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Keywords energy systems integration; economic principles; regulation; business models.

JEL Classification D4, L1, L5, L9, M2, Q4.

Contact tooraj.jamasb@durham.ac.uk

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Energy Systems Integration: Economics of a New Paradigm

Tooraj Jamasb[*]
Manuel Llorca

Durham University Business School, Durham University, United Kingdom

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Abstract

Energy Systems Integration (ESI) is an emerging paradigm emanating from a whole system perspective of the energy sector. It is based on a holistic view in which the main energy carriers are integrated to achieve horizontal synergies and efficiencies at all levels. The energy system may in turn integrate with other infrastructure sectors such as water, transport, and telecommunications to meet the demand for a broad range of energy and essential services. It also implies that energy security, sustainability, and equity objectives can be balanced more effectively. There is already progress in the technical aspects of ESI. However, such systems require not only physical solutions but they also need economic, regulatory, and policy frameworks to ensure efficient performance over time. Thus, it is important to better understand the economic features of integrated energy systems. To our knowledge this aspect is barely addressed in the literature on ESI. This paper does not attempt to survey the technical literature on the topic but to describe some of its relevant economic features. We discuss selected aspects that relate to industrial organisation, regulation, business economics, and technology. Finally, we offer some early considerations and policy recommendations.

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[*] Corresponding author: Durham University Business School, Mill Hill Lane, Durham, DH1 3LB, UK. Tel. +44 (0)191 3345463. E-mail: tooraj.jamasb@durham.ac.uk.

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1. Introduction

Since the implementation of reforms in the utilities sectors in the 1980s, the focus has largely been on improving economic efficiency through restructuring, regulation, and competition (Joskow and Schmalensee, 1983; 1986). This focus has gradually shifted to decarbonisation and environmental sustainability of the sector. The implementation strategy has been to improve the efficiency of energy sectors such as electricity and natural gas and network industries such as transport, water, and telecommunications. Some efficiency improvements have been achieved through the adoption of new technologies, restructuring, market competition, independent regulation, pricing reforms, and privatisation (Joskow, 2000; Newbery, 2000). However, the focus has mainly been on single energy vectors and sectors such as electricity, fuel, and heat.[1]

In order for the reforms of individual energy sectors to be worthwhile, the efficiency gains need to be larger than the likely higher transaction costs and the loss of economies of coordination with respect to a joint management of the industry activities (Brousseau and Glachant, 2002), which is generally assumed. However, utilising the potential for synergies and efficiencies from integration of different energy vectors has received little attention so far. As the efficiencies of the individual energy sectors improve, the limits of a partial approach to reform become more apparent and the technical, economic, and sustainability appeal of an integrated energy system becomes more evident.

The main premise of an Energy Systems Integration (ESI) paradigm is addressing the challenges of the energy trilemma and their trade-offs, i.e., energy security, energy equity affordability and access, and environmental sustainability. An integrated energy system will also bring the sectors involved one step closer to a transition towards provision of energy as service as opposed to energy supplies as products and commodities. ESI is also an inherently dynamic concept and while it advocates integration of energy systems it also requires and implies a long-term coevolution of these systems (O'Malley et al., 2016).

In addition to reliability and cost-effectiveness, a key motivation for the implementation of ESI is the sustainability concern. The energy sector is a major contributor to carbon emissions. This sector accounts approximately for 66% of the global Greenhouse Gas (GHG) emissions (IEA, 2015), which has contributed to a new record in atmospheric levels of CO_2 in 2016 (WMO, 2017). The energy sector, and in particular power generation due to its share of carbon emissions (roughly one-third of the CO_2 emissions from the energy sector; IEA, 2015) along with the relative ease to achieving reductions, has been the focus of the mitigation efforts until now. As a consequence, in recent years technological progress has resulted in large reductions in the cost of renewable

[1] An energy vector (also known as energy carrier) is a tool that "allows to transfer, in space and time, a given quantity of energy, hence making it available for use distantly in time and space from the point of availability of the original source" (Orecchini and Santiangeli, 2011, p.8127).

electricity sources. Nevertheless, the policy focus increasingly extends to other infrastructure sectors of the economy such as gas, heat, or transport.

The intuitive appeal of ESI for a transition to a low carbon energy sector is evident. However, it also gives rise to a number of important theoretical and practical economic considerations. The limited literature conceptualising energy system integration is either technical or general (see O'Malley et al., 2016; Ruth and Kroposki, 2014; for rare exceptions). Moreover, in addition to physical integration, an integrated energy system also relies on Information and Communication Technology (ICT) and requires a regulatory and policy framework based on sound economic principles and analysis, to achieve the technical potential of an integrated system.

A well-functioning integrated energy system requires economic, regulatory, and commercial frameworks that enable efficient operation and coevolution of the constituent parts as well as the whole system. It is important to note that it took many years to develop the market-oriented energy sectors, innovations, and regulatory and policy frameworks. Moreover, adapting these sectors to an integrated system will be a lengthy process and will need to evolve over time. So far the literature on the economics of the ESI is, to our knowledge, non-existent, and hence this gap is the main motivation of the present paper. This paper does not aim to survey the technical literature on the topic, but to be a primer on the economic aspects of ESI.

The remainder of the paper is as follows. Section 2 presents the paradigm and concept of energy system integration. Section 3 discusses the main economic, regulation, and business model aspects and considerations for an integrated energy system. Section 4 focuses on information and communications technology for systems integration and utility business models. Section 5 is conclusions and policy discussions.

2. Energy System Integration (ESI)

Since the 1990s, the dominant paradigm in the liberalised network industries such as gas, electricity, telecoms, and water, has been to unbundle – legally or accounting – their vertically integrated generation, network, and retail activities into regulated and competitive businesses (Armstrong et al., 1994; Newbery, 2000; Brunekreeft, 2015).[2] From an economic point of view, the separation of vertically interdependent segments has been justified based on the natural monopoly characteristics of the regulated segments (e.g., electricity transmission and distribution networks) and the potentially competitive nature of generation and retail supply.

[2] Previously these were mostly vertically-integrated state-controlled legal monopolies.

It should be noted that the traditional vertically integrated organisation of the network industries benefitted from horizontal economies of scale and economies of coordination stemming from vertical economies of scope (Meyer, 2012a, 2012b; Gugler et al., 2017). Therefore, the oversight arrangements for the regulated and competitive segments are aimed at efficiency improvements that exceed the foregone economies of coordination of the pre-reform unbundled industry. This would ultimately lead to an increase in social welfare as the gains are transferred to consumers through regulatory and market mechanisms (Jamasb and Pollitt, 2007).

