UNIVERSIDADE D
COIMBRA

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ASSESSMENT OF POLICY, TECHNOLOGY, AND BUSINESS MODEL ADAPTATION FOR SMART AND SUSTAINABLE ELECTRICITY DISTRIBUTION

PhD Thesis in Sustainable Energy Systems supervised by Professor Patrícia Carla Gama Pinto Pereira da Silva Vasconcelos Correia, submitted to the Faculty of Sciences and Technology of the University of Coimbra.

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Energy for Sustainability Initiative at the University of Coimbra
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I have been impressed with the urgency of doing.
Knowing is not enough; we must apply.
Being willing is not enough; we must do.

Leonardo da Vinci

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Completing this endeavor required focus, ingenuity, and self-discipline, all of which were only possible due to the people and institutions that supported the development of this work.

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Abstract

The growing diffusion of distributed energy resources including renewable energy generation, electric mobility, and electricity storage, in combination with the deployment of smart grids, and a more active role of consumers are reshaping the electricity sector infrastructure and utilities' business models. This is particularly challenging for electricity distribution utilities – Distribution System Operators (DSOs), in the European Union (EU) context, which operate at the interface of downstream connected consumers and distributed energy resources, and upstream large-scale electricity generation and transmission, therefore having a critical role in enabling adaptation and innovation across the supply chain.

This thesis focuses on studying the changing role of DSOs and aims to contribute to a more detailed understanding of policy, technology, and business model adaptation towards smart and sustainable electricity distribution. This is delivered through three policy-oriented empirical assessments. Firstly, a foresight analysis implemented through a Policy Delphi expert elicitation technique is presented, evaluating future alternatives to inform business model innovation, technological adaptation, and market design options. Secondly, a case study approach is unveiled highlighting the DSO's challenges and opportunities at present. Lastly, a capabilities assessment, applied through a Structural Equations Model (SEM), explores the ability of DSOs to implement business model innovations and adaptation in a rapidly changing electricity sector. These assessments build on novel primary data collected from over 200 electricity sector stakeholders, including regulators, academics, policy makers, and industry representatives, and 129 utilities from 27 EU countries.

The findings indicate a future in which DSOs continue with their core electricity distribution responsibilities, while expanding their business model to facilitate flexibility services, by integrating distributed energy resources in their operations. These future possibilities are contrasted with empirical evidence of a present situation in which DSOs are challenged by corporate inertia and regulatory barriers to pursue innovative business models and deploy smart grid technology, particularly in which the value of full scale rollouts of smart meters remains uncertain for DSOs. Notwithstanding the challenges of the structural reforms impacting the electricity distribution industry, the results obtained indicate the ability of DSOs to adapt their operations including core electricity distribution and smart grid deployment, integration and management capabilities. Moreover, DSOs performance was found to benefit from the integration of smart grid technology. Additionally, DSOs scale was identified as a determinant factor on operational performance, innovation performance, smart grid diffusion performance and business model innovation performance, with larger DSOs performing significantly better.

These findings enhance the relevance of network infrastructure to support the ongoing energy transition and validate the ability of DSOs to expand their business model and adjust their value capture and creation processes. Policy makers and the electricity distribution industry should consider the methodologies and insights presented throughout this thesis when tackling the challenges impacting the electricity sector.

Keywords: policy, technology, business model, adaptation, European Union, electricity distribution, smart grids, sustainable energy systems, utilities of the future.

Resumo

A crescente difusão de recursos energéticos distribuídos sob a forma de geração distribuída de origem renovável, mobilidade elétrica e unidades de armazenamento de eletricidade, em paralelo com a implementação de redes inteligentes e um papel mais ativo por parte dos consumidores está a contribuir para uma reforma do setor elétrico, com especial impacto na sua infraestrutura e no modelo de negócio das *utilities*. Estes impactos são particularmente desafiantes para as *utilities* de distribuição de eletricidade – Operadores de Redes de Distribuição (ORD), no contexto da União Europeia (UE), por se encontrarem na interface entre consumidores e recursos energéticos distribuídos a jusante, e geração de grande porte e transmissão de eletricidade a montante, sendo assim um elemento principal no apoio à inovação e adaptação ao longo da cadeia de fornecimento.

No âmbito desta tese foi analisada a alteração do papel dos ORD tendo como objetivo compreender o ajustamento de políticas públicas, tecnologia e modelos de negócio que permitam transitar para uma indústria de distribuição de eletricidade mais inteligente e sustentável. Para este efeito foram desenvolvidos três estudos empíricos. Em primeiro, através de um método *Policy Delphi*, foram analisadas um conjunto de alternativas futuras permitindo assim compreender as possibilidades de inovação do modelo de negócio, adaptação tecnológica e desenho de mercado. Em segundo, através de um método de estudo do caso, foram analisadas as atuais oportunidades e desafios para os ORD. Por último, através da aplicação de Modelos de Equações Estruturais (MEE), foi analisado o papel das competências corporativas na introdução de inovações no modelo de negócio a adaptação face a um setor elétrico em mudança. Estes estudos empíricos foram desenvolvidos com base em dados primários originais recolhidos no âmbito desta tese a partir de cerca de 200 peritos do setor elétrico, incluindo reguladores, académicos, decisores de política pública, e representantes da indústria, bem como através de dados de 129 ORD a operar em 27 estados membro da UE.

Os resultados obtidos indicam um futuro no qual os ORD continuam a ser responsáveis pela distribuição de eletricidade, ao mesmo tempo que expandem o seu modelo de negócio de modo a facilitar o desenvolvimento de serviços de flexibilidade através da integração de recursos energéticos distribuídos nas suas operações. No entanto, estas possibilidades futuras são contrastadas com evidência empírica de uma situação presente na qual os ORD enfrentam um conjunto de desafios relacionados com inércia corporativa e barreiras regulatórias que dificultam a introdução de modelos de negócio inovadores e a difusão de tecnologias de redes inteligentes, com especial enfoque na incerteza dos ORD face ao valor acrescentado de uma difusão de larga escala de contadores inteligentes. Neste contexto de alterações estruturais na indústria de distribuição elétrica, os resultados obtidos indicam que os ORD são capazes de adaptar as suas operações, incluindo tanto competências relacionadas com as operações tradicionais de distribuição elétrica, bem como competências de implementação, integração e gestão de redes inteligentes. Neste contexto, foi ainda identificado um impacto positivo da integração de redes inteligentes no desempenho operacional dos ORD. A escala dos ORD foi também reconhecida como um fator determinante em matéria de desempenho operacional, inovação, difusão de redes inteligentes, e adaptação do modelo de negócio, sendo que ORD de maior escala apresentam melhor desempenho.

Este estudo reforça a relevância da infraestrutura de distribuição na atual transição do setor elétrico e valida a capacidade dos ORD em expandir os seus modelos de negócio e ajustar os processos de criação de valor. As metodologias e resultados apresentados nesta tese podem ser considerados por decisores de política pública e por representantes da indústria de distribuição de eletricidade focados na adaptação do setor elétrico.

Palavras chave: política pública, modelo de negócio, adaptação, União Europeia, distribuição de eletricidade, redes inteligentes, sistemas sustentáveis de energia, *utilities* do futuro.

List of abbreviations

ACER	Agency for the Cooperation of Energy Regulators
ANOVA	Analysis of Variance
APPA	American Public Power Association
CAPEX	Capital Expenditure
CEER	Council of European Energy Regulators
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CHP	Combined Heat and Power
CI	Confidence Interval
COP	Conference of the Parties
DER	Distributed Energy Resources
DR	Demand Response
DSO	Distribution System Operator
EAFO	European Alternative Fuels Observatory
EC	European Commission
EEA	European Environment Agency
EFA	Exploratory Factor Analysis
ETIP SNET	European Technology and Innovation Platform on Smart Networks for the Energy Transition
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
GWh	Gigawatt-hour
ICT	Information and Communication Technologies
IEA	International Energy Agency
IFI	Incremental Fit Index
IRENA	International Renewable Energy Agency
kW	Kilowatt
LTS	Large Technical System
LV	Low Voltage

M€	Million Euros
MLP	Multi-Level Perspective
MV	Medium Voltage
MW	Megawatt
NRA	National Regulatory Authority
OECD	Organization for Economic Co-operation and Development
OPEX	Operational Expenditure
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
RMSEA	Root Mean Square Error of Approximation
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SEM	Structural Equation Model
SET	Strategic Energy Technologies
SRMR	Standardized Root Mean Square Error of Approximation
TEF	Triple Embeddedness Framework
TLI	Tucker-Lewis Index
TSO	Transmission System Operator
TWh	Terawatt-hour
US DOE	United States Department of Energy
VRE	Variable Renewable Electricity Sources

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Chapter 1

Introduction

1.1 Background and motivation

Global concerns with the impact of climate change on society have significantly contributed to push for a transition towards sustainable energy systems. In this context, climate and energy policies have been designed, implemented, evaluated, and consequently redesigned, with the goal to reduce anthropogenic greenhouse gas emissions, for which the electricity sector contributes to a large extent. Ongoing policy-driven efforts, combined with technological innovation, are gradually changing how electricity is generated, distributed, and consumed. These emerging electricity sector dynamics can be observed as the evolution towards smarter and more sustainable electricity systems. More sustainable, due to the growth in the share of renewable energy. Smarter, given the integration of monitoring, automation, and control technologies that facilitate the collection and use of data for a more efficient use of resources. According to Järventausta et al. (2010), noteworthy drivers for these dynamics include: the growing penetration of distributed generation; the motivation for market integration in the European Union (EU) and North America, given high shares of renewable energy; the increased importance of energy efficiency and demand response; and expectations for improved quality of service. Additional aspects relevant in the ongoing transition are the economic incentives for better use of electricity networks and infrastructure, which are expected to drive an evolution beyond investments into passive distribution assets; and the aging electricity distribution infrastructure, requiring a renewal that is in line with the changes in electricity usage patterns. Lastly, regulatory frameworks are also important elements to be considered due to their increasing efficiency demands, which challenge electricity distribution business profitability, resulting in adaptation needs for both the long and short-term in terms of network management.

In this framework of electricity sector transformation, electricity distribution network infrastructure and distribution utilities – distribution system operators (DSOs) in the EU context (cf. Section 2.3 for the definition of DSO), represent a central component in the electricity value chain, traditionally designed to allow electricity flows from higher-voltages upstream coming from large-scale generation plants, toward low-voltage downstream distributed loads (Pérez-Arriaga, 2013; Boillot, 2014). However, this traditional role of the infrastructure and DSOs is progressing partly due to new technology and policy dynamics. On the technology side, it is important to consider the growing diffusion of distributed energy resources (DER) in the form of distributed solar photovoltaic or wind generation, electricity storage, electric vehicles (EVs) and associated charging infrastructure, as well as the increase of information and communication technologies that contribute to better monitoring and control capabilities, which make distribution networks smarter (Gellings, 2009; Jansen et al., 2012; Aiello & Pagani, 2016; Castro & Dantas, 2017; Pereira & Silva, 2017). Additionally, on the policy side, recent EU policies stimulate a shift toward increased deployment and integration of clean energy sources and sustainable development. (European Commission, 2010, 2011, 2014a). These are further supported by the Energy Union (European Commission, 2015a), and the recent Clean Energy for All Europeans package (European Commission, 2016b), with specific proposals for redesigning the electricity sector (European Commission, 2017a, 2017d, 2017c).

In the EU, this transition builds on the structural changes brought by market liberalization (Pérez-Arriaga, 2013; Mallet et al., 2014), through which electricity distribution was established as a regional natural monopoly, mandated to act as a neutral market facilitator separated from competitive activities in generation and retail. In this context, the roles, and responsibilities of DSOs have been significantly policy-driven, and their operations regulated by National Regulatory Authorities (NRAs) at the Member State level (European Union, 1996, 2003, 2009b).

