sales to domestic consumers for power generation, heating, or petrochemical production (given that local transmission and distribution infrastructure exists), or sales to other countries, bound by the availability of exporting infrastructure. If neither infrastructure exists, then gas is re-injected to enhance oil recovery or it is flared.

3.3. Operation of infrastructure

Constant balancing of supply with demand has been the

[1] United States is the only country that conforms to the decentralized archetype concerning the ownership of oil and gas rights. In all other countries, the central governments or monarchs own the mineral rights, not the owner of the surface land.

Table 10
Ownership structures for power generation and gas production facilities.

	Gas production facilities		Power generation facilities	
	Complete centralization	Complete decentralization	Complete centralization	Complete decentralization
Ownership of energy vector	Non-transferrable sovereign ownership	Transferrable private/state ownership	Procured from upstream or N/A	Procured from upstream or N/A
Ownership of facility	State-owned integrated petroleum company	Integrated O&G company, independents	Integrated utility	Independent owners
Proposal of investment	State-owned integrated petroleum company	Owners	Integrated utility	Owners
Approval of investment	Various	Independent regulator	Various	Local planning authority
Operation	State-owned integrated petroleum company	Owners	Integrated utility	Owners
Investment remuneration scheme	Domestic and export sales	Domestic and export sales	Integrated into the approved tariffs	Sales

operating tenet for the gas and power supply chains; this is because the consequence of level production (periodic shortages of energy provided) is not socially acceptable, energy services being considered as essential. Surplus of supply, stored in stocks, is also infeasible for power and gas industries, given the difficulty of storing the energy vectors. Finally, imbalances of gas and power supply and demand are detrimental to the network infrastructure used to deliver them. Supply, rather than demand, is adjusted to maintain system balance, because managing demand has been difficult historically [22].

3.3.1. Causes of imbalance and sources of flexibility

The mid to short-term variations present in the consumption of gas and electricity are tied to the energy services that these energy vectors provide. An important fraction of gas is used for space heating in many countries, and heating demand is directly related to the ambient temperature, which varies diurnally and seasonally. Temperature also affects electricity demand in countries with high adoption of resistive heaters and air conditioning units. Electricity demand, in extensively electrified countries, is highly correlated with the general activity level on a daily and weekly basis. The degree to which gas and power consumption can be altered upon command is uncertain. From past and present experience, it is possible to reschedule some non-continuous manufacturing activities and some non-time-sensitive daily activities of households and businesses and this may be an important quantity when aggregated. These issues are summarized in Table 11.

Many factors influence the mid to short-term variations in the supply of natural gas and electricity. The possible causes of supply-side imbalance, other than physical failure of infrastructure, are: declining productivity of gas fields as the reservoir approaches depletion, disruption of pipeline supply for non-technical reasons, and the diversion of LNG supply away from its original route (enabled by flexible destination clauses). In the power sector, the most important cause of imbalance on the supply-side is intermittent renewable energy generation and power plants' failure [23].

The main supply-side sources of flexibility in the gas sector are: variable domestic gas production, pipeline contract swing volume (dependent on contract clauses), and additional gas procured through uncontracted import pipeline capacity, flexible LNG supply procured by diverting shipments from other routes and from the spot market, line-pack buffering capacity, and the use of gas storage facilities [15]. The extent to which gas production can be varied depends on the operating philosophy of the producer and the characteristics of the field. Line-pack and the ability of storage facilities to absorb or deliver additional gas depend on the existing store of gas within the pipelines/storage reservoir. Flexible supply options are subject to the constraints set out in the import contract clauses (swing volume) and to the alternative commercialization opportunities available to the exporter. The main supply-side sources of flexibility in the power sector, a widely debated issue, are considered to be: the ability of thermal and hydro generators to ramp up/down from their existing generation level, indirect energy storage through pumped hydro facilities and other storage technologies, the curtailment of renewable intermittent production, and power exchange with interconnected grids. The flexibility of generation units to change their output depends on their existing state (on/off, current generation level with respect to minimum and maximum stable loads). The ability of PHES to absorb and deliver power depends on its maximum and existing capacity. The exact nature of cross-border flow is dependent on the coordinated actions of agents in both countries. In summary, the sources of flexibility within a system are relative and are dependent on the state of the system. Table 12 summarises supply-end causes of imbalance and sources of flexibility.