However, unbundling of services has not removed the need for the physical connections and coordination of the vertically interdependent activities in network industries such as the electricity sector. At the same time, the operating environment of the electricity sector is changing from one with unidirectional power flows from large generators within vertically integrated structures to profit maximising competitive and regulated firms engaged in a market characterised by diversified and Distributed Generation (DG), active demand, and multi-directional power flows.

For example, in the UK, nearly 30% of total generation capacity in 2017 was directly connected to the distribution networks (DUKES, 2017). From 2012 to 2016, the capacity connected to the transmission network was reduced from 81.9 to 69.6 GW, while in the same period the capacity connected to the distribution networks increased from 14.5 to 28.8 GW. The bulk of the change in the make-up of the generation mix is due to the retirement of coal plants and addition of onshore and offshore wind and solar power (DUKES, 2017).[3] Another notable example of 'decentralisation' is the case of California, where roof-top solar energy showed the potential to generate 74.2% of the electricity sold by the utilities of the state in 2013 (Gagnon et al., 2016). Electric Vehicles (EVs) can contribute towards achieving the diverse objectives of the Demand Response (DR) programmes in California (Wang et al., 2018). EVs can increase the flexibility and reliability to the grid by permitting load, supply or storage of electricity at different times, which can help the management of intermittent renewable energy sources (Falvo et al., 2014).

Additionally, the concept of sustainability has increasingly become synonymous with mitigation of harmful emissions and in particular with carbon reduction and the climate change concern. The global public good nature of climate change implies that, in terms of damage prevention, a unit reduction in carbon emissions in a sector of the economy is as beneficial as a corresponding reduction in any other sector. Moreover, there are significant co-benefits such as reduced air and water pollution associated with a reduction in carbon emissions.

[3] See Appendix for breakdown of DG technologies connected to transmission and distribution networks.

However, the cost of achieving carbon reductions varies across the different sectors of the economy, which has channelled the direction of much of the efforts made towards specific activities. In recent years, the power sector has been the centre point of the efforts to achieve carbon abatement. However, as progress is gradually made in this sector, the focus is increasingly extended to other sectors of the economy such as the built environment and transport. From an economic perspective, an efficient burden sharing should imply equalising the marginal cost of abatement across the different energy vectors and sectors of the economy. An integrated energy system could help to achieve this target.

The overarching aim of ESI is to reach efficient or cost-effective sustainable energy systems. From a technical point of view ESI "is intended to combine energy carriers such as electricity, thermal pathways, and fuels, with infrastructures such as communications, water and transportation, to maximize efficiency and minimize waste" (Ruth and Kroposki, 2014, p.36). In addition, other goals related to the flexibility, reliability and affordability of the system can be included in the definition. From an economics perspective, ESI can be viewed in terms of horizontal integration and coevolution of energy vectors such electricity, fuel, and heat systems. The integration can be at the upstream (i.e., production), networks, or downstream activity levels of the energy vectors. For example, a smart electricity distribution network can integrate DG, storage, heat, and DR as resources to efficiently meet the demand for energy services (see Poudineh and Jamasb, 2014). Smart distribution grids represent an example of partial energy system integration at a limited scale.

The systems of single energy vectors have evolved gradually over many decades, due in part to technological path dependency, resource availability, and evolution of demand. These systems share common economic and environmental sustainability objectives in the form of cost savings, supply security, equity, and decarbonisation. Therefore, looking forward, there exist clear advantages in the integration and coevolution of the different energy systems. Given that these objectives are shared across the vectors, a horizontally integrated system can help achieving these objectives more efficiently. One example of ESI at small scale is represented by the cogeneration plants in Denmark, the Netherlands, and Finland. The technology produces electricity and heat at higher efficiencies and lower fuel consumption than conventional plants (Pirmohamadi et al., 2019). Another example is combined water and power plants in Abu Dhabi that produce both electricity and desalinated seawater and has a thermal efficiency of approximately 63% compared to 44% of the conventional plants (Mahbub et al., 2009).

Figure 1 illustrates the integration potentials between the main network industries that have already existed for some years in several countries around the world. An increased interconnectivity is a key feature of ESI which is facilitated through ICT infrastructure. Also, a well-functioning integrated energy system requires that this interconnectivity happens in an appropriate institutional and economic framework. The figure shows that there also exists a business economics case for multi-utilities to emerge.

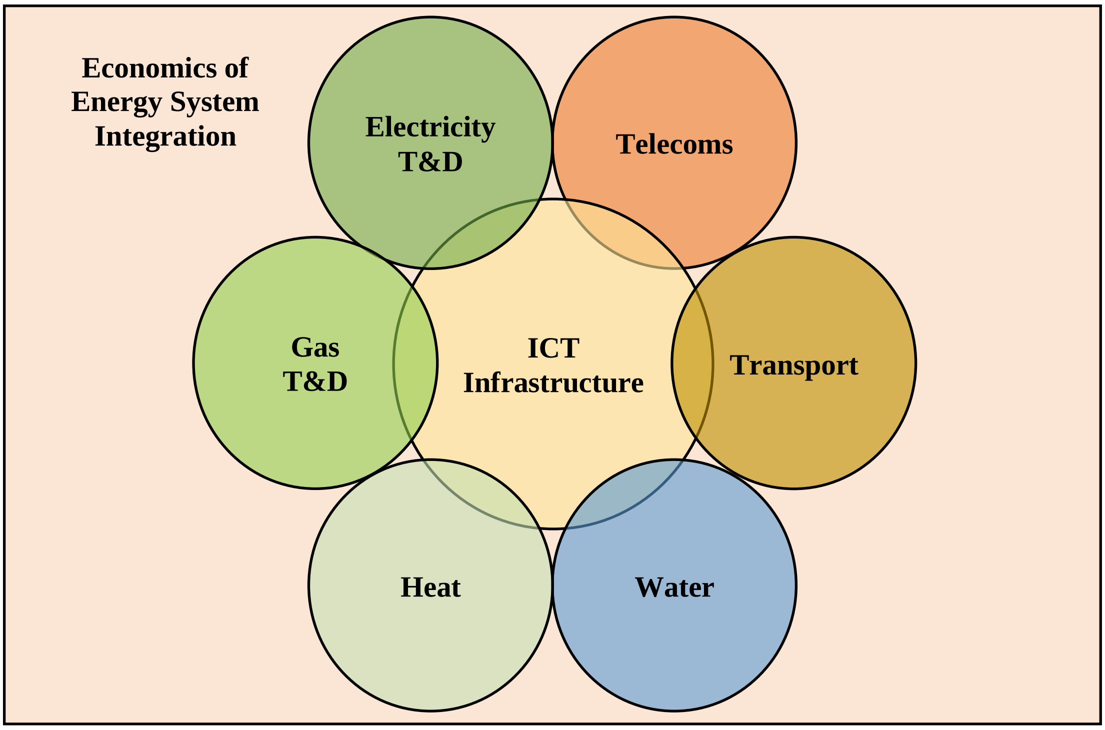

Figure 1: ESI as network of networks
Source: Own elaboration. Inspired by Sommer (2001a)
Note: T&D stands for Transmission and Distribution