However, the described changes represent possibilities for new tasks to be performed at the distribution level (Martinot et al., 2015). For instance, DSOs could become more active network managers by coordinating system flexibility made possible by the growth of distributed generation and smarter loads and enabled by the increasing levels of monitoring and control. Nonetheless, these possibilities lead to a series of challenges related to the extent to which DSOs should be involved in activities and services associated with a smarter and more sustainable electricity system, such as: promoting energy efficiency, demand response (DR), and demand side management measures; deploying, owning, and managing EVs charging infrastructure; deploying, and owning smart meters; managing distributed generation; and handling growing amounts of data (Oosterkamp et al., 2014). Given this, these areas have been recently presented as "grey areas" for DSOs in the future (CEER, 2014, 2015; Meeus & Glachant, 2018). The uncertainty around these new areas is associated with: the need for DSOs to act as neutral market facilitators in a liberalized sector; the possibilities for some of these activities to be developed in a competitive market; and, the fact that DSOs have an operational scale and connected grid-users base that could position them as adequate providers for innovative smart grid services.

The regulated monopoly nature of electricity distribution further exacerbates the challenges associated with adaptation, given that DSOs must continue providing a reliable and affordable service, while going through the challenges of a changing sector. The resulting challenges call for intertwined efforts to solve technological, institutional, and organizational issues underpinning electricity distribution transition and adaptation (Praetorius et al., 2009; Markard et al., 2012). This triad is also valuable for organizing recent research efforts aiming to shed light into these challenges and how to best overcome them. Technological adaptation-oriented research has contributed with knowledge on the integration of electricity storage in distribution systems (Carpinelli et al., 2013; Purvins et al., 2013; Guwy et al., 2014; Suberu et al., 2014; Zhao et al., 2015), integration of distributed generation sources from wind (Pinto et al., 2013; Broeer et al., 2014; Huber et al., 2014), solar (Diaz et al., 2013; Foster et al., 2013; Cheng et al., 2015; Goop et al., 2016; Sambandam et al., 2016), CHP (Ma et al., 2013; Zhang et al., 2014; Franco & Versace, 2017), and micro-CHP (Ruzzenenti et al., 2014; Adam et al., 2015; Navalho et al., 2017; Sorace et al., 2017), integration of EVs (Galus et al., 2010; Green et al., 2011; Richardson, 2013; Zakariazadeh et al., 2014), integration of smart meters (Depuru et al., 2011; McHenry, 2013; Dyson et al., 2014; Schenato et al., 2014; Barai et al., 2015; Pereira et al., 2015), implementation of DR (Aghaei & Alizadeh, 2013; Maharjan et al., 2013; Williams et al., 2013; Mazidi et al., 2014; Deng et al., 2015), deployment of active distribution management systems (Kanchev et al., 2011; Hernandez et al., 2013; Chukwu & Mahajan, 2014; Safdarian et al., 2014; Wang et al., 2015), and advanced grid monitoring and control (Giannakis et al., 2013; Laaksonen, 2013; Fadel et al., 2015), as well as the use of artificial intelligence methods (Aziz et al., 2013; Raza & Khosravi, 2015; Rigas et al., 2015), machine learning applications (Chang et al., 2017; Eskandarpour & Khodaei, 2017), and the role of blockchain in enabling local energy communities (Mengelkamp, Gärttner, et al., 2017; Mengelkamp, Notheisen, et al., 2017). Institutional adaptation-oriented research has contributed with knowledge on the adaptation of the existing regulatory framework (Joode et al., 2009; Lo Schiavo et al., 2013; Connor et al., 2014; Crispim et al., 2014; Fox-Penner, 2014; Ruester et al., 2014), with analyses of different regulatory approaches, such as incentive regulation (Jamasb & Pollitt, 2007; Cambini et al., 2014; Anaya & Pollitt, 2015), and innovative approaches to stimulate electricity distribution adaptation to smart grids (Agrell et al., 2013; Marques et al., 2014; Perez-Arriaga et al., 2017), which often include regulatory recommendations for NRAs (Niesten, 2010; Shaw et al., 2010). In addition, a number of studies on the impact of regulatory frameworks on adaptation have been published. (Cossent et al., 2009; Ropenus et al., 2011; Fini et al., 2013; Anuta et al., 2014; Shen et al., 2014). The above branches of research represent the ongoing progress across fields aiming at a better understanding of the technological and institutional changes necessary for the transition towards smarter and more sustainable electricity distribution.

In this context, the organizational adaptation aspects of electricity distribution have been explored to a limited extent, despite the importance of facilitating organizational change and business model innovation as part of the energy transition (Dubois & Saplacan, 2010; Markard, 2011; Pereira & Silva, 2016; Kiesling, 2016). Contributions from business model adaptation-oriented research have focused mostly on the impacts of market liberalization (Tsoukas & Papoulias, 2005; Trygg et al., 2007; Dubois & Saplacan, 2010; Persideanu & Rascanu, 2011), whilst fewer efforts are visible on understanding the ability of DSOs to adapt to a smarter and more sustainable electricity sector (Kossahl et al., 2012; Kiesling, 2016).

Exploring the business model innovation and adaptation dimension of electricity distribution becomes more relevant as the importance of the social sciences and humanities gains momentum within energy research (Sovacool, 2014; Sovacool et al., 2015), for which interest on individual and organizational behaviors and their potential can be observed as a growing body of knowledge (Verbong et al., 2013; Anda & Temmen, 2014; Soares et al., 2017). In this context, DSOs represent complex technological and policy-driven business organizations, for which a better understanding of their ability to adapt towards smart grids and innovate existing business models can contribute with sensible insights to ongoing policy debates (Meeus & Hadush, 2016; Pereira et al., 2018a; Pereira et al., 2018b).

Further, developing such a body of knowledge can shape future policies and electricity market designs to consider business model innovation possibilities, opportunities, and constraints. These go beyond technical aspects, such as the extension of distribution networks, and electricity distributed; and regulatory aspects, such as incentive models, and regulatory approaches. Future research must consider these technical and regulatory adaptation aspects in parallel with the complexities of business model and organizational evolution, which include technical, and managerial capabilities; and resources whose characteristics and flexibility to adapt to a rapidly changing paradigm remain significantly understudied to this day. This will allow for a more detailed understanding of the adaptability of DSOs and their existing business models, towards a more decentralized, decarbonized, and digital electricity sector.

There is a need to develop a body of knowledge focused on the adaptability of electricity distribution utilities in a changing electricity sector. It becomes relevant to focus on business model innovation and strategic capabilities, and how these are influenced by business characteristics (*e.g.*: ownership, connected consumers, unbundling type, technical characteristics, operational expenditures, capital expenditures, network length, electricity distributed, etc.) (Nisar et al., 2013; Helms, 2016), as well as market factors (*i.e.* sector structure, sector liberalization, regulatory method, innovation policies, etc.) (Cambini et al., 2016). Additionally, it is relevant to explore how different aspects influence the role of DSOs on engaging in innovation activities and smart grids diffusion efforts.

A better understanding of the adaptability of electricity distribution is expected to contribute with the knowledge needed for the debate related to future business model innovation and electricity market redesign (European Commission, 2015a, 2016b, 2017a, 2017d). These necessary research efforts combined with ongoing research on technological and institutional adaptation can facilitate the transition of electricity distribution to a configuration in which connected consumers reap the benefits of innovative technologies and cleaner energy sources, all part of a smarter and more sustainable electricity sector.

1.2 Research questions

The changes occurring in the electricity distribution industry challenge the traditional uses of network infrastructure and the role of DSOs. In this framework, while technological and institutional aspects have received significant attention in the literature, organizational and business model innovation issues have been explored to a lesser extent. However, a transition in technologies and policies that is not supported by an improved understanding of the organizational behavior of DSOs can hinder innovation in the sector and halt the delivery of benefits to connected consumers and the economy.

This thesis aims to increase the understanding of DSOs adaptability in a changing electricity sector considering policy, technology, and business model aspects, and provide empirical evidence for policy design. Subsequently, this research aims to reduce the knowledge gap related to the uncertainty around the future role of the DSO amidst the ongoing smart and sustainable electricity transition. Particularly, the approach taken contributes to a more detailed understanding of the sustainability transition in electricity distribution, focusing on the role of the DSO in the EU. Establishing the DSOs as unit of analysis contributes to greater analytical focus when considering the complexities of the ongoing changes in policy, technology, and business models. Furthermore, focusing on transition adaptation from a DSOs perspective aims to contribute to the development of knowledge on their organizational and business model characteristics, therefore resulting in actionable guidance for ongoing market design and distribution industry transformation debates in academic, industrial, and governmental settings. Additionally, focusing on the EU region provides a framework of analysis in which a shared ambition for the transformation of the electricity sector exists, expressed through shared climate and energy policies, and sustainable development strategies, notwithstanding the idiosyncrasies of each country.

Considering the aims of this thesis to contribute with novel research on the adaptation of electricity distribution in a changing electricity sector, three research questions were defined, establishing this study's scope and boundaries.

The role, activities, and responsibilities of DSOs in the electricity sector are the results of complex interactions between their existing technology, policy, and business model characteristics and the possible alternatives for adaptation in the future. The ongoing transition highlights the possibilities for change, thus becoming relevant to understand: ***What are the future alternatives for DSOs in a smarter and more sustainable electricity sector?***

The identified smart and sustainable transition results in changes to DSOs external environment, which lead to a diverse set of new challenges and opportunities, thus enhancing the importance to study: ***How do the shifts in business model, technology, and market design characteristics impact DSOs?***

The discussion on the electricity sector transformation and future role of the DSO enhances the demand to identify novel technologies and regulatory approaches and how these can be best integrated through innovative business models. These are important components of the electricity distribution industry, as a capital-intensive and regulated activity. These new possibilities require an assessment of: ***How capable are DSOs to implement business model innovation and adaptation in a rapidly changing electricity sector?***

1.3 Theoretical framework and methodology

The research goals and questions defined for this thesis focus on establishing a detailed understanding of the ongoing transition dynamics impacting the electricity distribution industry in the EU, specifically on the evolving role of the DSO. The development of this research required the consideration of different system components and their adaptation as the smart and sustainable energy transition unfolds. Considering the above, this thesis follows a conceptual framework and applies methodologies derived from sociotechnical transitions theory, which concentrate on studying the evolution and adaptation of complex interrelated social and technical aspects as a means to inform future development pathways (Finger et al., 2005; Fouquet, 2010; Bennett, 2012). Establishing a conceptual framework rooted in sociotechnical transitions literature benefits from its multidisciplinary and integrated approach, developed under the understanding that the transformation of technical systems is best understood by analyzing the intertwined relations of technology, social and institutional aspects, rather than by following a siloed engineering or economic approach (Bolton & Foxon, 2015).

For the purposes of this thesis, the electricity distribution industry transition is framed as a changing Large Technical System (LTS). Implementing the LTS conceptual framework in this regard proves particularly useful as its initial conceptualizations were derived from the appearance and evolution of electricity networks between 1880 and 1930 (Hughes, 1983). Now, one century later, the analysis of the complex processes underpinning the power sector, and the changing role of distribution infrastructure, are yet again critical. In this set up, it becomes pertinent to dedicate efforts for understanding this adaptation process, for Hughes:

> "[…] the effort to explain the change involves the consideration of many fields of human activity, including the technical, the scientific, the economic, the political, and the organizational. This is because power systems are cultural artifacts." (Hughes, 1983: 2).

Large Technical Systems (LTS) encompass a complex network of assets and technologies, organizations, and legislative elements, combined to deliver critical services to society (Hughes, 1987; Ewertsson & Ingelstam, 2004; Finger et al., 2005; Bijker et al., 2012; Bolton & Foxon, 2015). As a conceptual framework of analysis it enables the study of the interaction and evolution of the system elements, aiming at delivering an integrated view for a better understanding of its complex evolution and adaptation (Davies, 1996). In LTS, adaptation and development are driven by the occurrence of reverse salients and critical problems. A reverse salient occurs when an existing or new component operates uncoordinated with the overall system elements. In the case of electricity distribution, for instance, the growing diffusion of small-scale distributed generation from solar photovoltaic (PV) and wind technologies represent such reverse salients, challenging the traditional operation of the networks and the regulatory and business operations in place. Acting upon reverse salients and the challenges they create for the system is what enables transitions in LTS.

