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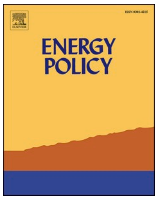

Energy Systems Integration: Implications for public policy[☆]

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ABSTRACT

Energy Systems Integration (ESI) is an emerging paradigm and at the centre of the EU energy debate. ESI takes a holistic view of the electricity, gas, and heat sectors to deliver a clean, reliable, and affordable energy system. By using the synergies within and between sectors, ESI aims to increase flexibility in the energy system, maximise the integration of renewable energy and distributed generation, and reduce environmental impact. While ESI-enabling technologies have been studied from a technical perspective, the economic, regulatory, and policy dimensions of ESI are yet to be analysed in depth. This paper discusses ESI in a multi-step approach. We first focus on the economics of ESI-enabling technologies. Then we briefly discuss how the EU national regulators incentivise their adoption. Major economic and policy barriers to ESI are identified and policy solutions to overcome these barriers are proposed. We conclude that current regulatory frameworks in the EU do not sufficiently stimulate ESI investments and only through proper design of incentives ESI can be adopted.

1. Introduction

Climate change concerns are transforming the energy industry from technical, economic, and political viewpoints. For centuries, fossil fuels have been the main sources of energy due to cost advantage and high energy contents. The energy and transportation sectors have mostly depended on fossil fuels, accounting for two-thirds of total CO_2 emissions (IEA, 2019). Hence, the focus of policymakers has been directed towards decarbonisation of these sectors. In light of the rapid technological developments in clean energy resources, the transition towards a zero-carbon energy industry appears now attainable. Technological advances have considerably lowered the cost of distributed generators, which use renewable rnergy sources (RES), such as wind and solar, and demand-side solutions.

As a result of cost reductions and policy support, renewable power generation has seen adopted at the industry and households and is a focal point of the EU's agenda. Although this trend has economic and environmental benefits, it also imposes a challenge to the energy sector. For instance, the integration of RES and Distributed Generation (DG) capacity will lead to higher operational and capital expenditures in transmission and distribution networks (Cossent et al., 2011, 2009; de Joode et al., 2009; Lo Schiavo et al., 2013). Moreover, economic and regulatory aspects of integrating DG into the electricity networks (and, recently, heat networks) need to be revised and improved (Cambini, 2016; de Joode et al., 2010; Jenkins and Pérez-Arriaga, 2017; Peças Lopes et al., 2007; Strbac, 2002).

As decarbonisation policies promote further adoption of RES generation, there is a need for an approach that supports streamlining of renewables integration while providing a sustainable and reliable energy system. To this end, the EU aims at encouraging the development of cost minimising solutions across sectors from a system perspective (European Commission, 2019a). By taking a holistic view of the energy systems to exploit the synergies between them, Energy Systems Integration (ESI) can reduce the investments required to achieve decarbonisation compared to a scenario in which investment planning is carried out separately for each network. Integration of a significant amounts of RES electricity and using this excess capacity to generate hydrogen in Power-to-Gas (P2G) facilities is an example of benefiting from the synergies between electricity and gas networks. Otherwise, this electricity would have been curtailed or stored in costly batteries. The

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same is true between heat and electricity networks in centralised or local Power-to-Heat (P2H) and Pumped Heat Electrical Storage (PHES). Future decarbonisation plans in these energy networks, as it is on the EU's agenda, cannot be achived without considering shared technological potentials which can significantly reduce the cost of the shift towards a zero-carbon future. These solutions can be more cost-effective than traditional capital-intensive solutions such as grid expansions and reinforcements.

Such synergies are not only found in the energy sector but also between energy, telecommunications, transport, and even other sectors. A cost-effective decarbonised transport sector requires planning of a cost-effective electricity infrastructure within the transport network to integrate Electric Vehicles (EVs) and other electrified means of transportation. This is needed for a reliable electricity network that is not bearing the costly flexibility issues on its distribution and transmission networks due to coupling with other energy networks and the integration of storage and conversion technologies.

In addition, digitalisation is creating new possibilities to speed up the energy transition and evolution of a spectrum to easily manage integrated energy and transport sectors. Examples of the role of the Information and Communication Technology (ICT) sector include demand response programmes which help balancing of energy demand and supply and the use of blockchain technology to improve communication among the grid users.

Integration, also called sector coupling, is recognised as a strategic means to make Europe the first climate-neutral continent by 2050 in the new European Green Deal (European Commission, 2019b), signed by the European Commission in December 2019 and supported by the European Parliament in January 2020. The key role of ESI in the EU's future energy sector is evidenced by the Ten-Year Network Development Plan (TYNDP) jointly prepared by the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Network of Transmission System Operators for Gas (ENTSOG) (ENTSOG and ENTSO-E, 2019). The scenarios described in the TYNDP will be used in Cost-Benefit Analysis (CBA) to identify European transmission and storage infrastructure projects that are crucial for the development of the European energy market integration.

ESI benefits from technological developments in the information and communication sector as well as in Energy Storage Systems (ESS) and conversion technologies to improve flexibility and reliability of energy systems while reducing the overall costs. In addition to technical advancements, implementing ESI requires coordinated system development policies and regulatory frameworks. However, the existing literature has almost exclusively addressed ESI from the technological and business-model dimensions.

This paper recognises the importance of these aspects, and provides an economic overview of the abovementioned technologies as well as discussing their role within an integrated energy system. The case for ESI stems from the economics of the energy sector, and the relevance of technology lies in its ability to shape and affect them. Regulation has a role in guiding this process while overcoming the barriers related to the structure of the industry. For this to be achieved, regulation needs to keep up with technological progress and the evolving needs of the energy system. This implies an improved coordination/cooperation between current sector-specific regulators and the deployment of a systemic view that might be attained through multi-sector regulation (Jamasb and Llorca, 2019). These subjects, contrary to the technical aspects of ESI, have not been explored adequately in the literature. The main contribution of this study is to identify and discuss regulatory and policy barriers towards the attainment of ESI and make recommendations to overcome these barriers.

The remainder of the paper is as follows. Section 2 discusses the concept of ESI. Section 3 is an overview of the technologies that facilitate the implementation of ESI. Section 4 presents an overview of conventional and most recent regulatory frameworks with respect to their approach towards innovation. Section 5 reviews the state of efforts in four major EU countries to foster network innovation, from a regulatory and investment perspective. Section 6 analyses economic and regulatory barriers towards ESI implementation. Section 7 discusses policy implications and presents conclusions.