Sommer (2001a) points out the role of deregulation and technological development – particularly in ICT – to a multi-utility business model in many countries. The study names a number of multi-utilities that relate to the sectoral overlaps featured in Figure 1, for instance, SEMPRA (Argentina) operates in both gas and electricity sectors, MÁV (Hungary) which offers transport and telecommunication services, or Metrogas (Chile) which provides services in gas and telecommunications. Most of the multi-utilities operate in two sectors, but some are active in more sectors, for instance, Vivendi and Suez Lyonnaise des Eaux in France, which operate in four different sectors.

Figure 2 depicts a simple architecture of an integrated gas and electricity system at the T&D network level. The relations and interfaces of the two systems permit a higher level of flexibility and efficiency in the system through potential substitution between energy sources to deliver the same services. Hosseini et al. (2018) explore the advantages of an integrated operation of gas and electricity T&D networks through a simulation. They show that coupled networks are in a better position than stand-alone networks to reduce carbon emissions and satisfy the energy demand under faults or variations of operating conditions such as those caused by variable renewable energy generation. However, they also find that this higher flexibility of the network may imply higher costs of operating the system.

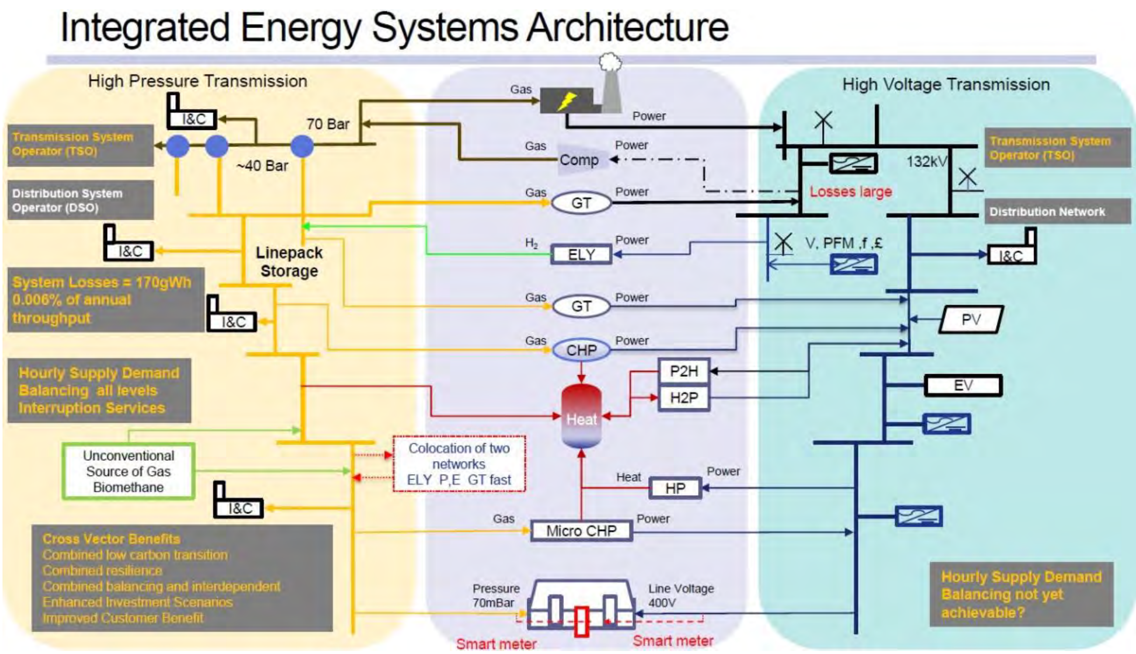

Figure 2: ESI between gas and electricity at T&D level
Source: Keith Owen (Northern Gas Networks)

This system architecture could be extended with financial and information flows that underlie the physical movements and delivery of energy to enable efficient operation of the system. Additional links with further sectors could be added to the framework and model. At the same time, reducing the institutional and regulatory barriers between the transmission and distribution networks could facilitate a vertical integration that would accommodate, for example, the integration of DR and regional integration (O'Malley et al., 2016). In general, ESI can be perceived at three different levels:

- First, in a broad perspective, energy system integration can be viewed as a 'network of networks' that encompasses a multi-vector energy system while each vector itself represents a network industry. Moreover, in order to maximise the synergies and efficiencies, ESI can be extended to include other network infrastructure sectors such as transport, data, and water.
- Second, each network industry, by definition, consists of vertically integrated activities. Therefore, vector and sector integration can be viewed in terms of

segments such as production, transmission, distribution and retailing. There may be a link between 'level' and 'scale', i.e., the higher we move up-stream in vertically integrated sectors the scale of system integration also increases as the utilities tend to be larger. Integration at higher levels can be more loosely arranged than through 'hard' physical connections but also, for instance, through coordinated planning and development.

- Third, better system integration can also be achieved within each of the above industries. In many countries, liberalisation has led to vertical separation of the energy industries. A system integration perspective also applies to the relationship between and within the separate segments of each of the industries concerned. For example, the role of electricity Distribution Network Operators (DNOs) and their relation to other actors such as the transmission grid operator, customers/prosumers, and distributed generation is being transformed. Active DNOs can better integrate electricity, heat, fuel, and demand response, and this will affect the conventional unidirectional balancing of load from transmission to distribution networks.

In sum, in a conventional non-integrated system, each energy vector meets the demand for a limited range of energy services. In an integrated system, demand for a given energy service can be met more efficiently and from a wider range of sources. For example, gas has historically been a major source of space heating. In an integrated energy system, the gas (or electricity) for space or process heating could be substituted with heat networks that are in turn based on different technologies. ESI should, therefore, not be perceived as a single universal model but as a paradigm based on a set of organising principles. The integration can be envisaged in the form of a multitude of integration efforts within and between each energy vector and other sectors.