The transition-oriented conceptual foundations of LTS have led to two noteworthy streams of knowledge development. Firstly, its direct applications for the understanding of changes in large technical system-based industries, such as energy networks (Markard & Truffer, 2006; Bolton & Foxon, 2015; Hasenöhrl, 2018; Palm & Gustafsson, 2018), water infrastructure (Dobre et al., 2018), and telecommunication, food, and transportation (Davies, 1996; Vleuten, 2018), to name a few. Secondly, its contribution to the evolving field of enquiry on sociotechnical sustainability transitions (Farla et al., 2012), and its specific analytical approaches such as the Multi-Level Perspective (MLP) (Rip & Kemp, 1998; Geels, 2002), and the Triple Embeddedness Framework (TEF) (Geels, 2014), which have been used to inform policy design for low-carbon development across technologies, firms, industries, and regions.

The relevance of LTS as a conceptual framework has been recently reinforced given its ability to facilitate the understanding not only of the systems' development and growth, but also of reconfiguration in mature systems, Figure 1.1, as is the case of electricity distribution (Sovacool et al., 2018). Understanding the recent adaptation dynamics towards a smart and sustainable electricity distribution industry in the EU benefits from this conceptual approach, as its original aim was specifically to study infrastructure-based, capital intensive industries (Truffer et al., 2010). Consequently, the LTS conceptual framework provides a sensible approach for understanding the sociotechnical transitions in electricity distribution, particularly the changing roles and responsibilities of DSOs.

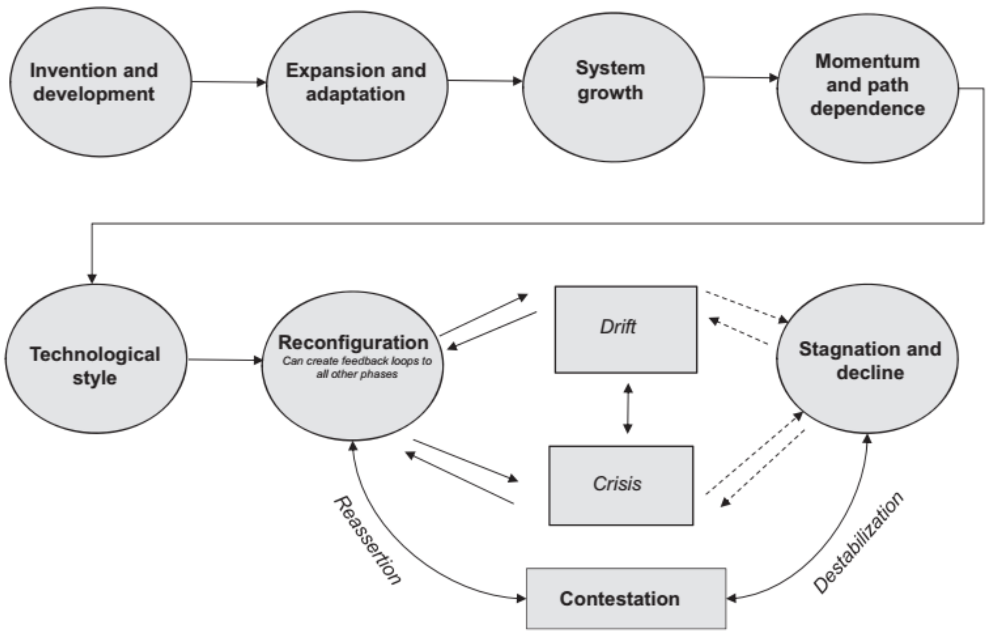

Figure 1.1 Conceptual stages in LTS
Source: (Sovacool et al., 2018: 23)

The empirical evidence generated under this conceptual framework results from the implementation of a combination of qualitative and quantitative methodologies to unveil relevant insights for policy, technology, and business model adaptation. The assessments conducted and presented in this thesis can be characterized as initiative-based learning approaches according to Turnheim et al. (2015). Initiative-based learning assessments are motivated to understand the adaptation of actors as sociotechnical configurations evolve, also described as experimental approaches to understand the complex evolution of unfolding transitions. Furthermore, these are structured to provide real-world empirical evidence (Schot & Geels, 2008), which contribute to revealing the characteristics of emerging trends and associated rich contextual information that is often overlooked in other analytical approaches, such as quantitative system modelling analyses, which follow robust and often inflexible research methods; or sociotechnical analyses, which whilst providing detailed transition analyses are often unable to provide actionable policy design guidance (Turnheim et al., 2015).

The added value of implementing an initiative-based learning methodology presents a few weaknesses related with the limited standardization of applied methods; the context-bound scope of the analyses conducted often also limited to a short period of analysis; and the potential difficulty to generalize the results obtained to an entire sociotechnical transition. Nonetheless, these limitations are counterbalanced by the value of the resulting policy adaptation guidelines, rooted in practice, and their relevance for policy makers and electricity distribution stakeholders. Additionally, following an initiative-based learning methodology enables a concrete identification and understanding of DSOs complexities, perceptions, and capabilities, which is only possible given its short-term orientation (Ison et al., 2007; Turnheim et al., 2015).

1.4 Thesis overview

The thesis manuscript it organized in six chapters.

Chapter 1

This chapter establishes the framework in which this thesis is developed. The background and motivation are outlined, which highlight the need to study the transition toward smart and sustainable electricity distribution, in particular regarding the role of DSOs. This knowledge need is tackled through the aims and scope of the research questions, also outlined in this section. Furthermore, the theoretical framework and methodology in which this thesis is developed are described, with attention to the value of sociotechnical transition studies and large technical systems in supporting research that aims to investigate the complexities and evolution of DSOs in a rapidly changing electricity sector.

Chapter 2

This chapter reviews the sociotechnical development of the electricity distribution industry in the EU. A review of policy-driven adaptation is presented focusing on the policies shaping market design and technological development and their impact on DSOs. This policy review and industry characterization provides background knowledge on the evolution of the electricity distribution industry and supports the assessments presented in the subsequent chapters 3, 4, and 5 focused on DSOs adaptation.

Chapter 3

This chapter presents a foresight study on business model innovation, technological adaptation, and market design policy alternatives. A Policy Delphi method was applied, involving two iterative survey rounds and 207 European experts, which assessed 57 policy alternatives. This expert elicitation technique provides insights regarding future possibilities for electricity distribution. Future alternatives were analyzed with data obtained from DSOs, TSOs, electricity generation companies, electricity retail companies, electricity sector associations, industry analysts and consultants, policy makers, regulators, and researchers and academics. These insights, encompassing a broad range of stakeholders, provide empirical evidence on different alternatives for the future of the electricity distribution industry and the future role of the DSOs.

Chapter 4

This chapter investigates the complex evolution and company and market design adaptation needs. Challenges and opportunities are analyzed through nine multi-stakeholder workshops, held in two EU Member States (Germany and Portugal) in 2016-2017, engaging distribution system operators, researchers, academics, and integrated utility companies. This assessment presents up-to-date insights on the impact of the ongoing smart and sustainable transition for DSOs.

Chapter 5

This chapter presents a capability approach to study DSOs business model innovation and adaptation. Capabilities were measured in 129 DSOs from 27 EU countries. The role of capabilities on adaptation and performance is investigated through a Structural Equations Model (SEM). The results obtained contribute to a better understanding of the ability of DSOs to deliver new business models and transform their roles, activities, and responsibilities amidst a rapidly changing industry. This empirical approach contributes to the ongoing debate on the future role of utilities, as it provides evidence on their ability to adapt.

Chapter 6

This chapter summarizes the contributions of this thesis, revisits the research questions and summarizes the main findings obtained through this thesis research. The barriers overcome through this work are discussed, and pathways for future work are outlined.

1.5 Thesis associated scientific publications

The development of this thesis was accompanied with the publishing of scientific journal articles, book chapters, working papers, and conference papers that can be divided in two sets. A first one is strictly linked to this thesis; a second group, although helpful to this area of research, is not connected with the specific contributions of this study.

The following contributions are directly related to this research.

Scientific journal articles

- **Pereira, G.**, Silva, P., Soule, D. (2019) "Utility adaptation and business model innovation in a rapidly changing electricity sector: a capabilities approach" Energy Policy *under revision*
- **Pereira, G.**, Specht, J. M., Silva, P., Madlener, R. (2018). "Technology, business model, and market design adaptation toward smart electricity distribution: Insights for policy making" Energy Policy 121(2018), 426-440.
- **Pereira, G**; Silva, P., Soule, D. (2018). "Assessment of electricity distribution business model and market design alternatives: Evidence for policy design" Energy and Environment.
- **Pereira, G**; Silva, P., Soule, D. (2018). "Policy-adaptation for a smarter and more sustainable EU electricity distribution industry: A foresight analysis" Environment, Development and Sustainability.

Book chapters

- **Pereira, G.**; Silva, P., Soule, D. (2019). Designing markets for innovative electricity services in the EU: the roles of policy, technology, and utility capabilities. In Fereidoon Sioshansi (Ed.). Consumer, prosumer, prosumager: How service innovations will disrupt the utility business model. California. Elsevier Academic Press.
- **Pereira, G.**; Silva, P. (2017). The smart grid and distributed generation nexus. In Nivalde de Castro and Guilherme Dantas (Eds.), Distributed Generation: International experiences and comparative analyses, (pp. 13-36). Rio de Janeiro: Publit.

Working papers

- **Pereira, G.**, Specht, J.M., Silva, P., Madlener, R. (2018). Technology, business model, and market design adaptation toward smart electricity distribution: Insights for policy making. Aachen. FCN Working Paper No. 3/2018.

Conference papers

- **Pereira, G**; Silva, P., Soule, D. (2017). "How to redesign the role of the electricity distribution system operators?", In 15th International Association of Energy Economics European Conference 2017, Vienna, Austria.
- **Pereira, G**; Silva, P., Soule, D. (2017). "What policies for an EU smarter grid environment? A Delphi-based foresight analysis on DSOs.", In 3rd International Conference on Energy and Environment: Bringing together Engineering and Economics Proceedings, Porto, Portugal.
- **Pereira, G**; Silva, P., Soule, D. (2017). "Policies for an EU smarter grid environment: A Delphi study on DSOs.", In 14th European Energy Market Conference, Dresden, Germany.
- **Pereira, G**; Silva, P; Madlener, R. (2017). "Adaptation dynamics toward a smarter grid: the case of electricity distribution system operators", In 3rd Energy for Sustainability International Conference: Designing Cities & Communities for the Future, Madeira, Portugal.
- **Pereira, G**; Silva, P. (2016). "Electricity distribution utilities in transition: research on organizational change", In 11th Sustainable Development of Energy Water and Environment Systems, Lisbon, Portugal.
- **Pereira, G**; Silva, P. (2016). "Determinants of change in Electricity Distribution System Operators – A review and survey", In 13th European Energy Market Conference, Porto, Portugal.

As mentioned above, while not directly related to this thesis, the following publications were also produced through the development of this research.

Scientific journal articles

- Silva, P., Dantas, G., **Pereira, G.**, Câmara, L., Castro. N. (2019) "Photovoltaic distributed generation – An international review on diffusion, support policies, and electricity sector regulatory adaptation" Renewable and Sustainable Energy Reviews 103 (2019) 30–39.
- Soares, N., Martins, A. G., Carvalho, A. L., Caldeira, C., Du, C., Castanheira, É., Rodrigues, E., Oliveira, G., **Pereira, G.**, Bastos, J., Ferreira, J. P., Ribeiro, L. A., Figueiredo, N. C., Šahović, N., Miguel, P., Garcia, R. (2018). "The challenging paradigm of interrelated energy systems towards a more sustainable future" Renewable and Sustainable Energy Reviews 95(2018), 171-193.