2. Energy Systems Integration

ESI is an emerging paradigm which proposes a holistic view of the energy systems, rather than a perspective based on single segments (i.e., generation, transmission, distribution, retail) within a specific sector (i.e., electricity, gas, heat). The goal is to reduce total system costs while contributing to achieving a clean, affordable, and secure energy system. The rationale behind ESI is the existence of synergies within and between energy sectors that can provide efficiency gains. These are attributable to vertical and horizontal economies of scope and to the possibility of lowering transaction costs between grid users. While some of these synergies have always characterised the structure of the energy system, others are now emerging due to technological progress.

The reforms that started in the 1990s led to the unbundling of vertically integrated utilities and to splitting them into competitive and regulated segments. As a result, transmission and distribution segments became subject to economic regulation to maximise social welfare.[1] As discussed by Jamasb and Llorca (2019), prior to the reforms, the vertical structure of network utilities enabled them to benefit from economies of scope. Gugler et al. (2017) estimate the cost savings due to vertical integration of transmission and generation in medium-sized utilities to be about 13%, with higher cost savings for larger firms. This cost reduction was the result of the common usage of inputs and of information and risk-sharing (Gugler et al., 2017). The rationale for unbundling was to exert competitive pressure on generation and retail segments, deeming that this positive effect would offset the synergies loss.

In recent years, the energy sector has rapidly changed from being purely efficiency-oriented to emphasise also environmental sustainability. EU countries have committed to cut CO_2 emissions to address climate change concerns. This has led to the adoption of RES generation, and a shift from a model with centralised generation and unidirectional power flows to one with distributed generation and bidirectional power flows. This transformation carries new challenges, mainly attributable to the non-dispatchability of renewables due to their intermittent nature. This makes it harder to balance electricity demand and supply. When peaks in electricity production occur, and the load cannot follow generation, curtailment of generators becomes necessary. Contrary, the use of conventional backup capacity (e.g., fossil fuels) is needed in the opposite scenario. DNV GL (2014) estimated that – without further investments in network capacity – more than 100 TWh of renewable energy will be curtailed per year by 2030. Cost-efficient integration of RES thus requires substantial investments in infrastructure for network expansion and for the installation of backup generation.

Although the need for investments cannot be avoided, regulators across Europe recognise that system flexibility can help reach a cost-efficient outcome.[2] While traditionally flexibility has been provided by matching generation to demand, new technologies offer flexibility by targeting both supply and demand. Demand Response (DR) can help consumers through price signals and match demand and supply. Energy storage – such as Electric Batteries (EBs) and Plug-in Electric Vehicles (PEVs) – and conversion systems – such as Combined Heat and Power (CHP) or Power to Gas (P2G) – allow storing energy when production exceeds demand. DG can help minimise transport costs and network

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[1] These possess natural monopoly characteristics and therefore are required to be regulated.

[2] Ofgem defines flexibility as "*modifying generation and/or consumption patterns in reaction to an external signal (such as a change in price) to provide a service within the energy system*" (Ofgem, 2013, para. 4).

losses by consuming energy closer to where it is produced. These technologies exploit synergies within and across energy sectors by enhancing coordination among stakeholders.

In order to identify and exploit these synergies, there is a need for a comprehensive outlook that encompasses all energy systems. Current discussions on viewing electricity distribution and transmission networks as a whole suggest that treating these networks with a whole system approach[3] (CEER, 2018) can provide further reliability and efficiency. However, this approach does not allow taking advantage of the synergies that exist between different energy systems since the focus is on the electricity sector. The ESI paradigm looks at how economies of scope and coordination as well as the synergies between energy networks, including electricity, gas, and heat, can provide an energy system that is clean, secure, and affordable.

Fig. 1 represents an integrated electricity, gas, and heat energy system.

With enabling technologies such as storage and conversion systems acting as the interfaces between networks, integration of energy networks can occur both at horizontal and vertical level. This integration can be organisational, operational or physical, and it can involve different stakeholders (generators, network operators, retailers, consumers) within and across sectors. More specifically:

- From an organisational point of view, it implies a bundling of activities, previously performed by different actors, under a single entity, to take advantage of economies of scope. An example, at vertical level, is self-consumption, where consumer and generator coincide. At horizontal level, this could result in the emergence of multi-utilities, that is, utilities which operate in different sectors, such as electricity, gas and heating. A further example is given by generators that operate in different markets, such as CHP generators.
- From an operational point of view, it works by providing interfaces that help lower transaction costs and increase coordination between operators. An example at vertical level is the use of EBs to offer ancillary services. At a horizontal level, we could have flexibility providers who use conversion technologies as P2G.
- From a physical point of view, it can mean cross-sectoral infrastructure planning (such as the scenarios described by the TYNDPs) in order to reduce total investment and operating costs.

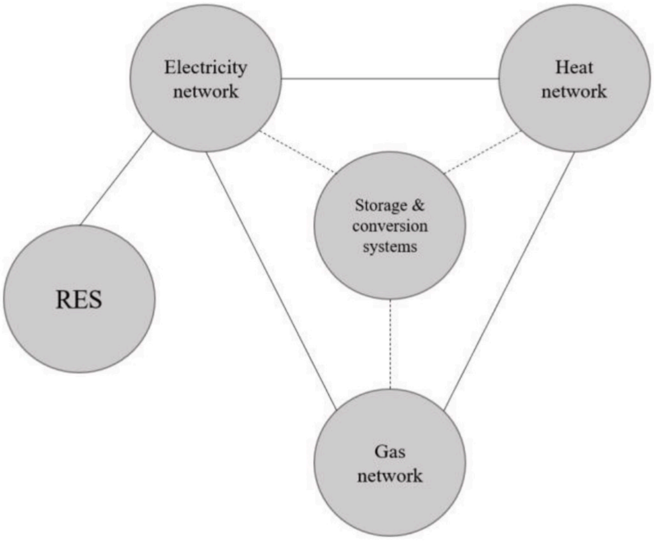

Fig. 1. Integration between the energy networks.

ESI is a combination of different types of integration. Due to the wide scope of ESI solutions, there is no specific single or optimal solution that can be recommended when adopting it. In fact, energy systems are idiosyncratic: path dependency and the need to consider local concerns, resources, and political agendas are likely to cause each country – and even different regions within a country – to require different ESI solutions. There is, therefore, a need for bespoke approaches that take into consideration these peculiarities and provide context-specific framework. Furthermore, Jamasb and Llorca (2019) point out to dynamic aspect of ESI and that it needs to coevolve with the energy system.

As in the case of RES generation and DG, technological progress can lead to changes in the structure of the energy industry, the appearance of new players and the emergence of new opportunities. Moreover, the boundary between markets and regulation is not fixed: although technological advances can shift its position, regulators also have a role in deciding it (Jamasb and Llorca, 2019). ESI needs to be able to recognise these changes to find and exploit new synergies were they to occur.