3.3.2. Coordination mechanisms

For the centralized archetype, most of the coordination decisions occur within organizations via administrative procedures (see Fig. 12). Information about the availability, variable costs, and technical parameters of the infrastructure assets required for coordination is centralized. There are relatively few entities involved in the supply of power and gas, and they are tied via long-term agreements that specify the exact terms of their coordination.

The national petroleum company, which manages the production of gas given existing capacity, makes operational decisions to dispatch the gas produced to export facilities and the national T&D network. The gas utility, in control of all gas storage facilities, pipelines, and midstream compression stations is responsible for the balancing of the entire transmission and distribution network. The integrated power utility, which contracts gas from the gas utility at regulated wholesale tariffs, is similarly endowed with the knowledge of the states and technical parameters of all power generation, transmission, and distribution assets in its possession. It is responsible for meeting all power demand in the national system by dispatching the portfolio of generators at its disposal.

For the decentralized archetype, most of the coordination decisions occur as transactions between organizations. Information required for coordination is decentralized and is communicated as bids and price movements via market mechanisms (see Fig. 13). The number of agents involved in coordination mechanisms for decentralized power and gas sectors is much more significant than in the centralized case.

Gas producers, integrated oil and gas companies operating internationally, or independent gas producers in the decentralized archetype, seek to commercialize their gas production in the gas forward and spot markets, or through long-term contracts. These commercial arenas can be domestic/regional or international, depending on the development of decentralization in other

Table 11
Demand-end causes of imbalance and sources of flexibility.

Segment	Causes of imbalance	Sources of flexibility
Gas consumption	Seasonal temperature cycle, weekly work cycle	Manufacturing schedule
Power consumption	Seasonal temperature cycle, daily activity cycle, weekly work cycle, public events	Manufacturing schedule, daily activities

Table 12
Supply-end causes of imbalance and sources of flexibility.

Segment	Sub-segment	Causes of imbalance[a]	Sources of flexibility
Gas production		Declining productivity of wells	Variation in production
Gas export	Pipelines		
	Liquefaction terminals		
Gas import	Pipelines	Disruption of supply	Dependent on pipeline contract clauses and uncontracted pipeline capacity
	Regasification terminals	Dependent on LNG supply contract clauses	Dependent on LNG supply contract clauses
Gas T&D			Allowable variation in line-pack
Gas storage			Variation in injection and withdrawal
Power generation	Nuclear		Limited variation in generation
	Coal and biomass		Allowable variation in generation
	Gas		Allowable variation in generation
	Hydro with reservoir		Allowable variation in generation
	Wind, solar and run-of-river	Intermittent renewable energy generation	Curtailment of production
Power storage	Pumped hydro		Variation in pumping and generation
Power T&D			
Power interconnector	AC		Automated frequency regulation by interconnected grid; energy trade dependent on market coupling scheme
	DC		Dependent on market coupling scheme

[a] Physical failure is a possible cause of imbalance for all infrastructure, therefore it is not listed individually.

countries and the availability of export infrastructure. Depending on the arena, the conventional delivery point, delivery date, volume level, price level, and duration of the trade can differ. The counterparties that trade with gas producers are: gas suppliers, entities that procure gas to sell in the retail market to small consumers, or large gas consumers such as power generating companies. Trade between gas producers and pure shippers – those mediating between gas producers and suppliers/large consumers, arranging for the transportation of gas between delivery point and city gate/consumption point – is also possible. Gas producers and gas suppliers/large consumers can also become shippers and arrange for the transport of gas through the transmission network by themselves. All gas shippers pay the owners of the transmission network according to their usage and a regulated tariff. They also participate in the balancing of the network at a particular point (physical hubs) or for a transmission zone with several entry/exit points (virtual hubs) together with the hub operator (physical hubs) or the transmission system operator (virtual hubs), to maintain it within acceptable pressure limits. The particular mechanism for gas balancing depends on the market design.