- **Pereira, G**; Silva, P. (2017). "Energy efficiency governance in the EU-28: Analysis of institutional, human, financial, and political dimensions" Energy Efficiency 10(5), 1279-1297.

Book chapters

- **Pereira, G.**; Silva, P. (2018). The case of Hawaii. In Nivalde de Castro and Guilherme Dantas (Eds.). International experiences for distributed generation: drivers, impacts, and adjustments. (pp. 65-100). Rio de Janeiro. Publit. *in Portuguese*
- Silva, P.; **Pereira, G.**; Viana, D. (2018). The case of Nevada. In Nivalde de Castro and Guilherme Dantas (Eds.). International experiences for distributed generation: drivers, impacts, and adjustments. (pp. 101-139). Rio de Janeiro. Publit. *in Portuguese*
- Silva, P; **Pereira, G.** (2018). The case of New York. In Nivalde de Castro and Guilherme Dantas (Eds.). International experiences for distributed generation: drivers, impacts, and adjustments. (pp. 140-178). Rio de Janeiro. Publit. *in Portuguese*
- **Pereira, G.**; Silva, P. (2018). The case of France. In Nivalde de Castro and Guilherme Dantas (Eds.). International experiences for distributed generation: drivers, impacts, and adjustments. (pp. 299-334). Rio de Janeiro. Publit. *in Portuguese*
- Silva, P.; **Pereira, G.** (2018). The case of Portugal. In Nivalde de Castro and Guilherme Dantas (Eds.). International experiences for distributed generation: drivers, impacts, and adjustments. (pp. 335-365). Rio de Janeiro. Publit. *in Portuguese*
- **Pereira, G.**; Silva, P. (2015). Energy Efficiency Governance in the European Union Member States – Analysis on Current Status. In Pedro Godinho and Joana Dias (Eds.), Assessment Methodologies: energy, mobility, and other real-world applications, (pp. 89-110). Coimbra: Coimbra University Press, ISBN: 978-989-26-1038-2.

Conference papers

- Ramalho, M; Câmara, L; **Pereira, G**; Silva, P; Dantas, G. (2017) "Photovoltaic energy diffusion through net-metering and feed-in-tariff policies: learning from Germany, California, Japan and Brazil", In 6th Latin American Energy Economics Meeting, New Energy Landscape: Impacts for Latin America, Rio de Janeiro, Brazil.
- Câmara, L; **Pereira, G**; Dantas, G; Castro, N; Silva, P. (2017). "Evolution of Solar Photovoltaic Support Policies in Brazil and Portugal: a review", In 3rd Energy for Sustainability International Conference: Designing Cities & Communities for the Future, Madeira, Portugal.

Chapter 2

Sociotechnical development of electricity distribution in the EU

2.1 Background

Analyzing future policy, technology, and business model adaptation alternatives and possibilities for DSOs requires an understanding of the main sociotechnical aspects that have shaped the development and current state of the electricity distribution industry in the EU. The review of sociotechnical development contributes to an understanding of the complex interactions between infrastructure and society (Long, 2013).

This chapter is structured as follows: Section 2.2 reviews the concept and relationship of smart grids and distributed generation. Section 2.3 characterizes the electricity distribution industry in the EU. Section 2.4 reviews the policy-driven evolution of electricity distribution, and Section 2.5 discusses and concludes.

2.2 Smart grids and distributed generation

The smart and sustainable transition impact on the electricity distribution industry can be observed through the diffusion of smart grid and distributed generation technologies and supporting policies. Given their relevance to understanding the sociotechnical progress of electricity distribution the concepts of smart grids and distributed generation are presented and associated integration challenges described.

2.2.1. Smart grids

The shift from traditional electricity distribution systems, designed around unidirectional electricity flows, distributing electricity from high voltage transmission lines to end-users, to a system that supports flexibility, bi-directional electricity flows, and enables the integration of innovative energy sources as well as information and communication technologies encompasses the evolution toward smart grids.

The International Energy Agency (IEA) in its Smart Grids Technology Roadmap defines smart grids as:

> "[…] an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end-users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, resilience and stability." (IEA, 2011: 8)

In a smarter distribution grid, digital and advanced technologies contribute to increase the monitoring and control capabilities of connected infrastructure, which include decentralized renewable electricity sources, electricity storage, electric vehicles and their charging infrastructure, smarter appliances, and demand response technologies. Moreover, advanced metering infrastructure enables remote data collection and creates opportunities for increasing awareness on consumers electricity usage. The combination of the electricity infrastructure, with a layer of information and communication technologies aims to increase distribution system capabilities to handle the growth of distributed loads connected to the distribution infrastructure. Smart grids facilitate the diffusion of distributed renewable electricity generation by supporting the integration of end-user side generation from PV, wind, and small scale combined heat and power, complementing the role of conventional centralized power sources (IEA, 2011; IRENA, 2015). Smart grids will result both from the modernization of existing systems, which will have to adapt given changes in electricity uses, as well as from the implementation of new systems that are designed for smart grid operations. Smart grids represent a transition toward new technologies, business processes, and distribution system operational management. Table 2.1 describes the main differences between traditional grids and smarter electricity distribution grids.

Table 2.1 Traditional grid and smarter electricity distribution grid characteristics

Characteristics	Traditional grids	Smarter grids
Connected consumers participation	Consumers have limited access to information and are passive users of electricity, with a consumption-only role.	Consumers are involved and participate through demand response initiatives and by connecting distributed energy resources to the grid.
Distributed generation and storage integration	System designed for large central power plants, with significant barriers for the uptake of distributed generation.	Distributed energy resources, such as small-scale PV, wind, and micro CHP can easily be integrated into the grid, supporting the growth of renewable energy participation.
Enables business model, product, and market design innovation	Limited business models and market structures, resulting in limited opportunities for consumers to participate in electricity markets.	Well integrated electricity markets are adapted to allow for consumer participation, by creating market opportunities for demand response and distributed generation.
Supports the transition to a digital economy	System operation focused on outages reduction, characterized by slow response to quality of service issues.	Power quality becomes a priority, enabled by a layer of digital technologies, which contribute to faster response times and increased customer service quality.
Asset optimization and operational efficiency	Business processes have limited access to operational analytics.	Increased access to data and analytics contributes to fault prevention and minimizes outages.
Self-healing capabilities	Focus on minimizing damages after faults are detected.	Monitoring and control technologies contribute to automatic detection of issues and fault prevention.
Infrastructure resiliency	System is vulnerable to external attacks and natural disasters.	Resilient to attacks and natural disasters due to system restoration capabilities.

Source: (US DOE, 2008)

Smarter distribution grids are an enabler for distributed generation integration (US DOE, 2009). The combination of smarter grid technology with increasing shares of distributed generation allows for more effective consumer demand management, as well as management of intermittent renewable electricity sources. The integration of distributed generation in distribution networks has an impact on electricity sector stakeholders, namely: connected consumers, policy makers and regulators, as well as third party developers (US DOE, 2009). Shifting from a unidirectional electricity flow focused system, to a bi-directional electricity flow, ICT enabled, framework, creates possibilities for existing system operations, standards, technologies, policies, and overall market design.

While the transition to smart grids is often policy-driven, as part of climate and energy policy packages, its delivery depends on the diffusion of technologies at the distribution level that enable new operational and asset management procedures from network operators. One of the first investments often pushed forward to enable smart grids is related to the metering infrastructure. A grid reliant on electromechanical or advanced meter reading hinders smart grid capabilities, as these two types of meters are only one-way communication devices. Therefore, evolving to an advanced metering infrastructure becomes relevant, to support two-way communication between distribution network system operators and connected grid users. This change gives distribution utilities the capability to be more active in system management, supporting load management, and improved quality of service (Farhangi, 2010). According to the IEA (2011) the increased control capabilities from rolling out advanced metering infrastructure contributes to:

- Implementation of time-of-use tariffs;
- Gather and store granular data on connected user's electricity consumption and production when behind the meter distributed generation exists;
- Development of more accurate load profiles;
- Better maintenance and outage management operations;
- Remote service connection and disconnection;
- Identification of non-technical losses; and
- Financial management through automated collection of consumers' data.

Considering the concept and framework in which smart grids are evolving it is important to emphasize that smart grids represent in most cases an evolution through upgrades on existing electricity distribution systems, rather than a replacement of existing infrastructure. Smarter distribution grids will be achieved through the implementation of new technologies, processes, business models, and development of necessary capabilities to operate in a more interconnected, and digital environment (Farhangi, 2010).

2.2.2. Distributed generation

Distributed generation technologies are a key component driving the transformation of electricity distribution, given their potential to be closer to the end-use loads, and connected to lower voltage distribution networks. Distributed generators are complementary to large central power plants, allowing for new applications and result from an increasingly established community of consumers that also produce electricity. Remarkably, distributed generation technologies supplied most of the electricity needs in the late 1800s and early 1900s, before large centralized power systems were deployed (Hughes, 1983, 1987). In the 1950s distributed generation accounted to 10%, mostly used as a back-up source or in transportation, while in 2010 it accounted for 36% of power capacity additions (Pepermans et al., 2005; Owens, 2014). The concept of distributed generation has often been loosely defined and associated with the idea of small-scale electricity generation units (Pepermans et al., 2005). Additional characteristics include its installation close to the point of consumption, flexibility in terms of installation and network connection, and intermittency associated with the availability of the primary energy resource used for generation, in which case solar and wind are highly intermittent (Dulău et al., 2014). The European Commission Joint Research Centre proposes the following definition:

> "Distributed generation is an electric power source, connected to the grid at distribution level voltages, serving a customer on-site or providing support to a distribution network." (L'Abbate et al., 2007: 33)

This definition considers distributed generation in the context of its goal and installation location, capacity and voltage, and the area to which it delivers power. In terms of goal, distributed electricity generation units are deployed as a source of electric power, much like what is expected from large power plants. Regarding location, distributed generation is expected to be located close to where consumption occurs, and connected to the electricity distribution network, or on the consumer side of the meter, being in that case a behind-the-meter source of power. Power delivery area is also relevant, while distributed generation is expected to be located and consumed locally, resulting excess generation has to be delivered to the distribution network, thus requiring due consideration for system capacity. System capacity for distributed generation is associated with small generating units; this capacity depends on the technology being used. Table 2.2 provides a summary of distributed generation technologies and associated capacities.

Table 2.2 Distributed generation technologies

Technology	Capacity range	Fuel options
Reciprocating engines	20 kW – 20 MW	Diesel, natural gas, and alternative fuels
Gas turbines	10 – 100 MW	Natural gas and alternatives fuels
Microturbines	30 – 250 kW	
Fuel cells	5 kW – 5 MW	Hydrogen and natural gas
Small hydro	1 – 100 MW	Renewable resources
Micro hydro	25 kW – 1 MW	
Solar PV	20 W – 100 kW	
Small wind	200 W – 3 MW	
Biomass gasification	100 kW – 20 MW	
Geothermal	5 – 100 MW	
Ocean energy	100 kW – 5 MW	

Source: (L'Abbate et al., 2007; Dulău et al., 2014; Owens, 2014)

The diffusion of distributed generation technologies, predominantly renewable sources such as PV and small wind, can impact electricity distribution network operations. Voltage profile changes can occur, resulting from the variations in electricity consumption and production, which differ from typical unidirectional networks. Power flows become progressively bi-directional, despite the overall goal of distributed generation being deployed for local consumption. Short circuits can occur more often, as well as load loss, and congestion in the system, all of which depend on generation and load levels. Moreover, power quality and service availability may be affected as more distributed generation plants are connected to the network (L'Abbate et al., 2007; Dulău et al., 2014). Conversely, there are various benefits that must be considered. Being close to loads, distributed generation, enables a better use of local energy resources, which results in access to low cost electricity for consumers connected to renewable electricity distributed generation. The growth on the share of renewable distributed generation contributes for fossil fuel consumption reduction, resulting in lower greenhouse gas emissions, thus benefiting the environment. Construction of distributed generation plants represents fewer burdens related to authorization and permits when compared to large power plants, thus resulting in faster access to electricity. A higher number of distributed generation plants can result in congestion reduction upstream in the system, which can lead to investment deferral for higher voltage transmission lines. Distributed generation can also contribute to increased energy security by reducing fuel import needs. Distributed generation from renewables is becoming an established source of power across regions, as presented in Table 2.3 and Table 2.4, in parallel with the continued growth of renewable electricity installed capacity, Table 2.5. Distributed renewable electricity generation units are typically variable renewable electricity sources (VRE), given their dependence on climatic conditions, meaning that there is no possibility to guarantee that these will generate power at a certain time, therefore these are characterized as non-dispatchable power technologies. Sources with this characteristic include wind, solar PV, small hydro, and tidal technologies (IEA, 2011). Dispatchable renewable energy technologies include biomass, geothermal, concentrated solar power, and hydro units (IRENA, 2015).