3. Economics of Energy Systems Integration

In a decarbonisation perspective, ESI offers the prospects of providing a given amount of energy (and even other) services with least costs and emissions (see, e.g., Hosseini et al., 2018). However, while a physical integration of the main energy vectors goes some way towards this aim (and the description of how an ESI will be in the near future is taking shape), there is a lack of description of this paradigm in terms of its economic fundamentals. Despite technical viability, achieving ESI will ultimately depend on the provision of suitable market, regulatory, and policy framework. This framework should be based on sound economic principles and provide appropriate signals and incentives for the different actors.

A central feature of the liberalised gas and electricity sectors is that they are commercially (e.g., legally or accounting) vertically unbundled along the constituent functions of production, transmission, distribution, and retail. Separate from this, effective competition and regulation in these sectors and achieving low-carbon objectives require adoption and integration of new technologies (e.g., renewables, smart grids, smart meters, ICT systems, etc.), regulations, business models, and policies in the energy sectors.

It then follows that an integrated system should also be viewed as a dynamic structure to be efficient over time. O'Malley et al. (2016) highlight the need to continuously evaluate the system to assess its greatest possible coordination potential. In order for systems integration to achieve its objectives, it requires not only a harmonised or coordinated system, but also a coevolution of its constituent parts to achieve dynamically optimum benefits. Even in the liberalised sectors the need for monitoring the performance and investment is regarded as important. However, this evolution should be periodically assessed to avoid instability and uncertainty in the system that would deter new investment.

It should be noted that the energy system integration as discussed here does not represent a return to the central planning paradigm or the pre-liberalisation vertical re-integration structures of the energy system. Rather, the ESI is viewed as a decentralised, market-based, and incentive-regulated system. The challenge of achieving effective energy system integration is to enable integration within and across the different energy vectors to utilise the technical, economic, and commercial synergies and efficiencies at the energy system level, while maintaining the vertically separated segments within a market-based and incentive-regulated framework. In other words, the notion of integrated energy systems implies a form of technical and commercial (partial or full) horizontal integration of functions across the main energy vectors.

3.1 Economies of Scope, Scale, and Coordination

An example of ESI at small scale is the dual fuel suppliers of energy, showing that some integration at the retail supply level has already taken place. This is at the same time as some retailers have voluntarily abandoned their vertical integration of supply and generation. In the case of the UK, this integration was believed to improve economies of coordination (i.e., gains arising due to joint management of the inter-dependent activities) to the firm. In other words, to some firms, horizontal economies of scope can be preferable to the coordination economies of vertical integration.

Liberalisation of energy and other network industries has involved, among others, the vertical separation of each sector into its main constituent activities. In the electricity sector, for example, this has led to the separation of generation, transmission, distribution, and retail supply. This separation results in an increase in some costs due to loss of economies of coordination among these activities. These costs can be significant. Therefore, in liberalised energy sectors, the benefits of market competition and incentive regulation of the unbundled activities need to exceed the foregone economies of coordination from the loss of vertical economies of scope. A more integrated energy system can increase the benefits of market-based energy sectors.

Horizontal economies of scope, on the other hand, normally emerge from joint utilisation of common capital and labour inputs (Baumol et al., 1982). Generally, a horizontal integration could allow exploiting these economies of scope through the savings achieved by multi-utilities that provide a broad range of services that exploit the same network or provide similar services (such as billing) to their customers. Therefore, economies of scope imply that costs savings can be achieved when certain goods or services are produced together compared to a situation in which they are produced separately. In the case of network industries, the reaping of economies of scope can be better understood through joint management of knowledge related to regulation, environment, planning, and policy development (Abbott and Cohen, 2009).

Economies of scope can be computed by comparing the costs of joint production, $C(q_a + q_b)$ for the example of two goods or services (a and b), and the cost of producing the same amount of them separately, $C(q_a)$ and $C(q_b)$. Baumol et al. (1982) define the following ratio to measure the degree of economies of scope:

$$S = \frac{C(q_a)+C(q_b)-C(q_a+q_b)}{C(q_a+q_b)} \tag{1}$$

If S is greater than zero, that means that there are cost savings derived from joint production. Moreover, the degree of economies of scope will be greater as this ratio increases. However, it should be noted that these potential savings in cost efficiency can be offset by the coordination costs that can arise due to organisational rigidities from joint production (see Rawley, 2010).

The network segments of energy systems are generally natural monopolies rendering competition inefficient thus serving as justification for subjecting them to regulation. The existence of natural monopolies is linked with the presence of economies of scale associated with large fixed costs. The capital intensive nature of networks imply large capital and fixed costs and low marginal costs such that their Marginal Cost is always below their Average Cost (*MC*<*AC*). The cost structure of the networks implies that they exhibit economies of scale over the whole relevant market size. In other words, it is more cost and quantity efficient for a single network to serve the entire market. The economic property of natural monopolies can be expressed as in (2).

$$C(\sum_{i=1}^{n} Q_i) < \sum_{i=1}^{n} C(Q_i), \quad \sum_{i=1}^{n} Q_i \geq \bar{Q} \tag{2}$$

where C denotes the unit cost of output, Q_i is the output by firm i, and $\bar{Q}$ is the total quantity of the product supplied in a competitive outcome.

Economies of scale in natural monopoly energy networks can also be viewed from the perspective of network effects (see, e.g., Brennan, 2009). Within this perspective, network externalities are the source of network effects with the latter leading to economics of scale and declining average costs. While natural monopoly is the main justification for economic regulation, network benefits that result from network effects can be important in implementing this regulation. Although activities such as electricity T&D are viewed as natural regional monopolies, the arrival of new technologies and solutions such as DG may, as a consequence, affect some monopoly characteristics that imply the creation of new business models, competitive markets, and regulatory challenges (Corneli and Kihm, 2016). Broadly, some of the boundaries between market and regulation are not fixed and can be redrawn as a result of technological progress and regulatory considerations.

Some studies have attempted to examine the existence of economies of scale and scope for network utilities. Salvanes and Tjøtta (1998) showed natural monopoly characteristics in Norwegian electricity distribution networks. Farsi et al. (2008) analyse the economies of scale and scope of multi-utilities (gas, water, and electricity) in Switzerland and find considerable economies of scope and scale and large differences across companies. Fraquelli et al. (2004) finds similar results for Italy. They show that economies of scale and scope for multi-utilities are smaller than the median of the sample, while for larger utilities such cost advantages are not observed. Meyer (2012b) analysed the US electricity utilities and estimated the cost increase from an unbundling of generation to be about 19 and 26%, while this was 8 to 10% for separation of generation and transmission, and 4% for the separation of transmission alone. Gugler et al. (2017) estimated the costs associated with vertical unbundling of the electricity sectors in Europe. According to this study, vertical integration implies savings of around 14% for the median sized utility and more than 20% for large utilities.