It is possible for any gas shipper to contract capacity with the independently owned gas import, export, and storage facilities (owners of the networks do not take possession of the gas that passes through their facilities; they charge regulated fees for the capacity services). This can be done through a long-term contract or by shorter-term transactions on the secondary market, when those that hold long-term rights sell or sublet their rights. In the retail market, small-scale consumers of natural gas enter into contracts with gas suppliers and pay the gas distribution network owners for their usage according to the regulated tariff.

Overall, the decentralized power sector follows a similar organizational pattern to the decentralized gas sector, with the difference that the balancing coordination mechanism represents a greater technical challenge: the gas network only requires to be maintained within a range of pressure, while the power network needs to maintain frequency and voltage across the network within narrow margins of design specifications in order to be functional. Electricity needs to be balanced on a real-time basis. For balancing needs that cannot be contracted within the balancing markets – the variations in demand and pre-scheduled supply that occur within the minimal settlement period allowed on the balancing market – the transmission system operator needs to acquire further balancing services in the ancillary services market, where only select generators/large-consumers can tender for contract. Finally, the role of shipper is not necessary within the electricity market: the transportation of electricity within the network does not need to be, and cannot be, arranged; it only follows physical laws – travelling within the circuits whose parameters are carefully tuned by the system operator.[2]

The stage of development and the relative significance of a range of aspects of gas and power markets – long-term supply contracts (5–30 years duration), short term trades with varying delivery dates ahead of agreement (up to 3 years ahead), and primary and secondary sales of access rights to competitive import, export, and storage assets – are different for gas and power sectors in different countries, given the different degrees of decentralization and the time it takes for markets to mature. Other than the temporal differentiation mentioned above, power and gas markets can also be differentiated based on their level of spatial integration, depending on the accessibility of import and export infrastructure: cross-border and even longer-distance trade occurs if the foreign supply is deemed competitive after accounting for the cost of transport. Currently, global trade of natural gas occurs via LNG, regional trade of natural gas takes place in Europe, North America, and Asia. The bulk of electricity trade is still confined within national borders due to limited interconnector capacities, although there are some

[2] In DC interconnector systems there is the possibility of control over direction of flows. In AC transmission there are experimental procedures, through FACT devices, to increase control over power flows.

Fig. 12. Long-term planning based coordination mechanism for centralized power and gas sectors.

Fig. 13. Market-based coordination mechanism for decentralized power and gas sectors.

exceptions exist.

Not all sources of flexibility are equal. The degree to which various sources can be used to accommodate variations in other part of the supply chain is limited by their ability to respond, driven by technical and commercial determinants, and the costs for doing so (Table 13). If the coordination mechanism employed leads to economically efficient results, then the sources of flexibility would be dispatched based on their marginal cost unless overwritten by technical and commercial constraints. For sources of flexibility for which spatial and temporal arbitrage is possible (supplying power or gas in another spatial market or delivering energy at a different time), the marginal cost that should be considered is the opportunity cost. Under both the centralized and the decentralized archetype, the dispatch of sources of flexibility to counterbalance causes of imbalances is part of the day-to-day operation of the gas and power sectors, with the difference that under the decentralized archetype, the coordination is achieved within markets, not administratively. Thus, short-term market dynamics, mainly in the

Table 13
Responsiveness, availability and delivery/uptake rate for various sources of flexibility.