3. Technologies for ESI

The role of integrated technologies is recognised in the literature. Badami and Fambri (2019) propose a methodological approach for analysing the synergies between different energy networks to cope with increasing RES penetration by using flexibility-enhancing technologies. Brown et al. (2018) propose a cross-sector and cross-border energy model of Europe to estimate the economic effect of flexibility options (energy conversion and storage) and cross-border transmission in a scenario where CO_2 emissions are reduced by 95% compared to 1990 levels. They find that the flexibility option leads to a reduction in total system costs of 28%, while cross-border transmission system cost saving is 25%.

Rather than analysing these technologies from a technical viewpoint, this section discusses the role they can play in ESI, their economic dimension, and their economic impact. We classify these technologies in three categories: ICT, storage systems, and conversion technologies.

3.1. Information and Communication Technology

ICT transforms the way energy networks interact with each other and with other network industries, such as the telecommunication and transportation sectors. Rapid technological development in the ICT sector facilitates the transition towards a low carbon energy system as well as the exploitation of the synergies that exist within and between energy systems. In fact, it is through ICT that grid user coordination, active participation of consumers, smart network management, and synchronisation between multiple energy networks become possible.

ICT is a core component of ESI, as it allows the collection of generation and consumption data that can be used to balance supply and demand within a network and to enhance the stability of the energy system. In addition, ICT facilitates the coordination and data exchanges within and between energy networks, which leads to lower transaction costs and more efficient network management. Furthermore, a better-synchronised energy system enables the use of conversion technologies and allows a price-driven choice of the energy mix, which increases the affordability of the system as a whole. This, together with information transparency provided by ICT, can increase competition and emergence of new business models in the energy industry (Jamasb and Llorca, 2019).

Improved communication between grid users is required to facilitate

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[3] Through a Whole System Approach (WSA), Distribution System Operators (DSOs) are required to take into account the benefits of other DSOs and Transmission System Operators (TSOs) when they plan their investments. This will require improved coordination between DSOs and TSOs as well as a holistic view of the electricity network rather than focusing on one segment (CEER, 2018).

the integration of DR,[4] DG, and, more recently, ESS and PEVs. DR and DG, in particular, are recognised by the EU in article 14/7 2003/54/EC of the electricity directive and later in Directive (2009)/72/EC to be an alternative to the installation of new network capacity that is required to meet additional demand (European Parliament, 2009, 2003). In electricity networks, communication between grid users is carried out through Smart Grids (SGs).[5] The diffusion of SGs in the EU has been analysed in detail by Cambini et al. (2016b). The study investigates the regulatory factors affecting SG investments in Europe using a dataset of 459 innovative SG projects. They show that incentive-based regulatory schemes and the adoption of innovation-stimulus mechanisms are key enablers of SG investments. Although SGs require significant capital expenditures, innovation in the field of ICT can reduce the cost of its enabling components (e.g., voltage regulators, feeder switches, capacitor banks). DG INFSO (2009) points out how standardisation can play a role in decreasing the cost of SGs.

Moreover, the use of ICT can provide further benefits in terms of new services to the grid. Through the use of blockchain technology, ICT allows to address the issues of grid security, privacy, and trust (Mollah et al., 2019). Emerging 5G networks and 5G-based Internet of Things could be key enablers of DR thanks to 5G's high transfer speed, reliability, security, low power consumption, and the vast number of connections (Hui et al., 2020).

3.2. *Energy storage technologies*

Energy storage is a multi-faceted concept and can be provided through several technologies. Pumped Hydro Storage (PHS) is currently the most utilised storage mechanism[6] with a capacity equal to 3% of the global generation capacity (Ameli et al., 2017). Nevertheless, recent years have seen the emergence of alternative technologies, mainly in the form of EBs. Storage systems in suitable parts of the value chain can help to decouple supply and demand of energy. In addition, they help integrate intermittent sources of energy more efficiently, which in turn can improve the flexibility and reliability of the energy system. Jamasb (2017) points out that storage technologies differ in size and type of services they can offer from very short-term reliability services to medium-term energy supplies.

Ugarte et al. (2015) suggest that the operation of storage systems can be classified as network- or market-oriented, depending on whether, respectively, network operators or end-users are the beneficiaries. By using storage services, the RES feed-in is managed more efficiently. Network operators can store the excess feed-in when the demand is low and utilise it when a peak in consumption occurs (Ugarte et al., 2015). In addition, operators can use data acquired through smart meters to reduce network congestion and decide about further network expansions considering storage capacities (VDE, 2015). Transmission operators can use storage systems to balance voltage and frequency and stabilise the grid.

Li and Hedman (2015) analyse the economic impact of energy storage systems on the cost of conventional generators in a scenario of high penetration of renewable resources. They show that, with the deployment of storage technologies in power systems with high penetration of RES, the average hourly costs for conventional generation is lower. They conclude that storage systems can reduce the need for traditional generation, which in turn lowers total system costs.

By using SGs and the price signals they receive from retail markets, traditional consumers[7] can decide whether to go off-grid and use private storage or electric vehicles as a form of a small-scale storage system or to stay connected to the grid. ESS can be particularly beneficial to prosumers. Where regulation allows it, prosumers can store their excess electricity production and self-consume[8] it later on to avoid both high volume-based and capacity-based tariffs.[9] Technological progress in consumer electronics and – more recently – of electric mobility, is making storage solution considerably cheaper (BloombergNEF, 2019).

Deployment of EBs requires large capital expenditure (Atherton et al., 2017), which is the main barrier to the adoption of these technologies (Bhatnagar et al., 2013). High capital cost reduces the competitiveness of EBs compared to other solutions that offer flexibility to the grid. Ameli et al. (2017) assess the impact of EBs on the operating cost of gas and electricity systems in Great Britain. Their results indicate that EBs can significantly reduce the operating costs of both systems. However, they argue that EBs are highly capital-intensive and only feasible when the capital cost is below £0.4 m/MW (and 2 MWh storage capacity). Despite their high capital costs, the system benefits of EBs could compensate for the high investments (Ameli et al., 2017). Moreover, the price of EBs is in sharp decline: 84% lower than 2010 (BloombergNEF, 2019). Thus, other flexibility-offering technologies could be a complement rather than a substitute to EBs to provide extra benefits to the energy systems.

Another emerging storage technology is PEVs. The expected high penetration of PEVs, with its possible use as a storage solution in the Vehicle to Grid (V2G) paradigm, has spurred the growing interest in the potential of distributed storage solutions. The diffusion of PEVs and the electrification of the transport sector will have major consequences for the energy system. In fact, under the assumption of bidirectional flows within a V2G paradigm, a scenario of high penetration of PEVs would imply a large amount of distributed storage, which at times could work as loads and at times as generators. However, Fernandez et al. (2011) point out that PEVs' overall effect will be an increase in consumption, thus requiring an upgrade to the distribution network to enable the charging. Their results show that, in a scenario with 60% EV penetration and depending on the charging strategies, investment costs for distribution operators could increase up to 15%, and energy losses in off-peak hours could increase up to 40%.