It is also noteworthy that despite the potential benefits and cost savings for the consumers, the information asymmetry between multi-utilities and regulators can lead to distortions in the regulated sectors and less competence in the unregulated markets, if multi-utilities operate in both type of markets (Calzolari and Scarpa, 2007). This will represent an added complexity associated with the presence of multi-utilities in integrated utilities sectors.

3.2 Evolution of the Utilities Sector

Regulating a liberalised energy sector involves oversight of markets and competition as well as economic regulation of the natural monopoly networks while protecting the interests of the consumers. Regulating an integrated energy system is even more complicated and the ongoing changes in the energy sectors will pose challenges for the regulation of the sector. Many of the new challenges will be related to new horizontal links and interactions across the different energy sectors. Figure 2 illustrates some of the possible interactions between the gas and electricity sectors.

Figure 3 illustrates the parallels in the development of telecommunications and electricity sectors. This evolution has taken place within the wider context of shifts in the political ideology, economic arguments, and technological progress which facilitated the liberalisation of network industries. In under three decades, the perceived view of the nature of the energy and other network industries has transited from a 'public service' to one of 'commodity' and in recent years increasingly as a 'service'. In the latter stage, utilities would cater to the energy needs of their customers than supplying a required level of energy (Fox-Penner, 2009). This transition has also parallels in the evolution of the telecommunications sector. Figure 3 also evidences the need for the regulatory regimes to keep up with the technology development and market dynamics. Pollitt (2010) analyses the lessons from the deregulation of the fixed line telecommunications sector in UK which began with the privatisation of British Telecom in 1984 and the creation of The Office of Telecommunications (Oftel) as the country's first independent sector regulator.

Period / Industry	Pre-Reform: Before 1990s ROR Regulation *Public Service*	Reform: 1990s-2000s RPI-X Regulation *Commodity*	Post-Reform: After 2000s Output-Based Regulation *Service*
Telecommunications	Wired Service	Wireless Service	Data Service
Electricity Sector	Deregulation	Distributed Generation	Products and Energy Services

Figure 3: Evolution of telecommunications and electricity sectors

The role of new technologies has been instrumental in transforming the network industries and enabling the development of liberalised sectors. While there has been a trend towards decentralised solutions in the electricity sector, the ICT has passed from wired to wireless services and then to data services. Parallels can be drawn between the changes happened in telecommunications and the current challenges in the energy sector, e.g., digitalisation (transition from analogue to digital systems and packaging of data/information) and storage (streaming vs. storage).[4]

These changes have also been reflected in the regulatory frameworks pertaining to these sectors. In the pre-reform scenario the type of regulation was a Rate-of-Return (ROR) one until RPI-X price control was designed by Littlechild (1983) to be applied to the telecommunication sector and posteriorly adopted by the energy regulators. In the current post-reform context, the UK Cabinet Office (2017) recommends the application of an outcome-based regulation which should be based on consumers' valuation of the services delivered by these network industries. The UK energy regulator, Ofgem, has already adopted an output-oriented approach to the regulation of transmission and distribution networks which is based on efficient revenues needed to deliver specific levels of different outputs such energy, service quality, and environmental impact in consultation with customers (Ofgem, 2017).

3.3 Regulation in Integrated Energy Systems

The likely emergence of multi-utilities in an integrated energy system setting will give rise to the question whether this development will also require the establishment of multi-sector regulatory agencies to oversee their activities. As with the utilities, the economies of scale and scope are also relevant for the effectiveness and efficiency of multi-sector regulators. Here, the scale dimension represents the number of utilities within these sectors to be regulated, while the scope dimension relates to the number of sectors to be regulated. Moreover, a multi-sector regulator can be more efficient in sharing the fixed costs of the agency as well as the experience and expertise from different sectors.

A consideration for regulators in relation to integrated systems with multi-utilities is whether the different products and services are complementary, substitutes, or unrelated. This has bearings for the regulation framework and organisation of the industries (Severinov, 2003). This is in turn related to the cost of information as a form of rent given by the regulator to the multiproduct firm. It should also be noted that even unrelated products may be bundled together as a means of gaining comparative advantage through offering services and convenience to customers and to increase consumer loyalty.

[4] We are grateful to Tilemachos Doukoglou for his comments on this point.

Laffont and Tirole (2000) compare single-sector and multi-sector regulation. They consider that differences in the degree of development of the regulators in a country along with the potential to develop expertise and possibility of hindering industry capture can make single-sector regulation more appealing. Iossa (1999) and Gilbert and Riordan (1995) show that the regulator needs to give a higher information rent to a multi-product firm. Dana Jr. (1993) shows that the information cost of regulation is lower for a duopoly structure when the correlation of the marginal product costs is high, and is lower for a monopoly when the cost correlation is low or negative. Linnerud (2007) finds cost correlation, cross-price elasticity, and social cost of public funds as the main determinants of industrial structure with regards to allowing the formation of multi-utilities.

The multi-sector regulator model has been viewed as a solution for small or poor countries. These countries are more likely to have fewer and smaller utilities and thus less competition in these sectors requiring regulatory resources. The presumption is that smaller or poor countries could better share and utilise their scarce financial and regulatory expertise across different sectors. However, the cost savings need to be weighed against a lack of developing sector-specific focus and expertise and risk of institutional failure of the single-sector agency (World Bank, 1997). Schwarz and Satola (2000) find that multi-sector regulation can partially offset the issue of weak institutions in some countries. The authors enumerate a number of key pros and cons that emerge from multi-sector regulation, namely, the existence of contradictory effects in terms of industry and political captures, the set of precedents that may affect the risk and uncertainty perceived by potential investors, and the economies of scale compared to the loss of industry-specific technical expertise.

Network charges should send efficient signals to market participants for location and use of network services. Network charges can be applied to production, demand, capacity, and usage levels (Pollitt, 2018). However, the methodologies for network charges are not coordinated and they can vary from one sector to another and even within a sector. Network utilities have for long benefitted from network effects. However, due to technological progress, the demand side is increasingly active and consumers are beginning to also benefit from the network effects, and not only the producers. Network charges can usefully facilitate integration of energy systems by harmonising the economic principles and the charging methodologies.

The total cost of regulation of several utilities sectors can be a factor in some countries. On the other hand, since 2003, the UK electricity and gas regulator, Ofgem, has significantly grown in size (in terms of number of staff), while apparently not owing this growth to increase in economic regulation but from assuming new functions. Meanwhile the water sector regulator for England and Wales, Ofwat, has become smaller in the same period (Stern, 2014).