	Responsiveness	Availability	Delivery/uptake rate	Marginal cost
Gas production variation	Daily nomination	Annual contract quantity, take-or-pay volume	Min/max daily contract quantity, maximum pipeline capacity relative to current use level	Indexed price
Flexible import pipeline supply	Long-term agreement: daily nomination Short-term trade: connected hub liquidity and price responsiveness	Long-term agreement: Annual contract quantity, take-or-pay volume; Short-term trade: sources of flexibility at connected hub	Min/max daily contract quantity, maximum pipeline capacity relative to current use level	Long-term agreement: indexed price; Short-term trade: opportunity cost to supply connected hub
Flexible LNG supply	Liquidity and price responsiveness of global spot market; distance of closest liquid supply	Availability of LNG on global spot market	Maximum terminal capacity relative to pre-scheduled capacity	Opportunity cost to supply global spot market
Line pack	Immediate	Gas packed and uptake/ injection rate	Maximum capacity of connection to grid	Opportunity cost to be used for transportation
Gas storage	State of storage (injection, withdrawal, idle)	Gas inventory	Well injectability/ deliverability	Opportunity cost to be delivered/injected at a different time
Thermal generator	Generator design	Fuel supply	Min/max stable load	Fuel cost
Hydro with reservoir/PHES	Generator design	Water in reservoir	Min/max stable load	Opportunity cost to be delivered/pumped at a different time
Interconnector	Liquidity and price responsiveness of interconnected grid	Sources of flexibility in interconnected grid	Maximum interconnector capacity	Opportunity cost to supply interconnected grid
Demand response	Contract agreement, notification system	Quantity contracted	Quantity contracted	Contract agreement

form of price fluctuations, are fundamentally affected by the sources of flexibility and imbalances involved, accessible via the existing infrastructure [36,39]. Long-term evolution of market price (the annual moving average price, rather than highly volatile daily or hourly prices), is dependent on the underlying long-term supply options and end-user demand, embodied in the change in supply and demand infrastructure.

3.4. Performance and regulation

3.4.1. Regulatory regimes

The pattern of industry and government objectives is fundamentally tied to the ownership structure of the sector. In the case of state-owned companies, the objectives of the industry, to a great extent, converge with those of the national government. It follows that, within the decentralized archetype, the objectives of the industry are dependent on the companies that constitute it – these objectives are separate, and sometimes opposite from, the objectives of the national government. The regulatory regime in place in each of these archetypes reflects this difference.

The regulatory regime for the centralized archetype is an administrative supervisory relationship between the government branch responsible for energy (dedicated or subsumed within commerce and industry) and the state-owned companies. The regulatory body's role is to approve the overall tariff, to design the structure that allocates the costs of energy provision among different sectors of the society, and to set objectives for the industry (economical and/or political).

Within the decentralized archetype, the ownership of the industry is dispersed among many different agents, large and small. Publicly-owned companies might or might not be present; but even in the case that they are, they are likely to embrace the *raison d'être* of private companies, that of maximizing the generation of economic value to shareholders. This objective is commonly operationalized as maximizing risk-adjusted return upon investment, but other operationalized goals are also possible, based on the company strategy (for example: market share maximization, growth maximization, and environmental impact minimization).

In the regulatory regime for the decentralized archetype, the government, via the activities of several regulation authorities, interacts with the many companies that form the gas-to-power supply chain. The government is responsible for primary legislation, while the independent regulatory authorities, on behalf of the government, are responsible for:

- the day-to-day monitoring of the structure of the industry (ensuring, for example, that it is sufficiently decentralized to allow competition),
- the coordination occurring within markets (ensuring, for example, that market behaviour conforms to the behaviour of an efficient market and is compliant with regulation), and
- the industry performance (ensuring that it conforms to government expectations).

3.4.2. Dynamics of regulation

The interaction between government regulation and industry self-regulation is relatively simple for the centralized archetype and government regulation tools are: the design and approval of the regulated tariff and the direct setting of industry standards (the so-called 'command and control approach'). In terms of self-regulation, an integrated utility uses operational and investment decisions for all its infrastructure assets to regulate its performance, according to the government objective and its own organizational objectives (such as operational and investment cost recovery/revenue maximization).