3.3. *Conversion systems*

Conversion technologies can increase the flexibility of the energy systems. They boost the degree of substitutability between energy sources and allow to decouple demand and supply by converting electricity into other energy sources that can then be consumed later, thus acting as a form of storage. This can lead to a more affordable energy system, as the need for backup generation capacity is reduced, and end-users can choose their energy mix more efficiently based on energy

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[4] DR aims at changing the shape of the load curve by allowing consumers to adapt their consumption through price signals. Deployment of DR requires advanced metering infrastructures, which are currently being rolled out in the EU countries and are expected to be available to over 70% of customers by 2020 (European Commission, 2014). DNV GL (2014) estimates that more effective use of DR in the EU can lead to annual savings of between €60 and €100 billion. In addition, it allows consumers to become active network users and enjoy financial benefits by adjusting their consumption in response to changes in the energy price.

[5] The European Commission defines a smart grid as "*an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it – generators, consumers and those that do both – in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety*" (DG ENER, 2011, p.2).

[6] According to the World Energy Council, PHS accounts for over 95% of today's energy storage (World Energy Council, 2016).

[7] By traditional consumers we refer to users who have not installed small-scale DG such as Photovoltaic (PV) systems and depend entirely on the grid for their electricity demand.

[8] Storage could increase the percentage of self-consumption of locally produced power from some 30% to 65–75% for households (European Commission, 2015).

[9] For peak load shaving purposes, capacity-based network tariffs can be used as an incentive to encourage self-consumption and use of storage by prosumers.

market prices.

While conversion systems are promising, their adoption will depend on whether technological progress can overcome two barriers: high investment costs and conversion efficiency. We focus on some already adopted technologies, such as Combined Heat and Power (CHP) and local power or gas to heat, and some emerging ones, such as Power to Gas (P2G). CHP enables the production of electricity and heat from gas while providing significant energy savings (up to 40%) and high conversion efficiency (60–85% depending on the power to heat ratio) (Brodecki et al., 2014). This technology is widely adopted in the EU, covering, in 2017, 11% of total electricity generation (Eurostat, 2020). The International Energy Agency (IEA) estimates that increased use of CHP can reduce investments in the power sector while cutting CO_2 emissions, leading to a reduction in global power sector capital cost of 7% by 2030 (Kerr, 2008).

When located close to final users, CHP can be used in District Heating (DH) networks to minimise inefficiencies by producing power and heat on-site. This limits network losses while using the residual heat that would be wasted by traditional thermal plants. Colmenar-Santos et al. (2016) assess the implications of substituting conventional thermal plants with CHP coupled with DH networks in the EU. They find that, with an annual investment of €300 billion, a reduction in fuel expenses of €100 billion per year and a 15% reduction of the final energy consumption can be achieved. These figures reflect the efficient but capital-intensive nature of the technology.

Local power and gas-to-heat refer to traditional and hybrid heat pumps, electric heaters, gas boilers and all other small-scale conversion technologies that can provide heating and cooling in the absence of DH. The aggregation and coordination of the loads of these appliances through SGs and DR programmes can act as a form of virtual energy storage, increasing flexibility and providing ancillary services to the networks (Cheng et al., 2017; Martin Almenta et al., 2016). Furthermore, the presence of hybrid appliances such as hybrid heat pumps allows end-users to make more efficient decisions when choosing the energy mix, considering price and technical aspects (e.g., outdoor temperature).

P2G allows the conversion of electricity into hydrogen or synthetic natural gas (e.g., methane). This technology could bring high flexibility to the energy system by absorbing the excess production of RES that would otherwise be curtailed when demand is low. This energy could be stored as gas for later consumption at peak demand times. P2G can play an important role in the integration of RES since gas is easier to transport and store than electricity and offers the largest long-term energy storage capacity.

Although a variety of pilot projects are being run, this technology has yet to see adoption. Several technical studies have assessed cost-efficiency of P2G, with sometimes contradictory results. Baumann et al. (2013) and Budny et al. (2015) show that P2G is not economically viable at present and could remain so in the near future. Budny et al. (2015) state that, for P2G to be sustainable, high feed-in tariffs of €100 per MW for hydrogen and €130 per MW for methane would be needed. Schiebahn et al. (2015) point out how renewable hydrogen, as a fuel for fuel cell electric vehicles, could make P2G cost-efficient. Adoption of P2G will ultimately depend on further progress to increase efficiency and reduce capital expenditures, and on the relative price of electricity compared to hydrogen and methane.

As can be seen, techno-economic studies suggest that the above-discussed technologies can provide benefits to various parts of the energy systems through cost savings or by providing flexibility options. However, the literature also suggests that these technologies are, in general, still costly. Their development requires either significant investments by end-users and large-scale service providers to operate them or large investments by system operators to accommodate them into the networks. In this context, regulation can play an important role to incentivise the adoption of these new technologies. Since TSOs and DSOs are firms, whether they invest in innovative technologies or adopt them is directly impacted by regulations and policies in place regarding innovation.

4. Economic regulation in ESI

New technologies and innovative projects are a central enabler of ESI. While new technologies assist in achieving social objectives, as mentioned in Section 3, by nature, innovation is both costly and risky. In this context, regulation should encourage network operators to increase their investment in R&D projects by providing them with monetary incentives. However, since the energy sector reforms of 1990s, the regulatory efforts have been focused on improving the efficiency of the utilities as well as service quality rather than stimulating innovation (Agrell et al., 2013; Cambini et al., 2016a; Joskow, 2014; Meeus and Saguan, 2011; Müller, 2011). As a result, regulatory approaches tend to emphasise the reduction of operational costs to achieve efficiency while allowing the pass-through of capital expenditures.

Although the cost of innovation in the electricity sector is high, investments in conventional technologies are more capital-intensive. Thus, under a regulatory scheme that allows the pass-through of capital costs, utilities tend to invest in more capital-intensive solutions (Meeus and Saguan, 2011) rather than less costly but risky innovative technologies. Nykamp et al. (2012) and Prüggler and Bremberger (2011) show how such an outcome is currently observable in Germany and Austria.

Furthermore, the uncertainty regarding the successful outcome of any kind of innovation or R&D activity is an obstacle that forces utilities to act with caution when deciding whether to invest in new technologies, including the ones enabling ESI. In this regard, the development and adoption of innovative technologies require support from policymakers as well as sound regulatory frameworks that provide monetary incentives to stimulate innovation.