Table 2.3 Renewable and variable renewable electricity generation and installed capacity in 2012

Generation by region in 2012								
Technology	**Global**	**European Union**	**OECD Americas**	**Latin America**	**Africa**	**Middle East**	**OECD Asia Oceania**	**Non-OECD Asia**
Total generation (TWh)	22 721	3 260	5 268	1 152	741	905	1 850	7 402
Hydro (%)	16.2	10.3	13.5	60.9	15.1	2.4	6.3	15.7
Bioenergy (%)	1.9	5.2	1.8	3.9	0.3	0	2.5	1
Wind (%)	2.3	6.3	3	0.6	0.3	0	0.8	1.7
Geothermal (%)	0.3	0.2	0.5	0.3	0.3	0	0.5	0.3
Solar PV (%)	0.4	2.1	0.2	0	0	0	0.5	0.1
Total RE (% of total)	21.2	24.2	18.9	65.8	16	2.4	10.5	18.9
Total VRE (% of Total)	2.7	8.5	3.2	0.6	0.3	0	1.3	1.8

Installed capacity by region in 2012								
Technology	**Global**	**European Union**	**OECD Americas**	**Latin America**	**Africa**	**Middle East**	**OECD Asia Oceania**	**Non-OECD Asia**
Total capacity (GW)	5 683	960	1 356	258	165	256	454	1 728
Hydro (%)	19.1	15.5	1.5	55.4	15.2	5.5	15.2	19.8
Bioenergy (%)	1.8	3.9	4.9	5	0	0	1.8	1.2
Wind (%)	5	11	0.3	1.2	0.6	0	1.3	5.5
Geothermal (%)	0.2	0.1	0.7	0.4	0	0	0.2	0.2
Solar PV (%)	1.7	7.2	0.1	0	0	0	2.2	0.5
Total RE (% of total)	27.8	37.9	14.3	62	15.8	5.5	20.7	27.3
Total VRE (% of Total)	6.7	18.4	0.4	1.2	0.6	0	3.5	6

Source: (IRENA, 2015)

Table 2.4 Wind and PV installed capacity growth rate between 2012 and 2013

Country	Wind growth (%)	PV growth (%)	VRE growth (%)
China	21	168	33
Japan	2	106	76
Germany	11	11	11
US	2	65	9
UK	26	59	31
India	9	78	14

Source: (IRENA, 2015)

Table 2.5 Renewables installed capacity in 2012 and potential in 2030

Region	% RE 2012	% RE REmap 2030
European Union	38	55
OECD Americas (excl. USA)	49	66
USA	17	49
Latin America (non-OECD)	62	80
Eastern Europe (excl. EU, incl. Russia/Turkey)	25	41
OECD Asia	21	53
China	28	42
India	28	57
Non-OECD Asia (excl. China/India)	22	43
Middle East	5	41
Africa	16	36

Source: (IRENA, 2015)

The expected growth on distributed variable renewable generation further emphasizes the relevance of deploying smart grids. Electricity distribution systems with distributed generation representing over 15% to 20% of total electricity generation capacity will experience significant operational complexities in a traditional network management approach. Smart grids can contribute to easing these difficulties by supporting control of variable generation, enabled through access to real-time data that supports system management, power and overall service quality and system flexibility (IEA, 2011; Buccella et al., 2014).

2.2.3. Integration and adoption challenges

This section reviews the distributed generation adaptation and challenges for electricity distribution. Section 2.2.3.1 reviews the system integration challenges. Section 2.2.3.2 reviews the economic and regulatory challenges. Lastly, Section 2.2.3.3 reviews the financial challenges.

2.2.3.1. System integration

The integration of distributed generation units into distribution grids impacts system operation. As most electric systems where not designed for high shares of distributed generation being interconnected, these may face additional challenges. However, as smart grids are deployed, these impacts will become part of normal business operations for distribution network companies. Different aspects lead to system impacts, including: the capacity of the distributed generation unit, the type of technology, the location and point of interconnection, to name a few (Basso, 2009). System impacts can manifest locally at the interconnection level and local distribution system, or span across the network to other areas, these impacts usually increase as the share of distributed generation expands. System impacts can be classified into: system protection and coordination; unplanned island; voltage related; service quality and, system capacity (Basso, 2009).

System protection and coordination

Distribution system protection is essential for system operation, as well as to secure safety and quality. Safety devices are distributed through the electricity distribution system, including: feeder breakers at substations, line reclosers, and fuses. The integration of distributed generation calls for a reassessment of the system protection practices and devices installed for this purpose (Pepermans et al., 2005; L'Abbate et al., 2007; Basso, 2009; Martinez & Martin-Arnedo, 2009).

Unplanned island

An unplanned distribution system island occurs when part of the system becomes separated from the rest, but the connected distributed generation units continue to deliver electricity to the islanded section to which they are connected. This type of impact can result in safety and quality issues. Furthermore, unplanned islands can put distribution utility workers at risk, if maintenance works are being conducted at the unplanned island location. Moreover, Basso (2009) argues that beyond personnel safety, an island can lead to equipment damage and increase outage times.

Voltage

Regulating voltage is an important part of electricity distribution system operations, as it is both a measure of quality of service, as well as a prerequisite for the adequate operation of local appliances, lights, and consumer electric powered devices. Given the importance of voltage regulation, distribution systems are equipped with voltage regulation devices to keep voltage at the required ranges. However, these technologies were designed for a unidirectional power flow system, which will require changes for system areas with reverse power flows originating from the increase in distributed generation (Azmy & Erlich, 2005; Basso, 2009; Ruiz-Romero et al., 2014).

Service quality

The impact of distributed generation for power quality becomes a concern once it exceeds 15% of the system capacity. For these cases the impacts include harmonics, direct current injection, and flickers (Pepermans et al., 2005; Basso, 2009; APPA, 2013). These impacts require the implementation of modern electronic devices to mitigate service quality disturbances (L'Abbate et al., 2007).

System capacity

The existence of distribution network capacity to handle distributed generation related power flows is an important aspect for successful system integration. Generally, constrains exist across distribution network segments on the level of distributed generation that can be interconnected without compromising operations. However, if distributed generation capacity and location is planned adequately, a higher number of interconnections should lead to congestion reduction. In any case it is important to study available system capacity (L'Abbate et al., 2007).

2.2.3.2. Economic and regulatory

The system impacts presented above are often connected with the economic and regulatory framework in which electricity distribution systems operate, which can enhance the difficulties for integrating distributed generation. Distribution systems operate as regulated monopolies, to guarantee fair prices for access to the infrastructure, non-discriminatory access to the network, as well as high quality service and reliability standards (Scheepers et al., 2007). Given their regulated activities, and the resulting constrains, economic challenges are often tied with regulatory barriers, which include: lack of incentives for integration; interconnection costs; market access, and bureaucratic barriers for interconnection.

Lack of incentives for integration

The integration of distributed generation requires technical upgrades in the system as well as adjustments in management processes and operations. As regulated natural monopolies, electricity distribution companies can have limited incentives for investing in the integration of distributed generation, as it can result in reductions on their efficiency indexes and consequently impact their financial performance.

Interconnection costs

Depending on the region, interconnection costs can result in negative signals for distributed generation diffusion. This can often occur in countries where national legislation has not yet been reformed for small-scale generation units to be connected to distribution networks.

Market access

Market access for small-scale distributed generators can be defiant in markets with high concentration, where larger players have significant economies of scale, thus creating barriers for distributed generators to compete. Moreover, spot market trading fees are considerably high for small-scale generators.

Bureaucratic barriers for interconnection

Access to distribution networks for distributed generation interconnection can be challenging depending on national laws and existing processes for obtaining authorization. As interconnection procedures have been designed for larger power generators, existing bureaucracies have to be adapted to enable interconnection for small-scale distributed generators, at fair costs.

2.2.3.3. Financial

Investors in distributed generation technologies, the owners, also face burdens associated with financing the investments for generation technologies. According to the California Public Utilities Commission (2013), these include: financial incentives; access to financing; technology costs, and soft costs.

Financial incentives

Financial incentives to support the diffusion of distributed generation technologies have been implemented across regions, due to the high upfront investment required, that otherwise would result in slow deployment rates. However, as technologies mature and their costs become closer to that of traditional electricity supply, the incentives start to become less attractive from a financial perspective. This transition from an incentive based policy framework to a market-driven framework can result in a slowdown in diffusion rates, and increase financing difficulties for those interested in a distributed generation installation (Rugthaicharoencheep & Auchariyamet, 2012; California Public Utilities Commission, 2013).

Access to financing

Financing instruments to support investment are critical to support distributed generation. The necessary technology requires a large investment upfront, which in the case of renewable distributed generation is mostly the only cost, apart from relatively smaller operation and maintenance expenditures throughout the lifetime of the system. The initial investment requirement can therefore act as a barrier for interested consumers. This issue can be overcome through the development of financing options tailored for distributed generation.

Technology costs

Equipment and technology costs are the main component of the investment necessary in a distributed generation installation, while incentives and financing instruments can contribute to offsetting part of the investment burden; this cost is still a barrier for diffusion. As adoption increases, and economies of scale at production are achieved the cost of the technology will further increase, which can contribute to reduce this hurdle.

Soft costs

Installing a distributed generation system encompasses a range of intangible costs. Soft costs in distributed generation installations include: permitting fees, to cover the process to obtain authorization to install and connect the generation unit to the electricity distribution system; administrative costs, to cover all the aspects related with technology acquisition, application to incentive schemes, and other bureaucracies; financing and contract related costs; engineering and installation costs; grid connection fees, government taxes; and any other costs associated with the entire project from when the decision to install distributed generation is made until the unit goes online. These costs represent a significant barrier, and one that is often hard to forecast in the planning stage, as some of these are context specific and can vary across locations, given differences in local policies and regulations, as well as the maturity of the market where the distributed generation unit is being installed.

The described distributed generation obstacles provide a wide-ranging perspective on the areas where difficulties often arise, thus hindering its diffusion. However, the existence of system integration, economic and regulatory, and financial related barriers indicate also the possibilities for innovation and improvement in terms of technologies, business models and operational processes, policies, and overall market design.

2.3 Electricity distribution industry and DSOs in the EU

In the EU context, DSOs are defined as follows:

> "[…] 'distribution system operator' means a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity." (European Union, 2009b: 63)

For this service of general economic interest, DSOs are remunerated through a regulated tariff. While this description might sum up the incumbent role of DSOs in the past, it falls short when it comes to the recent developments in the context of the energy transition. The traditional, asset-focused task of operating, maintaining, and developing distribution grid assets already extends to the operation of smart metering devices, with the DSO becoming a data hub operator (Eurelectric, 2010). The diffusion of distributed generation and storage assets as well as the coupling of the heat and the mobility sector result in the problem that private households can be less and less represented by standard load profiles, which increases the importance of having more granular information on local grids. Furthermore, the historical hardware approach to grid shortages focused on grid expansion can be complemented by operational solutions such as flexibility management.