Within the integrated utilities, state-of-the art operational and investment decisions are supported by optimization models and multi-criteria decision-making methods [32]. Their operational decisions are based on short-term demand forecasts, and the known status and costs of the infrastructure in place. Their investment decisions are based on their expectation of operational needs in the future, given increasing/unmet demand and the obsolescence of existing infrastructure. Uncertainty in operations

and planning (in terms of cost recovery for the firm) is relatively controlled, especially if cost-based regulation is used. Most information required for such optimization – operation schedule for planned expansion, technical parameters for installed infrastructure, expected demand – is known by the utilities from their activities throughout the supply chain. Also, uncertainty has little impact upon organizational revenues, for the exogenous changes in production/purchase cost of fuel are passed on to the end-users through the regulated tariff, as long as the method of tariff calculation is maintained constant.

The main dynamics in regulation for the centralized archetype are the interactions between government objectives, industry objectives, and the regulated tariff that mediates among them (Fig. 14). The dynamics mentioned here apply to vertically integrated utilities and regulated monopoly segments in a decentralized supply chain.

If the firms' costs are passed on to end-users via the regulated tariff, determined *ex post* (cost-based regulation), there is little incentive for cost efficiency. To address the lack of incentive for efficiency, incentive regulation (in which regulated tariff are determined *ex ante*, setting a cap on the maximum allowable revenue) can be adopted – some examples are price cap and revenue cap. Another variety of incentive regulation also connects government-set objectives to the regulated tariff through rewards and penalty (performance-based regulation).

The main challenges for the government regulator is information asymmetry between the regulator and the integrated utilities concerning the costs of providing power and gas efficiently. But, it can be (partially) overcome through repeated games (regulator audits the costs *ex post* and makes adjustments), benchmarking costs, and other performance parameters with comparable utilities (yardstick competition).

Within the decentralized archetype, there is a wide range of self-regulation measures available to industry firms to meet their own objectives: private companies can enter or exit all competitive segments of the gas-to-power supply chain. In addition, operational decisions of the firms include bidding to trade in the many different power and gas wholesale and balancing markets and bidding in derivative markets (not shown in Fig. 13, because power and gas derivatives are financial instruments used to hedge risk rather than to coordinate physical delivery). In the longer term, the firms evaluate and finance infrastructure investment and manage long-term contracts.

Privatization and liberalization change the mechanisms of influence at the state's disposal, but the state remains a major player, just as within the centralized archetype [14]. The moves that regulatory authorities adopt, in a pure decentralized archetype, are those that promote effective competition by addressing market failures in the form of imperfect competition, imperfect information, and externalities. Within the power and gas sectors, this means the following four key measures:

- unbundling and regulation of the network (natural monopoly) segments of the gas and power industry,
- liquidity and competitiveness checks for other segments,
- provisions to correct information asymmetry between suppliers and consumers, and
- internalization of negative and positive externalities resulting from the gas-to-power supply chain.

The main dynamics in regulation for the decentralized archetype are harder to track, because the impact of government regulation is on the competitive environment (industry structure and coordination mechanisms), which eventually trickle down to change industry behaviour by realigning them with respect to industry objectives. Within the decentralized archetype, the information required for evaluating operational and investment decisions – expected price in the particular market(s) and the level of use of the asset – is uncertain and varies according to coordination occurring in the markets, and estimated based on knowledge of the markets in which they participate [41]. Uncertainty, and its impact on return upon operations and investment, is an important consideration for industry agents within the decentralized archetype, for they alone are responsible for the risks associated. Government regulation design in the decentralized archetype requires even more care than in the centralized archetype, both in substance and in delivery method, because it not only impacts the perceived profitability of different industry conduct, it also affects its risk profile.[3]

The main challenge for the government regulator among its four key concerns has been the internalization of market externalities. An example of market-based government regulation is the restrain of sulphur dioxide emissions through tradable permits (Fig. 15). This is arguably one of the most successful cases of implementation of market-based instruments and it has provided inspiration for other environmental trading programmes [6]. Despite its success, however, close examination of the SO_2 cap-and-trade programme reveals that the outcome of the policy was dependent on the unintended consequences of other policies (positive interaction: effects of rail deregulation; negative interaction: state and source-specific emission constraints), and that politics trumps science and economics, in most cases, in setting targets for even market-based mechanisms [34].