It is conceivable that the convergence of utilities services and technologies used to provide them can lead to the creation of multi-sector regulators. One example is the Spanish CNMC (National Commission on Markets and Competition). In Spain, the energy regulator (gas and electricity) merged with telecommunications and the regulators of other sectors (competition, railway and airports, postal services, and audio-visual media). This change took place in 2013 with the objective of reaching a more effective supervision through a coherent and integrated view, and an organic simplification to avoid a complex institutional framework and reduce potential duplications (BOE, 2013). Moreover, other aspects such as resource scarcity and potential economic savings derived from economies of scale along with precedents in other countries in which similar simplifications in regulatory structures were happening also motivated the creation of the new multi-sector regulator.

There are examples of multi-sector regulators in developed economies that show that this model can be feasible. In Northern Ireland the multi-sector regulator (UREGNI) is responsible for the regulation of the electricity, gas, and water sectors. It is noteworthy that UREGNI regulator has only few utilities to regulate. Can multi-sector regulators in large countries with many actors become too large to manage or achieve their goals effectively? The answer is not very clear. The California Public Utility Commission is an example of a multi-sector regulator that has managed the task in a sizable economy (World Bank, 1997).

One final issue that can pose a challenge to efficient multi-sector regulation context is that a distortion even in one constituent sector may require a complete adjustment of the whole regulatory system. This derives from the general theory of the second best discussed by Lipsey and Lancaster (1956). It implies that when one or more optimality conditions are not attainable in an economy represented by a general equilibrium system, then the next-best solution can only be achieved by moving away from all the other optimum conditions. In other words, in this context, the second best theory suggests that integrating an efficient sector with an inefficient one may actually result in a social welfare reduction.

4. Utilities and Business Models in Integrated Energy Systems

4.1 Multi-Utilities

A logical extension of energy system integration is that this structure would create incentives for new market opportunities. This would in turn facilitate the emergence of new types of firms and among them multi-utilities – i.e., firms operating in more than energy or utility sector. Such a development would be inevitable, if the predictions suggesting energy markets evolving into markets for energy services materialise. Multi-utilities as a concept and business model have always existed and are not very uncommon. Countries such as Cape Verde, Colombia, Costa Rica, Gabon or Morocco have had state-owned firms that have provided simultaneous utility services (Sommer, 2001a).[5] However, the liberalisation trend in the network industries will require revisiting the pros and cons of multi-utility business models and the various theoretical and practical issues involved in their regulation (see, e.g., Sommer 2001a, b).

A high level of specialisation in the businesses is expected to facilitate regulation as the range of services provided by the companies is narrower and the tasks performed by them are similar. On the other hand, the costs of coordination are higher due to the increased complexity of the system and the larger number and types of participants. The level of integration (number of different networks) and geographic scale (local, regional, national) will depend on the specific conditions of each system. Regulation of the distribution networks and their pricing methodologies will need to adapt to the needs of smart network technologies (Li et al., 2015; Brunekreeft et al., 2015) as well as to ESI with the objective of ensuring cost-reflective tariffs to end-users. In that sense, it is reasonable to carry out some harmonisation efforts to avoid strategic behaviour from multi-utilities as some costs could be shifted from competitive activities in one sector to regulated activities in another sector (Farsi and Filippini, 2009).

It should be also noted that the regulatory framework will over time influence the industry structure through different incentives, for example, via diverse compensatory systems for mergers as shown by Saastamoinen et al. (2017) for the case of Norwegian electricity distribution networks. The EU Directorate General of Energy and Transport requests policy makers to analyse the degree of economics of scope before making decisions regarding the separation of different activities in different sectors (DG Energy and Transport, 2004). Joint management however may also make the regulation of multi-utilities difficult due to the heterogeneity that may imply running businesses in different areas of services and privacy issues related to holding customer information held by the multi-utility.

Multi-utilities can achieve cost reductions or bundle their products and services to customers. In the UK some energy retailers already offer combined gas and electricity contracts to their customers. In theory, a regulator with near perfect information could allow horizontal diversification of utilities into other sectors if it could perfectly monitor the cost reducing efforts of the utilities in different markets (Sappington, 2003). However, this condition is not normally present in practice. Indeed the quality of information from diversified firms can deteriorate. Horizontal and vertical integration

[5] On the whole, multi-utilities are more likely to occur in private liberalised sectors in order to benefit from economies of scope. But as many firms are still consolidating their position in the core activity and also due to regulatory uncertainty or barriers, state-owned multi-utilities have been observed in more cases. We are grateful to an anonymous referee for comments on this issue.

also result in private information held by the multi-utility and thus making regulation difficult (see Calzolari and Scarpa, 2007).

In Norway, the energy regulator has required legal separation of electricity distribution utilities from their activities in the telecommunications sector although this potentially deprives the companies from some economies of coordination. While electricity distribution is a natural monopoly and thus a regulated activity, telecommunication is a competitive industry with a regulated segment in the local loops. The utilities, would in principal, benefit from economies of scope. Horizontal diversification could present the firms with some possibility of shifting costs from a competitive activity to a regulated activity that earns a certain rate of return on the regulatory asset base. In this case the benefit of preventing the utilities from shifting costs was thought to exceed the (socio-economic) benefits of economies of scope.

4.2 Business Models

Since the liberalisation of network industries, the private actors in these sectors have exhibited a high degree of responsiveness to market conditions and regulatory incentives and changes in them. Policies that are devised without regards to this will likely lead to unintended consequences. A naïve approach to ESI would be to design and manage the system by a central planner[6] instead of relying on market and incentive mechanisms. Despite the attractiveness of this solution, this approach has proved to be unsuccessful mainly due to the lack of flexibility to respond to changes in the operating environment, i.e., lack of economic case, regulatory incentives, price signals, subsidies, etc. Indeed the resilience of market actors in terms of ability to response to market design and regulatory incentives through evolution of their business models can serve as instrument of achieving policy objectives.

In some instances the best-response behaviours may not deliver 'satisfactory' solutions for the society as a whole thus leaving scope for intervention. Brown and Sappington (2017) find that an optimal regulatory policy frequently implies a bias against new projects on distributed energy resources due to substantial cost sharing with utilities, which reduces the rents received by the incumbent utilities. They also find that the DR policy designed by Federal Energy Regulatory Commission (FERC) in the US to compensate consumers for reducing their electricity consumption during periods of peak demand and high costs can produce welfare losses.