In practice, standard regulatory approaches such as cost of service (rate-of-return) and fixed-price (incentive) regulations do not provide utilities with enough incentives to invest in innovative projects (Bauknecht, 2011). As conventional regulatory approaches fail to provide incentives for innovation and investment in energy networks, innovative regulatory frameworks should be developed. So far, the solution has been to devise hybrid regulatory frameworks that take a different approach towards R&D costs compared to other network expenditures (Bauknecht and Brunekreeft, 2008). Bauknecht (2011) discusses in detail innovative regulatory approaches towards innovation, including input- and output-based incentive mechanisms, as well as hybrid approaches that combine the traditional ones.

In particular, output-based mechanisms are relatively new in the regulation of energy utilities. They focus on improving the performance of the utilities with regards to the quality of their services as well as the desired sustainability targets. Regarding innovation, in contrast to input-based mechanisms, which focus on minimising production costs, output-based models focus on the outcomes of innovation (Bauknecht, 2011). However, defining the outputs to be incentivised is complex, and requires detailed information regarding the results of the innovative projects, as well as extensive budget and skills on the regulator's side (Glachant et al., 2013).

Although output-based mechanisms are successful in encouraging the utilities to increase investment in innovative solutions, defining successful innovation is as hard as separating the cost of innovation from other costs in the input-based mechanisms. Therefore, designing a regulatory framework which is both reliable in promoting innovation and easy to implement will be a challenging endeavour for regulators. For these reasons, regulatory authorities around the world apply a combination of these mechanisms to promote innovation in the energy networks while improving their overall efficiency.

5. Evidence from selected EU countries

In the previous sections, we emphasised the importance of technological and regulatory solutions to achieve ESI. In this section, we provide a summary of the regulatory frameworks that are being used around Europe to foster network innovation (including ESI). In particular, we look at the regulatory schemes in the United Kingdom, Germany, France, and Italy, with a focus on the incentives they provide for the adoption of innovative solutions in electricity and gas sectors. Table 1 summarises the current regulatory scenario in those countries.

The UK has been the most proactive country in fostering innovation through regulation through the RIIO (Revenue = Incentives + Innovation + Outputs) (Ofgem, 2010) regulatory framework. RIIO offers an innovation stimulus for each network, consisting of three measures: the Network Innovation Allowance (NIA),[10] the Network Innovation Competition (NIC),[11] and the Innovation Roll-out Mechanism (IRM). To provide an insight on the quantitative impact of the innovation stimuli, we categorised – based on the technological domain – the projects that started between RIIO's introduction in 2013 and September 2018, with a budget over £1 million and which have been financed under NIA and NIC. The 118 projects make up for almost 75% of the overall NIA and NIC budgets. Seven categories have been used, with each project being assigned to a single group – the most relevant one – even in the case in which its scope would encompass more than one. The findings are reported in Table 2. [12]

Innovation in the UK has been mainly regulation-driven. However, other countries have taken different approaches. In Germany incentives to R&D and adoption of new technologies are mainly provided under large ministerial programmes funded by the Federal Government to reflect the national energy policy (BMWi, 2018), leaving the regulator with a limited role in this regard. France and Italy, on the other hand, have taken a hybrid approach: incentives are provided through adjustments by the regulator to the revenue allowance as well as grants given under EUand national programmes. Table 3 categorises network innovation projects being performed in these countries by TSOs and DSOs as well as their funding resources and allocated budgets. Appendix A provides sources on analysed projects.

Although our overview does not claim to be exhaustive due to the difficulty of acquiring data on investments in innovation, what emerges is a lack of investment in ESI. Even investments in ESI-enabling technologies do not seem high enough to keep up with EU decarbonisation targets.

6. Economic and policy barriers

The lack of investment in ESI can be explained by the existence of different economic and policy barriers to its adoption. While some of these will disappear naturally as technology advances, direct policy actions are required to address most of them.

The first economic barrier is the cost of ESI-enabling technologies. Some of these technologies are capital-intensive, such as CHP. Others are costly because they are at the beginning of their lifecycle, and the cost of investment could significantly decrease once their adoption increases, as it is happening with EBs. A high cost of adoption is an important concern, particularly for final users.

The second barrier is the intrinsic risk of these innovative projects, both in term of the economic viability of in-development technologies (e.g., P2G) and in terms of consumer acceptance (e.g., DR). The risk-averse nature of firms in the energy sector can be a strong limiting factor in fostering the adoption of these technologies.

The third barrier is the institutional constraints in incentivising the adoption of innovative technologies when the existing regulatory framework calls for a technology-neutral approach. The Directorate-General for Competition (DG COMP) of the European Commission suggests that incentives to innovation should not favour one technology to another (DG COMP, 2013). Technology-neutrality will allow the market to select the 'best' innovative solution to adopt without further interventions from the regulator (CEER, 2018). However, as noted by DG-COMP (2013), technology-neutrality should not lead to the adoption of cheaper and mature solutions while postponing investments in more costly but promising technologies.

The fourth barrier is the coordination between grid users (i.e., generators, TSOs, DSOs, retailers, consumers), and especially TSOs and DSOs. For the delivery of a clean and reliable energy system at the lowest total cost, ESI requires grid users to provide the service that minimises the overall system cost. However, this may not be optimal for some users, who may lack incentive to adopt it. This is particularly true for DSOs. The integration of DG has led to higher operational expenditures for DSOs due to the greater complexity arising from managing a two-way system and from the capital expenditure of the DG connection. The diffusion of PEVs will make the loads less predictable and will require major investments in the grid. Conversion and storage systems will also enhance the complexity of managing the distribution network. DR and DG contribute to load shaving and load shifting. By doing so they reduce or defer the need for costly network reinforcement investments and thus improve cost efficiency of the networks.

Aside from this, coordination in itself can be costly as it requires interaction within and between sectors. The problem of coordination is not exclusive to the interactions between different energy systems. With the increasing penetration of PEVs, the integration of electricity and transportation networks is challenging for both energy and transportation regulators. A focal concern is the tariff design and charging mechanisms, with a specific call for decoupling which guarantees to utilities constant revenues and profits regardless of how much energy they deliver (Abrardi and Cambini, 2015; Brennan, 2013). In addition, establishing who and how should finance, construct, and operate charging infrastructures is an unsolved challenge. The question of whether DSOs should play a role in the roll-out of PEV charging infrastructures is currently debated across the European Union (Wargers et al., 2018).

The fifth barrier is access to data. An efficient communication stream facilitates coordination between upstream and downstream grid users within and between networks. Smart meters and smart grids can collect data on the state of the grid and on user consumption. These data need to be accessible for new business models to emerge and to allow optimisation throughout the energy system. Distinguishing between these types of data is important from a privacy perspective, as users' consumption data are personal and subject to strict legal rules for their access. In both cases, the user that controls these data may not have incentives or even the legal possibilities to share them with other grid users. DSOs may not wish to share detailed information on the state of the grid with other parties (e.g., TSO or aggregators). Consumers may not wish to disclose detailed data regarding their consumptions and the appliances they have installed to a distributor that could use them to perform DR as it can be perceived as a privacy intrusion.