Another aspect not considered in the traditional definition of a DSO is the degree of distribution concentration, where significant differences exist across Europe. Germany, for example, at about 880 DSOs, is on top of the list among the EU member countries, whereas countries such as Ireland, Portugal or Lithuania have a single or dominant DSO (Eurelectric, 2013; Prettico et al., 2016). Furthermore, Member States are subject to EU legislation, which is challenged by each country's idiosyncrasies and the existence of different regulations in each of the 28 Member States (European Commission, 2015a), as well as a heterogeneous electricity distribution industry across countries. Table 2.6 provides a perspective on this heterogeneity and presents the number of DSOs, number of DSOs serving over 100 000 consumers, and the total number of connected consumers.

Table 2.6 DSOs and connected consumers

Country	Number of DSOs in 2011	Number of DSOs with ≥ 100 000 consumers in 2011	Total number of connected consumers
Austria (AT)	138	13	5 870 000
Belgium (BE)	24	15	5 243 796
Bulgaria (BG)	4	3	4 915 497
Cyprus (CY)	1	1	535 050
Croatia (HR)	1	1	2 300 000
Czech Republic (CZ)	3	3	5 837 119
Denmark (DK)	72	6	3 277 000
Estonia (EE)	36	1	652 000
Finland (FI)	85	7	3 309 146
France (FR)	158	5	33 999 393
Germany (DE)	880	75	49 294 962
Greece (GR)	2	1	8 195 725
Hungary (HU)	6	6	5 527 463
Ireland (IE)	1	1	2 237 232
Italy (IT)	144	2	31 423 623
Latvia (LV)	11	1	873 856
Lithuania (LT)	1	1	1 571 789
Luxembourg (LU)	6	1	265 000
Malta (MT)	1	1	436 947
Netherlands (NL)	11	8	8 110 000
Poland (PL)	184	5	16 478 000
Portugal (PT)	13	3	6 137 611
Romania (RO)	8	8	2 639 318
Slovenia (SI)	1	1	925 275
Slovakia (SK)	3	3	2 392 418
Spain (ES)	349	5	27 786 798
Sweden (SE)	173	6	5 309 000
United Kingdom (UK)	7	7	30 828 266
Total	2 323	190	266 372 284

Source: (Eurelectric, 2013)

The EU electricity distribution industry is composed of 2 323 DSOs, of which 190 serve over 100 000 consumers. These larger DSOs have been mandated to unbundle their electricity distribution activities from other generation, transmission, and retail activities as part of the market liberalization process (European Union, 2009b). Conversely, DSOs below this threshold can be exempted from unbundling, supporting economies of scale possible by aggregating other activities, such as water and gas distribution (Eurelectric, 2013). In terms of industry structure, it is possible to observe considerable differences in the number of DSOs across Member States.

These differences are generally the result of historical, political and geographical characteristics of each country (CEER, 2016).

Complementing the structural characteristics of electricity distribution, Figure 2.1a provides a perspective on DSO concentration, which measures the relationship between a country's DSOs and distributed power [1]. In general, EU Member States have a medium to low concentration level, with Croatia, Cyprus, Greece, Malta, Ireland, Lithuania, and Slovenia having a high concentration level.

From a regulatory perspective DSOs, as natural monopolies, operate under the rules of National Regulatory Agencies. (NRAs) These establish the regulatory framework that simulates competition given that DSOs are not subject to competitive market forces, and control quality of service (Meeus & Hadush, 2016). Figure 2.1b offers a perspective of the regulatory mechanisms in place across the EU following Cambini's aggregation in cost-based models, hybrid models, and incentive models (Cambini et al., 2016) [2]. EU countries are mostly applying a mix of incentive and hybrid regulatory approaches, with only Belgium, Croatia, Cyprus, Greece, and, Malta applying a cost-based model. The reduced number of countries applying a cost-based model can be explained considering the small incentives for cost reduction it induces, as well as the possibility for over investment under this type of regulation (Pérez-Arriaga, 2013; Cambini et al., 2016).

Beyond the general regulatory framework implemented at each Member State Figure 2.1c provides information on the existence of innovation inducing mechanisms in a country's electricity distribution sector regulations. DSOs amidst the energy transition face challenges due to the integration of new technologies, consumers, and producers' behaviors, and a changing market design. These changes require investments in new assets and can entail new costs that are not familiar for DSOs or the NRAs. As some of these new costs and investments opportunities are new, they represent a possible risk, as the added value and resulting benefits are often uncertain. Regulatory frameworks have traditionally existed to avoid risky investments

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[1] High concentration, for Member States in which one DSO is responsible for over 99% of the distributed power. Medium concentration, for Member States in which one DSO has a dominant position with over 80% of the distributed power, or alternatively when three of the largest DSOs in a Member State are responsible for over 60% of the distributed power. Low concentration, for Member States in which the three largest DSOs are responsible for less than 50% of the distributed power (Eurelectric, 2013; Cambini et al., 2016).

[2] Cost based regulation models ensure the DSO collects its investment and operational costs, plus an authorized rate of return. Incentive based regulation gives DSOs the possibility to enhance profits in case certain performance criteria is met (Cambini & Rondi, 2010). Hybrid regulatory approaches combine aspects of cost based and incentive regulation, often using a cost based approach for capital expenditures, and an incentive approach for operational expenditures (Cambini & Rondi, 2010; Eurelectric, 2013, 2014; Cambini et al., 2016).

from the network monopolies. However, the energy transition and the progress toward smarter distribution grids calls for a framework that supports innovation. EU regulators are in the process of understanding how to best create regulations that accomplish these goals (Eurelectric, 2016). In the EU there are innovation stimulus in place for Slovenia, Greece, Ireland, Austria, Denmark, Finland, Slovakia, Italy, Portugal, France, and the United Kingdom. All these countries have a regulatory framework that follows either a hybrid or incentive model, except for Greece that applies a cost-based approach (Cambini et al., 2016; Eurelectric, 2016).

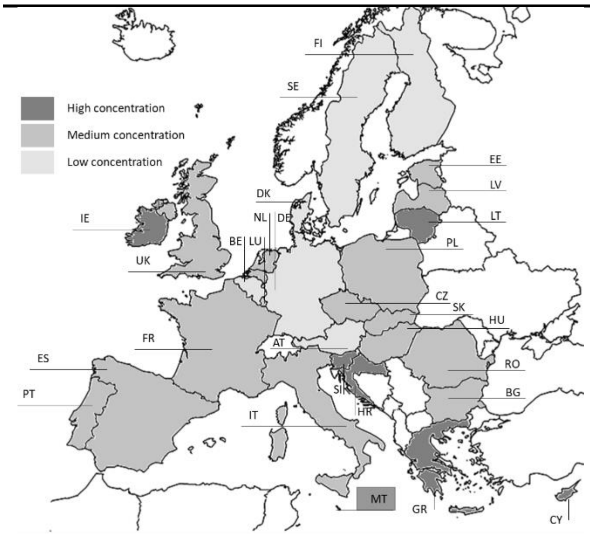

Figure 2.1a DSO concentration

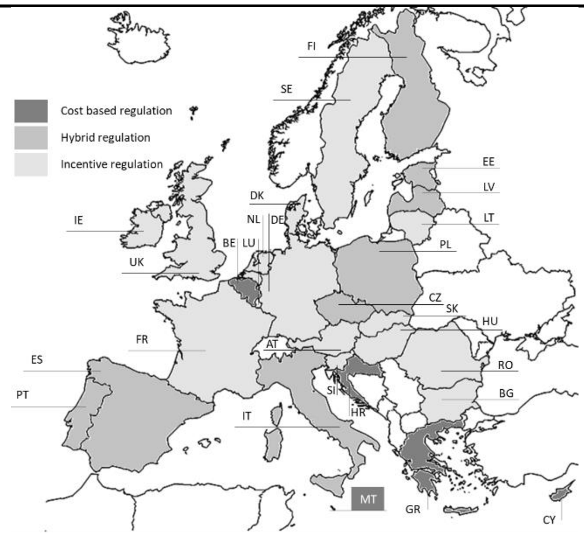

Figure 2.1b DSO regulatory mechanisms

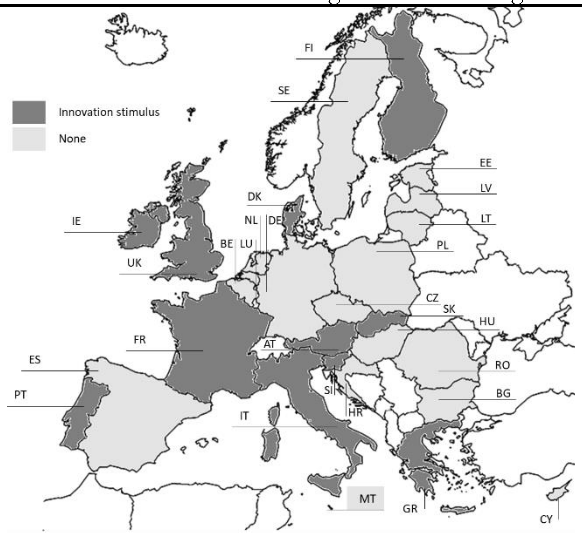

Figure 2.1c DSO innovation support schemes

Figure 2.1 Electricity distribution industry in the EU

Sources: (Ernst & Young, 2013; Eurelectric, 2013, 2014, 2016; Cambini et al., 2016)

The differences among EU countries electricity distribution industry structure and regulatory frameworks increase the complexity of the electricity sector market transformation efforts. Nonetheless, EU policies have been implemented to drive the necessary adjustments in the electricity sector, consequently impacting distribution and the role of the DSOs. EU policy-driven electricity distribution industry evolution instruments are reviewed next.

2.4 Policy-driven evolution of electricity distribution

This section reviews the policy-driven evolution of electricity distribution. Section 2.4.1 reviews the policies related to market design adaptation. Section 2.4.2 reviews the policies for innovation and technological development.

2.4.1. Policies for market design adaptation

The ambition to deliver an internal electricity market for EU consumers has been a long-standing ambition of the European Commission and its Member States. The importance of delivering clean, affordable, and secure electricity has motivated the dedication of efforts and resources to adjust the existing liberalized electricity sector market design (European Commission, 2012b). Consequently, the evolution of electricity distribution activities in the EU has been driven by successive policy packages aimed at achieving structural reforms in the electricity sector. This section organizes implemented instruments in two stages of structural change. The first stage comprises all actions taken toward market liberalization, while the second comprises actions taken toward a smarter and more sustainable electricity sector, Figure 2.2.

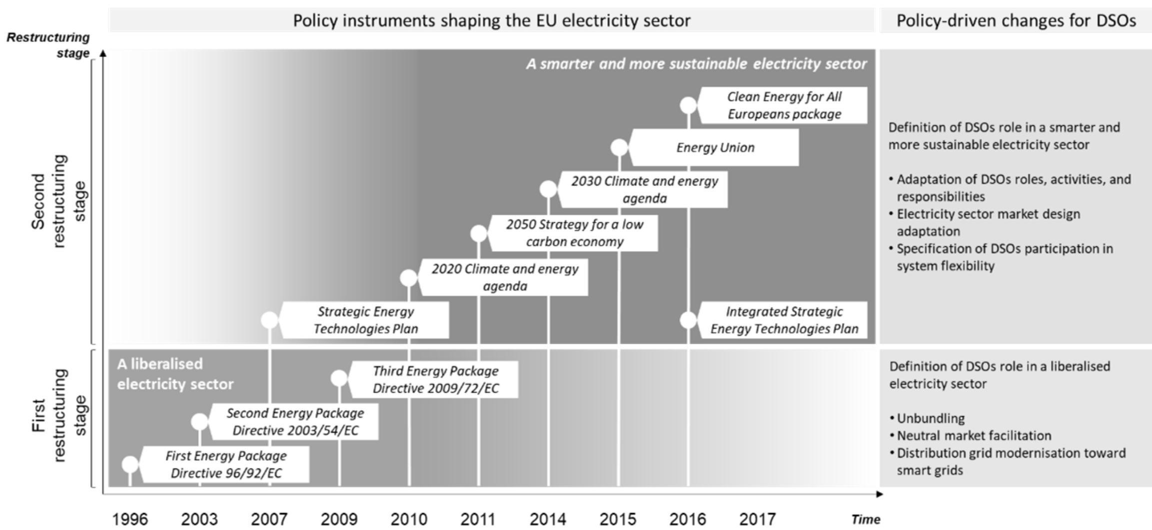

Figure 2.2 Policy instruments shaping the electricity sector and impacts for electricity distribution
Source: Author's own [3]

[3] From this point forward all figures and tables without source reference are the author's own elaboration.