In practice, the exact structure of the power and gas industry in a given country can be a hybrid thus the government regulation adopted can be a mix of command-and-control approaches with market-based mechanisms which, together, result in increasingly complex interactions. An example of such complexity is the interaction among support systems for electricity from renewable energy sources, between the RE support schemes, and the EU Emission Trading Scheme (EU-ETS), which have been described in various studies [7,11,29]. This evidence supports the view that greater consideration needs to be given to the interrelationships among regulatory instruments, which are increasingly complex.

4. Demonstration of application: development of a simulation model

In this section, a simulation model developed based on the SCPR framework proposed is presented to demonstrate a possible use for the framework. The research process used is documented to demonstrate how the holistic analytical framework can guide the development of research studies with more specific scope.

In order to inform the scoping and formulation of the simulation model, the UK's gas-to-power supply chain is surveyed through the lens of the holistic framework proposed, resulting in a qualitative case study that covers the ownership structure, state of infrastructure, coordination mechanism, and regulatory measures in the UK's gas and power sectors. The full case study can be found in Ref. [27]. The most important findings of the qualitative case study are summarized below. The ways in which they have informed the development of the simulation model is presented in parallel.

The case study found that the UK's gas and power sectors are among the most decentralized in the world, approaching the decentralized archetype presented in the framework. Ownership across the extended gas-to-power supply chain is diverse,

[3] For this reason, the entire framework has avoided using the term 'deregulated' to refer to the decentralized archetype.

Fig. 14. Regulation dynamics for the centralized archetype.

independent owner/operators that only focus on one segment such as gas production, gas storage, gas import/export, and power generation exist. Integration across segments also exists, especially in the downstream: the 'Big Six' energy companies are integrated across gas storage, gas supply, power generation, and power supply. They own and operate about three quarters of British power generation capacity and more than 95% of gas storage capacity. However, the wholesale gas and power markets are monitored by the regulator Ofgem, which has found them to operate competitively. This justifies the representation of the UK's gas and power markets

Fig. 15. Example of regulation dynamics for decentralized power sector.

Fig. 16. Scope of simulation model developed.

as perfectly competitive markets in the first prototype of the simulation model, ignoring the effect of market power.

The decentralized agents operating in the UK's gas and power sectors rely on market mechanisms for short-term coordination to balance demand. In the gas sector, before the decline of domestic production, much of the flexibility to meet seasonal variation in gas demand was provided by the flexibility option contained within long-term contracts with UK gas producers. However, that flexibility has declined with the domestic production level. Today, gas imported from Norway and the Netherlands through long-term contracts is playing a more important role in the management of seasonal supply/demand imbalance. Flexible import/export

through the Interconnector, LNG spot cargoes, and gas storage are also sources of flexibility that are used by shippers to resolve imbalances. In the power sector, the imbalances in supply/demand are met through a mix of sources of flexibility: the most important ones are gas-fired generation, coal-fired generation, pumped storage, and interconnector import/export from France and the Netherlands.

Given the assumption of competitive market (justified above) and the range of flexibility sources found to be available to the UK, the simulation model represents the UK's gas market as an optimizing process with monthly resolution, where market participants (producers/shippers/suppliers) behave competitively given existing contractual and infrastructural constraints. The market outcome is one in which inter-temporal arbitrage (via storage and denomination of long-term contract volume) and inter-market arbitrage (via flexible import/export from Belgium and flexible LNG import) is used to minimize the overall cost to meet gas demand. The market price of gas is taken to be the marginal cost of the supply source that is needed to meet an additional unit of demand. Similarly, the power market is formulated as an optimizing process with hourly resolution, where generators/suppliers behave competitively given existing technology and infrastructural constraints. The market outcome is one in which the operation of different generation assets is optimized to minimize the overall cost to meet residual power demand, the difference between total demand and non-dispatchable generation. Intertemporal arbitrage (via pumped storage) and inter-market arbitrage (via flexible imports/export from France/the Netherlands) is also enabled. The market price of power is taken to be the marginal cost of the generation technology or import source that is needed to meet an additional unit of demand.