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[10] The NIA is an annual allowance for network licensees to fund small R&D and demonstration projects. This allowance is added to the base revenue when determining the annual amount that the licensee can recover from its customers. The Authority decides on the project approval only on special circumstances, otherwise it is automatic once it is disclosed through an appropriate website. Up to 2017, about £60 m were made available annually through the NIA (Ofgem, 2017).

[11] The NIC is an annual competitive process run to finance a selected amount of large development and demonstration projects. For each sector, transmission and distribution operators compete for funding. NIC provides up to £70 m per year for electricity networks and £20 m per year for gas networks and funds up to 90% of a project's total budget, forcing operators to bear some of its cost. Up to September 2018, about £200 m have been granted (Ofgem, 2017).

[12] Network operators have the obligation to disclose data on NIC and NIA projects on the Smarter Networks portal to help disseminate knowledge. The portal can be reached at http://www.smarternetworks.org/(ENA).

Table 1
An overview of policies to foster network innovation in four EU countries.

	United Kingdom	Germany	France	Italy
Type of regulation	Revenue cap with output, efficiency and innovation incentives	Revenue cap with expansion incentives	Hybrid: revenue cap with cost of service elements. Efficiency incentives	Hybrid: revenue cap with cost of service elements. Efficiency incentives
Regulatory period length	8 years	5 years	4 years	8 years (electricity), 4 years (gas)
Innovation incentives	Innovation stimulus packages: adjustments to revenue allowance and competition for funding	50% cost recovery for innovative projects that fall under ministerial funding programmes	Full cost recovery for innovative projects approved by the regulator	WACC mark-up for innovative projects
Costs added to RAB (Regulatory Asset Base)	*Capex* and *Opex*	*Capex* and *Opex*	*Capex*	*Capex*
Innovation funding	Regulation-based	Government-based: grants given under ministerial funding programmes	Hybrid: regulation, government, and EU-based	Hybrid: regulation, government, and EU-based

Table 2
Classification of UK's NIC and NIA projects (above £1 million budget).

Category	No. Projects	Budget (£m)	Avg. Budget (£m)
Network Management[a]	62	325.4	5.2
Low carbon technologies and energy efficiency	7	56.1	8.0
EV and hydrogen vehicles	5	11.0	2.2
Smart Grids	13	65.5	5.0
Storage systems	2	2.9	1.4
Energy systems integration	1	5.2	5.2
Others	28	85.9	3.1
Total	**118**	**552.1**	**4.7**

Source: Elaboration on data available from the Smarter Networks portal.
[a] This category comprises technologies that improve network reliability, control, safety, and service quality.

The sixth barrier is consumer acceptance. We mentioned the possibility of consumers being against the collection of their data and diffusion of technologies deemed intrusive. However, consumers may also resist to investments in innovation that leads to higher tariffs. The risky nature of innovative projects makes so that blindly funding innovation spending is not viable, since this may be costly compared to the benefits gained from innovation. These investments need to be assessed while having in mind potential consumer gains, both in term of economic returns and environmental gains. Furthermore, although integrating RES and DG in an ESI scenario leads to lower system costs, it still requires large investments in the networks compared to a situation where no action is undertaken. This can lead to consumers' resistance to innovation in the energy networks in a case where the costs are passed entirely to them.

The seventh barrier relates to the role of the regulator. The regulator should define the boundary between regulated activities and the market. For instance, while the penetration of EVs significantly impacts DSOs' operation (Wargers et al., 2018), there remains ambiguity regarding whether to involve DSOs in the roll-out of PEVs. Another example is in the differences in the approaches by the European regulators on whether to allow DSOs to own and operate storage systems. The matter is delicate due to the risk of having a monopolist operating in a potentially competitive market. While in Norway DSOs can own and operate ESS, in the UK storage is classified as generation, and therefore DSOs can own, but only third parties can operate it due to unbundling constraints (CEER, 2019). In Italy, the regulator allows DSOs to invest in storage systems, but this investment cannot be recovered through distribution tariffs unless it is justified through a cost-benefit analysis (CEER, 2019). The lack of a clear and uniform policy regarding what network operators are allowed to do can influence the emergence of new players, new business models and the adoption of ESI-enabling technologies.

The eighth barrier is the behaviour of prosumers behind-the-meter. Further diffusion of DG and storage systems can lead to a scenario of increasing independence of prosumers from the grid. These users may rely less and less on the network as their share of self-consumption increases. By consuming less energy from the grid, they contribute less to the operation, maintenance, and expansion of the infrastructure. These costs are covered through network charges, which constitute part of the final energy price charged to consumers. With fewer consumers paying network charges, and with these costs being mainly fixed, the final price of energy could raise significantly. This, in turn, would make leaving the grid more appealing, which could create a self-sustaining cycle that would leave consumers who cannot adopt DG and storage with an

Table 3
Overview of network innovation projects in Germany, France and Italy.

Country	Germany			France			Italy		
Project category	Source of funding	Total budget	Main stakeholders	Source of funding	Total budget	Main stakeholders	Source of funding	Total budget	Main stakeholders
Smart Grids	National and private funds	€600 million	TSO and DSO	EU and national funds and increase in network tariffs	€832 million	TSO and DSO	Increase in network tariffs (+2% WACC for 12 years)	€17.4 million	DSO
							National Operational Programme (PON): EU + national funds	€180 million	DSO
Storage	National and private funds	€200 million	TSO, DSO and consumers	Increase in network tariffs	€160 million	TSO and DSO	Increase in metering tariffs (+2% WACC for 12 years)	€253 million	TSO
	Low-interest loans by Government-owned development bank	€80 million	Consumers						
Conversion	Increase in network tariffs (Surcharge to electricity from CHP)	Max annual fund of €1.5 billion	Generators	EU, national and private funds	€30 million	TSO	–	–	–

Source: See Appendix A for a detailed list of analysed projects.

unsustainably expensive energy system (Jamasb, 2017).

The final policy barrier is whether the European regulators have the resources and disposition to intervene on the whole energy system cohesively. Typically, energy sectors have been regulated separately from one another, and regulatory decisions regarding economic activities within each energy network are taken independently. This may lead to overspecialisation and a lack of holistic view, which is a strong requirement for ESI to be successful. In particular, this sector-specific approach may deprive investment in those innovative technologies that calls for an integrated view as required within the ESI paradigm.