2.4.1.1. A liberalized electricity sector

The EU electricity sector was gradually liberalized through policy packages intended to create a competitive internal market to deliver better quality and more affordable electricity to European citizens. Prior to EU electricity sector liberalization, most Member States' electricity sectors were vertically integrated, and consisted largely of publicly owned companies. The realization that the economic efficiency of the generation and supply segments could be increased through competition motivated the separation of these activities from the network activities of transmission and distribution (Kopsakangas-Savolainen & Svento, 2012). This structural reorganization of the sector assumed that competitive generation and supply would need to be supported by a well-functioning electricity distribution network infrastructure, which would continue to be regulated as monopolies (Joskow, 2008).

The First Energy Package, Directive 96/92/EC (European Union, 1996) introduced competition for electricity generation, and opened the market for competition at the retail level for large consumers. In addition, non-discriminatory access to networks was established, while generation and retail were unbundled from the monopoly activities of transmission and distribution. This package defined DSO responsibilities as: providing a secure, reliable, and efficient service; acting as a neutral market facilitator by providing non-discriminatory access to electricity networks; and prioritizing renewable energy sources when dispatching generating units. DSOs were also made accountable for the privacy of sensitive commercial information collected through their operations.

The Second Energy Package, Directive 2003/54/EC (European Union, 2003), introduced additional measures: retail market competition was expanded to the household sector, legal unbundling of network activities from competitive activities was mandated, and National Regulatory Authorities (NRAs) for Member States were established. Through this package electricity distribution tasks evolved further: DSOs became responsible for providing the necessary information to system users for efficient access to the networks. They were also required to follow a transparent and non-discriminatory process in their procurement of energy to cover system losses. Furthermore, distribution system expansion planning was required to consider demand-side management and distributed generation as alternatives to upgrading or replacing network capacity.

The Third Energy Package, Directive 2009/72/EC (European Union, 2009b), introduced procedures for retail supplier switching, ownership unbundling for transmission system operators, and mandated the development of network codes at the EU-level. This policy package also argued the importance of modernizing electricity distribution networks toward smart grids to stimulate distributed generation and energy efficiency.

During this stage of structural change toward market liberalization, DSOs assumed growing responsibilities for enabling competition through neutral market facilitation. The need to modernize distribution grids was also raised, however no explicit guidance was provided for how this modernization should unfold, or how and to what extent DSOs should participate in deploying smart girds.

2.4.1.2. A smarter and more sustainable electricity sector

Following the EU actions toward liberalization, efforts have been pursued to establish a smarter and more sustainable electricity sector, consequently impacting electricity distribution. Recent policies address climate and sustainable development challenges, as well as ongoing technological innovation. Policy-driven efforts for a more sustainable electricity sector are visible in the 2030 goals, which build on the previously set 2020 targets (European Commission, 2010), and support the 2050 strategy for a low carbon economy (European Commission, 2011). These goals target an increase in the share of renewable energy of at least 27%, a reduction of greenhouse gas emissions of minimum 40%, and an increase in energy efficiency of 30% (European Commission, 2014a, 2016b), These goals are further supported by the Energy Union policy package, introduced in 2015, designed to deliver an integrated energy system, with consumers at its core, as stated in its vision (European Commission, 2015a):

> "[…] our vision is of an Energy Union with citizens at its core, where citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, participate actively in the market, and where vulnerable consumers are protected. To reach our goal, we have to move away from an economy driven by fossil fuels, an economy where energy is based on a centralized, supply-side approach and which relies on old technologies and outdated business models. We have to empower consumers through providing them with information, choice and through creating flexibility to manage demand as well as supply. We have to move away from a fragmented system characterized by uncoordinated national policies, market barriers and energy-isolated areas." (European Commission, 2015: 2)

This vision highlights the importance of fundamentally transforming the electricity system and the role of adapting technologies and business models to enable new services and empower consumers. Moreover, the Energy Union proposes an integrated regulatory framework in lieu of the current arrangement in which 28 Member State level regulatory approaches co-exist under the European Union climate and energy policies (European Commission, 2015a). The scope of action of the Energy Union is wide-ranging, targeting broad-based adaptation of the European energy system, Figure 2.3. Nevertheless, within this broader ambition it is possible to identify specific action steps that focus on the transformation of the electricity system, directly affecting electricity distribution, DSOs, and the electricity sector market designs.

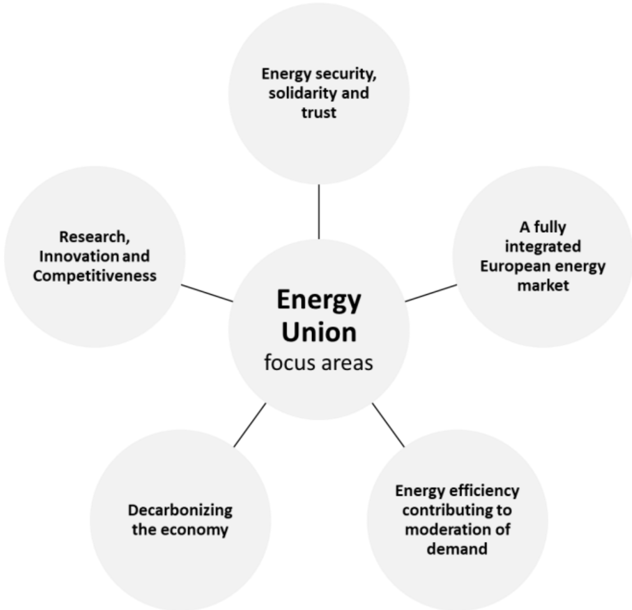

Figure 2.3 Energy Union focus areas
Source: Elaboration based on European Commission (2015a)

The Energy Union focus area for a fully integrated European energy market has direct implications for the electricity sector. Its focus includes reforming both the sector's infrastructure and policies. In terms of infrastructure it specifies the importance of increased interconnections among Member State's electricity systems. Only with an adequately interconnected electricity market can European citizens access and benefit from a common pool of increasingly clean energy resources. In this regard, an interconnection target of 10% of the installed electricity production capacity of each Member State has been set for 2020, and a target of 15% for 2030. The policy package also highlights the investments needed to update existing infrastructure and introduce smart grid and digital technologies.

Regarding the electricity sector's policy framework, the Energy Union aims to ensure the adequate implementation of existing policies, namely the full implementation of the 3rd Electricity Sector Package, Directive 2009/72/EC. This will provide a strong foundation for introducing policy proposals that shape existing market designs. Electricity sector market redesign is driven by the increase in renewable energy sources connected to the grids, which requires greater levels of system flexibility management. Achieving the required demand and supply side flexibilities will require infrastructure adaptation, but also an adjustment of the regulatory frameworks that ultimately shape the distribution utilities' business model.

Building on the momentum created by the Energy Union package, the European Commission is adapting the electricity sector market design, through the Clean Energy for All Europeans policy proposals (European Commission, 2016b). These proposals are motivated by the increased penetration of distributed renewables and digitalization of the electricity sector, which create new possibilities for businesses and households to use, generate, store, and trade electricity. Reforming existing DSOs, and other electricity sector incumbent roles, as well as new approaches to market design is important to enable these possibilities (European Commission, 2017c).

These policy proposals also specify roles for DSOs, including their involvement in system flexibility management, electric vehicle charging infrastructure, data management, smart metering, and distributed generation management. The proposals for a new electricity directive, as a recast of Directive 2009/72/EC, give DSOs the responsibility to cost-effectively integrate distributed generation from renewables, heat pumps, and electric vehicles. The proposals reflect the importance of enabling and incentivizing access and use of these new resources to the benefit of the grid's management and operational efficiency. They also suggest distribution utilities play a role in procuring services through distributed energy resources, demand response, and electricity storage technologies. Services should be accessed through market-based approaches, used to achieve greater efficiency in distribution network operation, and minimize network reinforcements and expansions whenever possible.

These market design proposals give Member States guidance on the steps necessary to enable a transition in electricity distribution. According to these policy proposals each EU country is called to implement distribution network use guidelines, in the form of network codes, and market rules for the provision of new services and how distribution utilities can access these services. Network tariff redesign is also a key area of action, intended to reduce barriers to flexibility services, and enable the improvement of grid efficiency. Additionally, European countries are now responsible for introducing distribution network development roadmaps. These roadmaps are expected to support the adequate integration of renewable distributed generation, the development of storage facilities, and the electrification of transport. Moreover, the roadmaps will allow system users to understand the future expansion and reinforcement plans of distribution grids. Roadmaps must be published at least every two years and provide information on the medium and long-term flexibility services needed.

The ongoing market design policy proposals provide guidance for the future of EU electricity distribution by indicating that their responsibilities include the long-term capacity of the distribution system, in addition to the economically efficient operation of the networks, minimizing environmental impacts and supporting energy efficiency improvements. Besides their core electricity distribution responsibilities, DSOs are incentivized to procure flexibility services, including congestion management services, to improve network infrastructure management and efficiency.

The policies highlight the need for a regulatory framework enabling these new services. This framework must ensure the non-discriminatory participation of all market players in this new market for flexibility services, including the owners and managers of renewable energy generation units, electricity storage, demand response and aggregators. Additionally, the regulations to be implemented must consider the remuneration of the costs incurred by DSOs in procuring these new services, including digital technologies and infrastructure costs. Further, all electricity sector stakeholders must have non-discriminatory access to relevant data. The future EU electricity market design proposals indicate also that DSOs will benefit from flexibility services, while generally prohibiting their ownership, development, management, and operation of electro mobility charging points and electricity storage, Table 2.7.

Table 2.7 DSO responsibilities in new market design

Activity	Distribution utility responsibility				
	Own	**Develop**	**Manage**	**Operate**	**Exception**
Integration of electro mobility assets (Recharging points)	No	No	No	No	No other parties were granted this activity. Is approved by the regulator. The operation occurs in a non-discriminatory manner.
Electricity storage facilities	No	No	No	No	No other parties were granted this activity. Is approved by the regulator. The operation occurs in a non-discriminatory manner. When electricity storage facilities are fully integrated network components.

Source: Elaboration based on Council of the European Union (2017b); European Commission (2017b)

The presented market design proposals clarify the role of DSOs in providing innovative services based on the growing share of distributed energy resources and digital technologies. Specifically, the policy framework argues for implementing and developing flexibility services through market-based mechanisms while ensuring that distribution grids can benefit by procuring these new services as a source of increased operational and investment efficiency.

2.4.2. Policies for innovation and technological adaptation

In addition to an updated electricity market design, the evolution of the EU energy system also requires technological innovation and research to achieve a decentralized, decarbonized, and digital electricity sector. The Energy Union addresses this challenge in the focus area on Research, Innovation, and Competitiveness, Figure 2.3. It promotes an integrated innovation ecosystem in which academic-industrial collaborations can develop and market technologies effectively, putting the EU at the forefront of renewable energy, storage, and smart grid technologies (European Commission, 2015a). This is supported through the EU's strategic energy technologies plan – SET plan – for a focused and efficient technological research and innovation adaptation process, which identifies areas of action that contribute to Energy Union priorities, Table 2.8. Additionally, it supports the coordination of low-carbon innovation at the EU and national levels (European Commission, 2018).