A segment-by-segment inspection shows that the UK's gas and power network infrastructure is very mature. The import capacity of gas is also found to be significantly above current demand ((156 Bcm/year vs. 70 Bcm/year). Currently, investment in two particular segments are most affected by uncertainty: domestic gas production and power generation. Without new investment, the UK's domestic gas production capacity is expected to continue its steep decline since 2000. The quantity of investment that can be expected to enhance recovery from declining fields, or to develop increasingly difficult reserves, is uncertain. Rising exploration, development, and production costs, as well as expected gas price and fiscal regime, affect gas producers' investment decisions. A power generation capacity crunch is perceived in the UK, given decommissioning of oil and coal generation capacity (driven by regulatory constraints and falling revenues) and the expected retirement of nuclear power plants. The continuing evolution of market price of power and the regulatory changes contained in the Electricity Market Reform affect power generators' investment decisions. New development is also expected in the power interconnectors segment, as the interconnector capacity is expected to double by 2020.

Based on findings from the case study, the scope of the simulation model, the first prototype in a lineage of continually evolving models, includes the endogenous representation of gas producers and power generators' investment decisions. The short-term operational decisions participants in the gas and power wholesale market and those engaged in long-term contracts, are also represented endogenously. Infrastructure change in other segments (gas storage, gas import/export, power interconnectors) is specified exogenously, and the use of these infrastructure is represented implicitly in the formulation of the power and gas wholesale markets as infrastructure constraints that must be met. The gas and power suppliers are represented implicitly as the exogenous demand that needs to be met by the wholesale markets, but the gas and power retail markets are out of the scope of the simulation model, so is the transmission and distribution network (the copper plate assumption is adopted) and the power balancing mechanism. The exact scope of the simulation model is mapped onto Fig. 16 to locate the focus of the simulation model developed relative to the overall decentralized coordination mechanism. It helps to elucidate what are the dynamics that are investigated in detail and which ones are overlooked.

The simulation model captures the self-regulating nature of the long-term investment decision made by power generators and gas producers. It also captures the self-regulating nature of the short-term operational decisions made by the direct participants of the gas and power wholesale markets. Five feedback loops are identified:

1. price responsive gas supply: short-term self-regulation of the gas wholesale market participants, where movements of the gas market price attract or push away price-responsive supplies of gas to meet the market demand;
2. availability of gas production capacity: long-term self-regulation of gas producers, where movements of the gas market price incentivise or disincentivise long-term investment in gas production capacity, which eventually affects gas market price with a delay;
3. price responsive power supply: analogous to L1, but for power market participants;
4. availability of power generation capacity: analogous to L2, but for power generators;
5. price responsiveness of power sector gas demand: self-regulation of gas and power market participants, where movements of the gas market price incentivizes or disincentivizes the use of gas for power generation.

The specific model structure adopted is illustrated in Fig. 17. Following System Dynamic conventions, causal relationships between variables are traced through arrows. The five key causal loops that can be traced are indicated via blue loop symbols. Key exogenous variables, uncertain variables which are not specified by the model, but fed to it as an input, are labelled in red. And, grey boxes indicate that causal links leading to and departing from these boxes are processed by an underlying sub-model.