7. Conclusion and policy implications

ESI can be an effective way to integrate RES and DG while providing a reliable and affordable energy system. However, the implementation of this paradigm and the improved coordination between different energy systems requires not only the adoption of innovative technologies but also new policies and regulation. This Section discusses the main policy interventions needed to enable ESI. With this aim, Table 4 lists the barriers identified in Section 6, together with potential policy solutions. We discuss in detail each policy solution in the following.

7.1. Innovation incentives

ESI requires investment in new technologies, and network operators are naturally positioned to lead the process. Therefore, regulatory frameworks should incentivise investments by networks in innovation. The implementation of output-based incentive regulation is well suited for this goal, as it shifts the focus from economic efficiency to an efficient delivery of outputs specified by the regulator. Regulators should recognise that, due to asymmetry of information, firms are better positioned to know the best ways to deliver an output, meaning which technology will work best and at the lowest cost. Therefore, firms should be required to take on an active role in determining how to deliver outputs (Ofgem, 2010). On the other hand, clear output specification is needed to avoid opportunistic behaviour or short term focus, which may lead firms to choose sub-optimal investment solutions. Gaining the know-how to calibrate outputs will inevitably require a trial-and-error approach by regulators. However, looking at countries that are adopting output-based incentive regulation (e.g., the UK) can provide useful guidance.

Adopting a Totex approach is another important step in incentivising innovation. Traditionally, regulatory frameworks have treated capital (Capex) and operational expenditures (Opex) differently: by adding Capex to the RAB, they introduce a bias to Capex-heavy investments. However, ESI-enabling technologies provide flexibility to the grid: they reduce the need for investments in grid and generation capacity, but they create a more complex network. Therefore, they cause a rise in Opex that is more than offset by the reduction in Capex. If a bias to Capex is present, firms could prefer to invest in costly Capex-heavy solutions. The Totex approach considers both Capex and Opex, thus eliminating the incentive to favour capital intensive investments. This approach, pioneered by the UK, is being followed by other EU countries such as Italy (AEEGSI, 2017) and, in a narrower scope, France (CRE, 2018).

Network innovation also needs to be fostered through specific incentives, as they lower the risk the regulated firm bears. In this regard, the regulator can take two approaches: to fix the revenue allowance and the expected result of the innovation process beforehand, or to fix the revenue allowance for innovation but leave network firms with the freedom to decide how to spend it. The Italian and French energy authorities take the first approach. In Italy, the regulator chooses which SG projects should be financed and awards them with an extra capital remuneration. In France, the regulator approves or rejects the innovation plan and budget of each network firm for the regulatory period.

The UK uses both approaches. With the Network Innovation Competition, the regulator decides which projects to finance and by how much. On the other hand, through the Network Innovation Allowance, it assigns to each operator an allowance that the operator can use on innovation projects that do not need regulatory approval. The latter approach might provide the right balance of risk and remuneration at a stage where there is a need to invest a lot in innovation. The mixed-approach allows the regulator to guarantee the affordability of innovation while leaving firms with the flexibility to suggest new solutions. Furthermore, risk can be reduced by sharing the results of innovative projects. When investments are financed through innovation stimuli, regulators should impose network operators to disseminate the results of their innovative projects irrespective of failure or success (such an approach is taken both in the UK and in Italy).

Another potential approach is to use regulatory sandboxes. This regulatory approach includes case-by-case exemptions for the innovative projects which are constrained by specific regulatory rules (Broeckx et al., 2019). The regulator evaluates the projects and then defines a set of rules to be lifted for a certain period. Although this approach facilitates innovation and allows investors to develop their innovative solutions with less regulatory burdens, it still needs to be carefully implemented. Which projects should benefit from the exemptions, how long should be the exemption period for each project and which actors should be able to implement these projects are the issues that the regulator should take into account upon deciding on adopting regulatory sandboxes.

Finally, regulatory sandboxes are only valid when regulation does

Table 4
Policy solutions to barriers for ESI implementation.

Proposed Policies	Barriers								
	Cost of techs	Innovation risk	Tech-neutrality	Coordination	Data access	Consumer acceptance	Boundary regulation/ market	Behind-the-meter behaviour	Regulator's capabilities
Innovation incentives	x	x	X						
Drive consumer actions	x	x				x			
Foster emergence of new players	x	x					x		
TSO/DSO adoption	x						x		
ICT & data access		x		x	x				
Incentivise coordination				x	x		x		
Decoupled revenues				x				x	
Cross-sector development plans	x			x		x			x
Coordination at the EU level	x	x	x	x	x	x	x		x

not keep up with the technology. Regulation is, and certainly needs to be, evolving alongside technology. This means that current rules should be eventually redefined to cover technological shifts appropriately. In this sense, regulatory sandboxes can be considered as an attractive solution to promote innovation only for a limited period during which regulation is lagging behind and not the solution itself.

7.2. *Drive consumer actions*

Consumers need to play an active role in ESI. Adoption of household-level storage systems (e.g., electric batteries) and conversion technologies (e.g., hybrid heat pumps) could be incentivised through tariff-based support mechanisms, like feed-in tariffs for DG, or through government grants or loans. The latter approach has been taken in Germany, where the government has provided low-interest loans through its development bank KfW for battery storage units that are installed alongside PV systems. While, up to 2016, KfW has given 60 m euros in funding, this spurred investment of about 450 m euros (BMWi, 2017). Investment by private citizens can help these technologies develop towards a mature stage, thus lowering their cost while also reducing the burden for the energy system. The need for such incentives would disappear once the technologies are mature enough, as the savings they provide make up for the investment cost. While consumers benefit from these technologies through arbitrage, prosumers could use them to increase their self-consumption rate and be off-grid during peak loads. This can be beneficial to both prosumers (lower final electricity bills) and network operators (lower network costs). Consumer acceptance of more intrusive technologies can also be increased through appropriate price signals. DR could be more attractive should it lead to a lower energy bill. Detailed consumption disclosure could also be conditional on a reduction in the price of consumed energy, or to some other form of monetary incentive (without this exempting from the need to comply with privacy protection rules).

7.3. *Foster emergence of new players*

Aside from consumers, other grid users could benefit from tariff-based support mechanisms. Where markets are still not deemed mature, these mechanisms could help new business models to emerge. Flexibility providers could install storage and conversion systems to provide services to the grid. Through the CHP Act (BMJV, 2019a), in Germany, a surcharge is granted to electricity generated through CHP. This has been used to promote construction and modernisation of cogeneration plants and heat networks. By treating storage as generation, similar pricing policy as for DG can be adapted to ESS, which implies diverse tariff mechanisms for importing and injecting electricity.