Along with the inclusion of more distributed generation and demand response to the system, new business models will emerge. Similar to the literature on smart grids (see e.g., Rodríguez-Molina et al., 2014; or Shomali and Pinkse, 2016) there is a need to

[6] This can be seen even as some form of benevolent dictatorship.

study how new businesses are likely to create, deliver and capture value in an integrated energy system. Gassmann et al. (2014) present the basics elements of a business model in terms of (i) value chain, (ii) value proposition, and (iii) revenue model. Given the amount of discretion that decision makers can exert over sector structure, design of organised markets, and regulatory framework, all the above three elements of business model can be enabled or prevented by them. Also, ESI does not necessarily imply a sole ownership of integrated systems by the same actor. Rather, Jamasb et al. (2018) propose a business model for electricity distribution networks that is suitable for developing countries and relies on innovation, external collaboration, and partnerships that could be achieved through organisations specialisation and outsourcing of activities.

The changes in the structure of incumbent utilities and the arrival of new actors in the German electricity market following the Energiewende illustrates the extent to which the utility business models become a dynamic feature of the market (see Brunekreeft et al., 2016). Some German utilities separated their renewable activities from conventional generation and network activities. More recently, business models have evolved through asset swaps where E.ON divested generation assets to specialise in network and retail business while RWE divested assets to merge conventional and renewable assets into a new utility. It is therefore essential to better understand the dynamics and driving forces in integrated systems to shape an appropriate regulation and policy framework. Some actors may choose to specialise in a given sector or activity. For example, Ørsted A/S (formerly DONG energy) divested its petroleum activities to focus on renewable energy and in particular wind.

There are many ways that incumbent utilities are redefining their business models. However, a closer examination reveals some common thread among these. First, as economies of coordination are difficult to utilise due to increasingly strict rules for upholding unbundling and the desire of some firms to specialise in a segment of the industry, some attention is now focused back on the benefits economics of horizontal scale. In an integrated system, it is likely that significant benefits from horizontal economies of scope are identified thus leading to the emergence of multi-utility firms. This is where the theories of industrial organisation and the real world complexities of multi-sector regulators overseeing the operation of multi-product utilities meet.

5. Information and Communication Technology in Integrated Systems

Smart energy systems of future will be instrumental in integrating the different energy vectors. At the same time, they will integrate large amounts of DG and DR resources within the networks (Soares et al., 2012; Poudineh and Jamasb, 2014). As mentioned earlier, in the UK, the electricity generation capacity connected to the distribution networks has seen a rapid rise. Distributed installations tend to be relatively small in terms of their capacity but they are large in terms of numbers. Technical data are required for planning, operation, and maintenance of networks. This information can be of value to major demand and generation sources and as well as other actors such as aggregators as various stakeholders have an interest in how the networks are likely to develop over time. The need for enlarging the transmission and distribution capacity could be reduced through enhancing the management of the demand for energy (Ruester et al., 2014; Jenkins and Perez-Arriaga, 2017).

An integrated energy system requires a larger degree of synchronisation of its constituent parts. Advanced ICTs will facilitate efficient delivery of additional energy source and consumption of energy. Advanced metering infrastructure along with new intermittent supply and demand side actors, and increased interaction between them requires enhanced ICTs in terms of hardware and software. This also entails a higher harmonisation of systems and information standards, which are focused on the data exchanged by different entities, and communication standards, focused on the physical infrastructure.

Information and communications technologies can reduce the transaction costs of this coordination. Lower transaction costs can increase competition by lowering the barriers to entry and allowing new business models to foster. Increased transparency, on the other hand, can reduce the information asymmetry between the sector regulator and the firms, market power, and strategic behaviour. Some operational data such as power flows, system dispatch merit order, network congestion, and network energy losses can be of commercial value to generators and suppliers and assist them in their decisions. In addition, the ICT will also need to increase trust between the many different participants in the system through new technologies such as Blockchain.

Until recently the main beneficiary of the network effects in the energy sector have been the utilities and in particular the transmission and distribution networks. Aggregation of demand from a large number of users allowed the networks to smoothen the load and balance the supply and demand and increase the efficiency of the operations, planning, and investments. However, the continuous development in ICT is increasingly enabling the consumers to reap more benefits of large numbers of customers and to take advantage of network externalities and network effects for managing their demand response and energy exchanges with the grid and other users. As technological progress increases the network effects in integrated systems, this will require that the regulatory framework be revisited accordingly (Brennan, 2009). Due to the decentralisation of power generation and arrival of different renewable and storage solutions, the nature of maintaining system reliability will also change. ESI will require some flexibility to manage the uncertainty through ICT solutions. Moreover, the increase in the number of links among the many nodes of a decentralised but highly coordinated system requires digital interconnection security.

In addition to technical data, other relevant information for the system are commercial and financial data to inform participants which include real-time wholesale and retail prices, network charges, balancing and ancillary markets, etc. Other external information, such as the statistics provided by weather forecasting services, will also be of extraordinary importance. Such data are increasingly valuable to network operators and market participants as the share of renewable energy connected to transmission, distribution, and consumer premises increases. As the energy markets increasingly move towards service and value-based propositions, the importance of ICT in provision of them will also grow. Related to this, Joskow (2011) shows that the use of levelised cost is inappropriate for comparing dispatchable (i.e., conventional) against intermittent (i.e., renewable) technologies and market value-based metrics should be used instead. Neuhoff et al. (2007) discuss that market value models incentivise project developers to invest in system-friendly locations and technologies for renewable energy installations.

From the economics point of view, network industries such as telecommunications exhibit network effects and network externalities. This means that the value of being part of a network increases with the number of the members in the network (Katz and Shapiro, 1994). This places the firms operating the networks in a strategic position with regards to decisions concerning technical compatibility and network sharing and how to appropriate these benefits (Economides, 1996). A degree of compatibility is, however, generally required by the regulators as in the case of smart meters, but this could be subject to variations. Networks may lead to specialisation, as Bramoullé and Kranton (2007) show for the provision of public goods. Participation by contributors or free riders can be determined by their position in the network and individual incentives. This specialisation can be beneficial for the society and hence it is important to establish the right incentives to take advantage of potential welfare increase. This could be applicable to a situation with prosumers, consumers, storage units, and EVs in ESI.

Development of ICTs is crucial for smart energy grids and ESI. Their role can be likened to the development of the telecommunications industry and that of the power sector after deregulation and emergence of DG, DR, storage, EVs, etc. One example is the importance of ICTs in smart electricity distribution networks. In this segment there are significant system benefits from aggregation of users in the form of network effects. In a DNO with active demand, users give feedback to the system by adjusting their consumption in response to generation or network constraints or price signals. This network effect is mainly possible with enabling technical and commercial data and information systems. This effect increases with the emergence of smart meters, cloud-based services, etc. In that sense, aggregators which can be retailers or independent agents, can be instrumental for creating system or network benefits.