The basic logic of the gas and power market sub-models has already been introduced. The causal relationships of loops 1 and 3 are contained within these market sub-models. Loop 5, the interaction between the power sector's gas demand and the gas market, is represented through an iterative converging algorithm that redispatches gas market until an equilibrium has been reached between the price of gas and power sector gas demand. The causal relationships contained by loops 2 and 4 are represented via the interconnected market, forecasting, and investment decision sub-models. The forecasting sub-model represents the expectation formation process of investors, translating current market outcome and other conditions to forecasted ones, which are inputs required by the investment decision sub-models. The investment decision sub-model represents investors as rational agents that maximize expected Net Present Value of potential investments, where the funds available for investment are constrained by the investors' operating cash flow. Finally, the investment made in gas production capacity or power generation capacity is commissioned after a construction delay, which in turn influences the balancing of supply and demand in the gas and power markets.

The simulation model thus formulated is a set of causal relationships represented explicitly and modularly in mathematical terms. In itself, the scoping and specific formulation of the model can be used as a group exercise to align and clarify research

Fig. 17. Causal loop diagram of the simulation model.

objectives. More importantly, the simulation model allows for automated inference of dynamics, based on the causal relationships and model inputs specified. Therefore, through sensitivity analysis and scenario analysis, the simulation model can be used to investigate quantitatively the effect of uncertainties in the power generation segment on the natural gas sector (e.g. carbon price, decommissioning of nuclear capacity, renewable support scheme, etc.), and the effect of uncertainties in the gas production segment on the power sector (e.g. exploration prospective, fiscal regime, import opportunity cost, etc.) on the power sector.

Using historical data as model inputs for the years 2011–2015 and estimates for the years 2016–2030, a base case scenario, consisting of the values or pathways of more than 80 exogenous parameters, is developed and simulated. The output of the simulation model is compared to the historical outcome in the UK's gas and power sectors as one model validation measure. The output of the model for years beyond 2015 is checked for its interpretability. Select results from the simulation of the base case scenario included to demonstrate the granularity of results that can be achieved (see Fig. 18–21).

Currently, the simulation model represents self-regulation of the power generators and gas producers endogenously as feedback loops. In the future, it is of interest to represent the government's regulatory action, in the form of changing subsidies, emission constraints, or other regulatory interventions, is also represented endogenously.

5. Conclusions

Increasingly, the natural gas and power industries have been

Fig. 18. Breakdown of UK gas supply for 2011–2030 under the base case scenario.

Fig. 19. Comparison of actual and simulated UK gas price.

Fig. 20. Breakdown of weekly average generation for 2011–2030 under the base case scenario.

Fig. 21. Comparison of actual and simulated UK gas price.

experiencing integration through the rise of natural gas-fired power generation. The performance and future evolution of the extended gas-to-power supply chain is dependent on drivers and constraints in both industries. Therefore, a coherent understanding of both sectors is becoming important for industry firms, power and gas system operators, utilities, regulators, and government bodies responsible for overall energy policy.

The extended gas-to-power supply chain is a complex socio-technical system with physical, commercial, regulatory, and policy 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 paper provided a holistic view of this complex system, that using concepts from the Structure Conduct Performance (SCP) paradigm, rooted in industrial organization, in combination with System Dynamics in order to take into account the dynamic nature of the system, the effects of delay and accumulation. The framework assists by acting as a lens through which gas-to-power interdependence can be identified and discussed, and by anchoring more specific investigation of interdependence for a given energy system.

The key concepts covered include industry ownership structure (which influences agents' participation and their motivation), the infrastructure in place and the mechanism employed to coordinate its use (which influences investment and operational decisions of industry agents), and the dynamic interaction of the above via governmental and industry self-regulation. Contextual information, important for the application of the SCPR framework to the specificities of the gas and power sectors, is also provided., The holistic framework presented, therefore, proposes a new methodology for policy makers and other industry agents to understand how regulatory changes interact with the sector structure, infrastructure capacity, and market decisions.

We also provide an example for developing studies with more specific scope, by presenting a simulation model based on gas-power interdependence in the UK. Using historical data as model inputs for the years 2011–2015 and estimates for the years 2016–2030, a base case scenario is developed and simulated.

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