7.4. *TSO/DSO adoption*

Equating storage to generation has led most European regulators to forbid TSOs and DSOs to operate storage systems. Indeed, where the context could allow new grid users to provide such service, having a monopolist operate in a competitive market would be detrimental. However, since energy systems are different from one another due to scale, geography and a variety of other reasons, in some cases, a competitive market would not develop. Regulators should, under such conditions, allow network operators to own and operate storage and conversion systems. Allowing DSOs and TSOs to own and operate storage can significantly reduce infrastructure costs and the need to build excess capacity (Ugarte et al., 2015). Similarly, operating conversion systems could allow network firms to take advantage of economies of scope. Such a scenario should not require providing firms with any incentive, as investing in such technologies would be advantageous for them due to the overall cost reduction. Allowing this type of investments could be a temporary measure used to increase adoption and lower the cost of these technologies. Once the conditions for a competitive market are mature, network firms could be required to divest (allowing for an adequate remuneration of previously invested capitals and avoiding regulatory opportunism).

7.5. *ICT and data access*

While ESI entails physical exchanges of energy within and between energy systems, it is mostly data and information exchanges that make the integration possible. Therefore, investments in ICTs in the form of smart grids and smart meters should be incentivised. Data transparency rules and clear third-party access policies could be used to increase coordination among grid users.

7.6. *Incentivise coordination*

Coordination will also require remunerating the new services that network firms provide to the system. This has been recognised by the Italian regulator, which introduced a mitigation-service fee that the DSO receives from the TSO when it helps to limit the impact of interruptions in the transmission grid by allowing back-feeding in the distribution network through appropriate grid rearrangements (AEEGSI, 2015). Similarly, the TSO pays the DSO for having access to real-time data on the state of the distribution grid, which is then used by the TSO for balancing reasons (CEER, 2018). Some other solutions mentioned by Hadush and Meeus (2018) that may be helpful to address the issue of TSO/DSO coordination are:

- The establishment of Independent System Operators (ISOs) for the joint operation of the systems in the borders between TSOs and DSOs.
- Having DSOs as market facilitators, either as aggregators of the bids of DG in the wholesale market or limiting their role to prequalification. DSOs would cooperate with ISOs to compute and ascertain the available capacity that could be allocated by the market at the borders between TSOs and DSOs.
- Promoting modifications to make regulators more proactive and adaptative to quick changes in the sector. In that context, regulatory sandboxes can serve to test new approaches that might foster coordination between system operators.

7.7. *Decoupled revenues*

ESI requires decoupling network firms' revenues from energy consumption. This is needed to both coordinate grid users and to ensure profitability for distributors, which could face increases in costs and reductions in revenues in an ESI scenario. DSOs could be required to connect DGs, conversion and storage systems, while their revenues would be linked to the number of connections provided. Such an approach is used in Germany, where DSOs' revenue allowances are adjusted by an expansion factor that takes into account the amount of DG connected (BMJV, 2019b). As sales and consumption of energy will increasingly differ, system costs will make up for a higher proportion of the final user's energy bill. The need to provide an affordable energy system for everybody will require prosumers to contribute to the network irrespective of self-consumption rate (Cambini and Soroush, 2019).

7.8. *Cross-sector development plans*

Lowering system costs requires coordinated development plans for network operators. Network firms' investment decisions should take into account the whole energy system to exploit existing synergies. Regulators could either require that network firms do so in their business plans or they could raise (lower) revenue allowances for firms that (do not) do so. Furthermore, innovation incentives could also be conditional on the fact that the innovation provides system benefits. In defining the new rules for RIIO-2, the UK's regulator Ofgem has recognised the need for an integrated approach, and it expects network firms to provide whole system solutions in their business plans (Ofgem, 2019a, 2019b).

7.9. Coordination at the EU level

As the EU has identified ESI as a priority (ENTSOG and ENTSO-E, 2019), there is a need to ensure greater coordination at European level. This could be achieved by giving more leverage to the Agency for the Cooperation of Energy Regulators (ACER), although its prescriptive power would need to be limited to recognise the peculiarities and different demands of each state's energy system. The EU coordinator would need to engage with relevant stakeholders to identify opportunities to deliver cross-country integration solutions (e.g., North Sea offshore grid integration). It would foster exchanges between regulators, disseminating best practices, and helping create regulatory know-how. It would also look at successful pilot projects throughout Europe to identify what is technologically needed by the market and to impose standards for the industry. Granting access to the results of network firms' innovation projects would reduce risk and prevent duplication of effort.

In our discussion of possible policy interventions to drive ESI, we refrain from providing too specific solutions. This follows from recognising that ESI needs to be a bespoke approach that considers the characteristics and needs of the systems. As the barriers its adoption may face will differ from case to case, so will the policies needed to overcome them. In our analysis, we provided a menu of possible solutions, with the idea that ESI can be achieved through a proper design of incentives to grid users.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Carlo Cambini: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Raffaele Congiu:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Tooraj Jamasb:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Manuel Llorca:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Golnoush Soroush:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing.

Appendix A. List of Projects and Sources

Project Name	Source	Country
NIC and NIA projects	http://www.smarternetworks.org/	UK
FREEDOM	http://www.smarternetworks.org/	UK
SINTEG	https://www.bmwi.de/	Germany
Energy Storage Funding Initiative - R&D and demonstration of storage technologies	https://www.bmwi.de/; https://forschung-energiespeicher.info/	Germany
KfW Banks – loans for EBs	https://www.bmwi.de/	Germany
CHP Act	https://www.gesetze-im-internet.de/kwkg_2016/BJNR249810015.html	Germany
WindNODE	https://www.sinteg.de/; https://www.windnode.de/	Germany
SMILE	https://smile-smartgrids.fr/	France
FlexGrid	http://www.flexgrid.fr/	France
SG pilot projects	http://www.smartgrids-cre.fr/	France
11 pilot projects in isolated networks	Délibération de la Commission de régulation de l'énergie du 4 octobre 2018 portant décision sur la compensation des projets de stockage centralisé dans les zones non interconnectées dans le cadre du guichet d'octobre 2017.	France
RINGO	Délibération de la Commission de Régulation de l'Energie du 7 décember 2017 portant approbation du programme d'investissements de RTE pour 2018.	France
Jupiter 1000	https://www.jupiter1000.eu/	France
SG pilot projects	https://www.arera.it/	Italy
e-Distribuzione - SG projects	https://www.e-distribuzione.it/; http://www.ponic.gov.it/	Italy
e-Distribuzione -Open Meter project	Deliberazione 6 aprile 2017–222/2017/R/EEL - Sistemi di smart metering di seconda generazione (2G): decisione sul piano di messa in servizio e sulla richiesta di ammissione al riconoscimento degli investimenti in regime specifico di e-distribuzione S.p.a.	Italy
Terna S.p.A. - Project Lab and Large Scale Energy Storage pilot projects	http://www.terna.it/	Italy

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