Smart distribution networks integrate decentralised resources such as DG, DR, and storage units and require a combination of different data and information systems with the aim of reducing time delays and transaction costs. A reduction in transaction costs through ICTs can increase competition by lowering the barriers to entry. Also, increased transparency reduces information asymmetry and market power and strategic behaviour by actors. Smart grids and ESI enable a range of demand services and responses from a large number of smart devices and require large amounts of data and communications. As a result, data traffic congestion may occur and affect the quality of the services. Avoiding this problem requires reducing the trip delay time between different nodes and layers of the ICT architecture.

Heron et al. (2018) simulate a three-tier tree-star topology with three node types and finds an inverse relationship between the round-trip delay and the number of substation nodes. The system is technically optimised for the maximum of local hubs simulated implying that cost is the main restriction. From an economic viewpoint, the marginal cost of additional hubs should be equal to the marginal benefits (or revenue) of the investments. This may be reflected in the opportunity cost of time delays. Simulations indicate that for many substation nodes, the marginal gain in terms of delay reduction tends towards zero. On the contrary, as large reductions in installation cost of new substations are not likely, the optimal number of substations could be not high. Related to this, Buchmann (2017) discusses the merits of centralised and decentralised data exchange systems with a view to their scale and scope. The study proposes using a 'polycentric' design where competition determines the optimal degree of decentralisation of the system.

6. Conclusions and Policy Discussion

An integrated energy system can be viewed as a means towards achieving the objectives of the trilemma of energy security, decarbonisation, and affordability. The appeal of ESI is the ability to utilise the synergies and overlapping of the main energy vectors and infrastructure sectors towards achieving their shared objectives. However, in order for an integrated system to create added value, the benefits of the system must exceed that of the sum of its constituent parts. Despite the increasing technical literature about ESI, there is still a lack of understanding on how that system will look like and what will be the main issues from an economic perspective. In this paper we have tried to discuss some characteristics of ESI related to economic principles, regulation, and business models.

As system integration is increasingly technically feasible, the economic and regulatory aspects of this new order are unexplored. While ESI presents obvious efficiency benefits, such as reducing the transaction costs, providing flexibility to meet the demand for energy services, and economies of scope, it also presents challenges. Therefore, there is nothing automatic about the benefits of integrated system as opposed to non-integrated ones. The performance of the integrated system and design will ultimately be determined by the economic and regulatory framework and rules.

An integrated energy system will bring about inevitable changes in the business models of the incumbent firms as well as emergence of new ones. Multi-utilities are likely to emerge to benefit from horizontal and vertical economies of scope but, as discussed, this will pose practical economic and regulatory challenges. Regulatory framework should enable new business models to evolve in both the competitive and regulated parts of the system. Integrated infrastructure systems will also revise the issue of multi-sector regulation. It is noteworthy that efficient multi-sector regulation may require a complete overhaul of the whole regulatory system even after distortions in a single energy sector, according to the theory of the second best.

Finally, the unbundled but vertically dependent sectors will remain highly dependent on their networks to deliver system integration. It is through networks that the system can integrate diverse generation resources and aggregate demand. In this sense, utilisation of network externalities and benefits in the integrated sectors will be a key feature of ESI. New technologies will be the main facilitator of the integrated systems. New technologies will enable physical interaction of different activities in new ways. However, ICT will be the catalyst of system integration by allowing efficient utilisation of physical systems while facilitating the role of economic mechanisms in integrated systems.

This paper is the first attempt towards outlining the economic aspects of energy system integration. Several topics addressed here deserve further examination, while other areas such as the social and behavioural aspects of system integration need to be studied. Additional analysis is needed to further develop the socioeconomic issues of energy system integration. Future lines of research include discussing the definition of ESI based on real data and measuring to what extent an integration of energy systems has already been achieved. As it has been mentioned before, ESI will be context-specific and hence will take different forms depending on the particular conditions of each system. However, if we assume the pillars of the energy trilemma as the main goals of ESI, it will be helpful to perform policy analyses to inform decision-making and the success in achieving the intended targets.

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Appendix

Transmission Network - Total UK	2012	2013	2014	2015	2016
Installed capacity (MW)	**81,909**	**76,393**	**74,608**	**70,943**	**69,649**
Coal*	25,811	20,736	18,873	17,013	14,257
Combined Cycle Gas Turbine	33,091	31,829	30,904	30,468	30,878
Conventional Thermal Gas	540	540	540	540	540
Oil	2,725	1,370	1,370	-	-
Nuclear - Magnox	490	490	490	-	-
Nuclear - Pressurised Water Reactor	1,191	1,198	1,198	1,198	1,198
Nuclear - Advance Gas-cooled Reactor	7,550	7,685	7,720	7,720	7,720
Open Cycle Gas Turbine	1,292	1,423	1,387	1,248	1,199
Hydro	1,213	1,213	1,226	1,228	1,228
Onshore Wind	1,805	2,713	2,747	2,777	3,660
Offshore Wind	2,397	2,721	3,507	3,716	3,628
Bioenergy	976	1,647	1,817	2,226	2,460
Pumped Storage	2,828	2,828	2,828	2,828	2,900
of which, good quality Combined Heat and Power	2,159	2,113	2,141	1,976	1,976

Distribution Network - Total UK	2012	2013	2014	2015	2016
Installed capacity (MW)	**14,482**	**16,299**	**20,193**	**25,555**	**28,843**
Coal*	589	28	33	22	22
Combined Cycle Gas Turbine	2,562	2,530	2,586	2,363	2,221
Oil	468	448	350	374	302
Diesel Engines	134	134	138	138	-
Open Cycle Gas Turbine	166	105	90	90	-
Conventional Thermal Gas	707	833	883	835	862
Hydro	482	496	503	548	607
Onshore Wind	4,099	4,803	5,789	6,445	7,263
Offshore Wind	599	975	994	1,378	1,666
Bioenergy	2,183	2,372	2,731	3,032	3,275
Photovoltaics	1,756	2,873	5,424	9,535	11,899
Wave/Tidal	7	7	9	9	13
Other Fuels**	732	695	664	788	714
of which, good quality Combined Heat and Power	3,806	3,811	3,752	3,754	3,595

* Includes mixed fuel stations (coal/oil, coal/gas) and co-firing coal stations.
** Includes coke oven gas, blast furnace gas, other gas/liquid/solid waste and waste heat from high temperature and chemical processes.

Source: DUKES (2017)