Table 2.8 SET plan support to Energy Union priorities

Energy Union priority	Strategic Energy Technology plan action
Global leadership in renewable energy technology	Develop low-cost renewables
Smart energy systems with consumers at its core	Solutions for energy consumers Flexible energy systems
Energy efficiency, with focus on the building stock	Energy efficiency in buildings Energy efficiency in energy intensive industries
Sustainable transport technologies and services	Battery technology for electro-mobility and stationary use Renewable fuels and bio energy
Carbon capture innovation for storage and use	Carbon capture and storage Carbon capture and use
Safe operation of nuclear energy sources	Nuclear safety

Sources: Elaboration based on European Commission (2015a, 2015d, 2016c)

The SET plan promotes the shift to a smarter, more flexible, and integrated approach to deliver energy to consumers. The plan includes an integrated innovation approach that prioritizes the identification of new opportunities to increase flexibility, and resilience; and a new technology innovation and development governance approach, more result oriented and with greater transparency (European Commission, 2015d, 2018).

The Energy Union's emphasis on smart, consumer-centric energy systems, together with the SET plan for achieving smarter, more resilient, and secure energy systems, directly affect the electricity sector and DSOs. This action area targets the development and demonstration of innovative power system components, more flexible thermal generation, demand response and storage technologies and services, in addition to more efficient heat pumps and combined heat and power units. It also supports advances in electricity transmission technologies, techniques for physical and cyber security, and demand data analytics (European Commission, 2015d).

Delivering technological innovation in these areas will contribute to the transformation of the electricity system and DSOs operations and business models. The European Technology and Innovation Platform on Smart Networks for the Energy Transition – ETIP SNET – brings together a diverse set of EU stakeholders to support this transformation. It aims to define a strategy for research and innovation, identify existing barriers to innovation, and effectively exploit research and innovation outputs (ETIP SNET, 2017b).

The strategy of ETIP SNET considers the policy push for electricity markets and system transformation promoted by the Energy Union, which will impact electricity generation, transmission, and distribution networks, while calling for new ways of interaction between networks operators, integration of new technologies as well as greater system interconnection. These broader goals resulted in specific focus areas for DSOs, which should focus on (ETIP SNET, 2016b):

- Network upgrades, through the introduction of new technologies, methodologies, and tools that improve operations;
- System flexibility, by increasing distributed load management capabilities, such as those from electric vehicles or distributed generation;
- System reliability, through the implementation of network contingencies management procedures;
- Information and communication technologies and digitalization, to increase the connectivity of DSOs with other stakeholders and their monitoring and control capabilities;
- Market design and regulatory environment, by considering alternative institutional arrangements for electricity distribution and associated governing rules that contribute to convergence between innovation, sustainability, and competitiveness in the internal energy market.

It particularly aims to address upcoming network infrastructure challenges associated with the growing need for flexibility options. Changes challenging the role, planning, and management of network infrastructures include the following (ETIP SNET, 2016b):

- Variable generation connected to networks often located far from consumption areas;
- Changes in load characteristics partly due to the electrification of mobility and building energy efficiency measures;

- Integration of European electricity transmission networks and associated governance;
- Expansion of the EU internal energy market, consequently increasing the scope of responsibilities and interaction of market makers – transmission and distribution network operators – with market players.

Considering these challenges DSOs will have a key role in facilitating end user participation in retail markets because of their involvement in shaping future market designs and regulations. Data management and analytical capabilities will be necessary at the distribution level. Possible applications may range from generation to consumer behavior forecasting to network infrastructure monitoring, maintenance, and planning. DSOs will also need to plan for the necessary network reinforcement to accommodate both electrification of mobility and changes in building loads resulting from energy efficiency improvements. Additionally, they will need to deploy information and communication technologies, such as smart meters, in supporting a more engaged consumer base. Lastly, DSOs will have to ensure the availability of the necessary infrastructure and operational processes for the growing share of variable renewable generation connected to the distribution network (ETIP SNET, 2016b). To address these distribution-specific challenges, the planned research and innovation actions focus on network upgrades, system flexibility and reliability, digitalization, market design, and regulation. Given the complexity of this innovation task, combined with the diversity across EU countries, the ETIP SNET operate through the governance structure described in Figure 2.4.

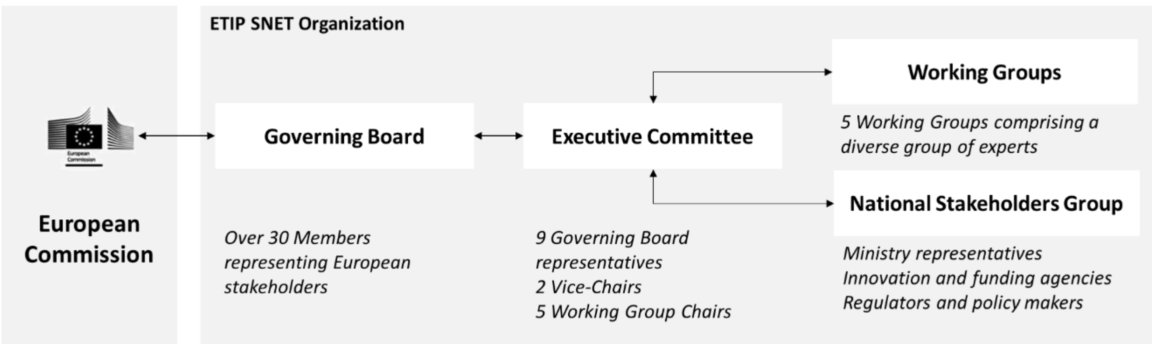

Figure 2.4 ETIP SNET platform governance structure

Source: Elaboration based on ETIP SNET (2017b)

The Working Groups focus on the following areas of innovation and technological adaptation, as follows:

- Reliable, economic, and efficient smart grid system: focus on exploring disruptive business and technology opportunities that support energy system optimization through affordable investment and operational costs;

- Storage technologies and sector interfaces: target new technology developments for storage applications that can increase system flexibility;
- Flexible generation: considers the technology and business model opportunities to support the delivery of the flexibility needs on an integrated power system;
- Digitalization of the electricity system and consumer participation: evaluates upgrading information and communication technologies across the entire value chain to enable new business models and services;
- Innovation implementation on the business environment: focuses on ensuring that the EU industry is engaging on the relevant research and innovation areas to deliver the electricity sector of the future.

Complementing the thematic Working Groups, the National Stakeholders Group ensures that the innovation and technological adaptation efforts match the needs and trends at the country level, by liaising with national governments and regulators. Figure 2.5 illustrates the interactions of the different working groups across domains.

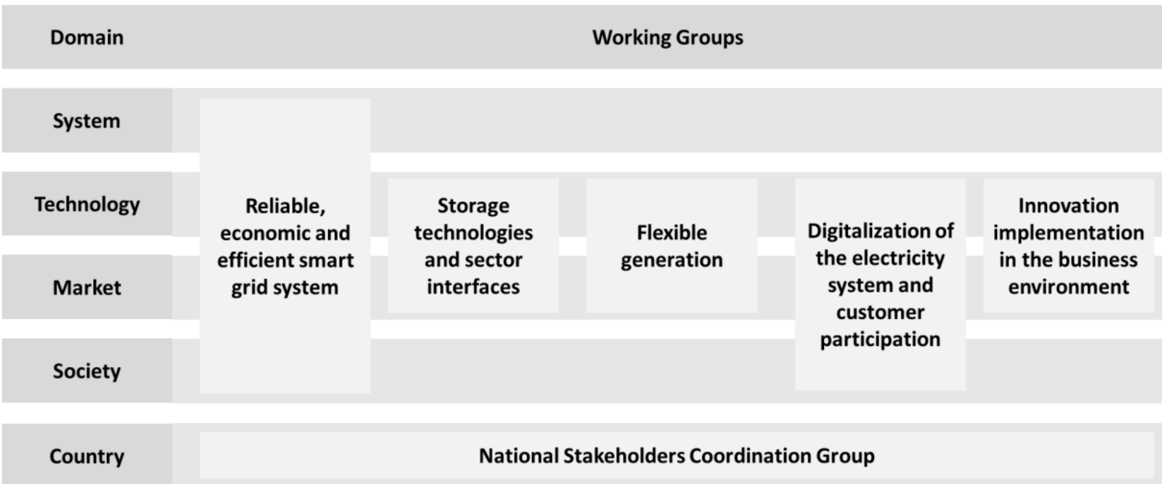

Figure 2.5 Working group interactions across domains
Source: Elaboration based on ETIP SNET (2016a)

In addition to guiding innovation on the future power system, the ETIP SNET estimates the financial resources needed to deliver the proposed innovations. Table 2.9 shows the estimated investment needs for the research and innovation areas related to electricity distribution, and which will influence technology adaptation most directly. These estimates are the total investments expected from all relevant stakeholders from 2017 to 2026.

Table 2.9 Investment needs for distribution system research and innovation priorities

Cluster	M€	%	Focus area	M€	%
Integration of smart customers and buildings	263	18	Active demand response	124	8
			Energy efficiency from integration with smart homes and buildings	139	9
Integration of decentralized generation, demand, storage, and networks	622	42	System integration of small DER	68	5
			System integration of medium DER	79	5
			Integration of storage in network management	100	7
			Infrastructure to host EV/PHEV – Electrification of transport	100	7
			Integration with other energy networks	150	10
			Integration of flexible decentralized thermal power generation	125	8
Network operations	442	30	Monitoring and control of LV network	142	10
			Automation and control of MV network	100	7
			Smart metering data processing and other big data applications	100	7
			Cyber security (system approach)	100	7
Planning and asset management	148	10	New planning approaches and tools	100	7
			Asset management	48	3
Total	**1475**			**1 475**	

Source: Elaboration based on ETIP SNET (2016b)

Technological adaptation will depend to a significant extent on delivering the research and innovation roadmap set through the ETIP SNET and reaching the estimated investment needs. Considering this, in 2018, the European Commission and its Member States introduced a set of initiatives to accelerate technological innovation and complement the SET plan and ETIP SNET efforts. The actions are introduced as an implementation plan for the ambition of the Strategic Energy Technologies Plan – SET plan – focus area to increase the resilience, security, and smartness of the energy system (European Commission, 2015d, 2018). In the collaborative process of structuring the implementation plan, EU energy system stakeholders introduced three initiatives to ensure the necessary efforts for adapting electricity systems (European Commission, 2018).

The initiative for optimized power systems

This initiative aims to deliver an optimized European-level power system. Its ambitions include the delivery of the necessary technological innovation to support system reliability, and economic and operational efficiency, while increasingly being able to accommodate higher shares of variable renewables. This will include technologies that increase system flexibility and enable consumer participation. This initiative has an estimated investment of 350 M€ per year until 2024.

The initiative for local and regional energy systems

This initiative aims to adapt local and regional energy systems to enable the integration and efficient use of high shares of renewables. This will contribute to achieving local sustainability ambitions at the community level, while supporting the goal of reaching a fully integrated European energy system that fosters the sustainable use of clean energy sources across countries. This initiative has an estimated investment of 250 M€ per year until 2025.

The initiative on innovation environments for smart devices and services

This initiative will address the digitalization of the sector and cybersecurity capability development, as well as new market models and regulatory options to support field experiments. This initiative has an estimated investment of 100 M€ per year until 2022.

The technology adaptation and innovation efforts steered through the Energy Union demonstrate the intricate governance mechanisms needed to support innovation across 28 countries. The ambitious goals of both the ETIP SNET and the SET plan's initiatives will require substantial investments and stakeholder engagement across EU countries. Thus, it is valuable to consider past EU engagement and investments in smart grid research and innovation as an indicator of European countries' abilities to deliver on these goals. The European Commission Joint Research Centre, through its Smart Grid Observatory, provides an analysis of the evolution of smart grid investments across the EU. The latest available results include information from 950 projects, totaling almost 5 Billion Euros in investment, up until 2015. Figure 2.6 shows the cumulative investments for both research and development (R&D) and demonstration projects across the EU. The growing investment trend can be observed as an indicator on the importance of smart grid innovations, as well as the ability of European countries to deliver such investments.

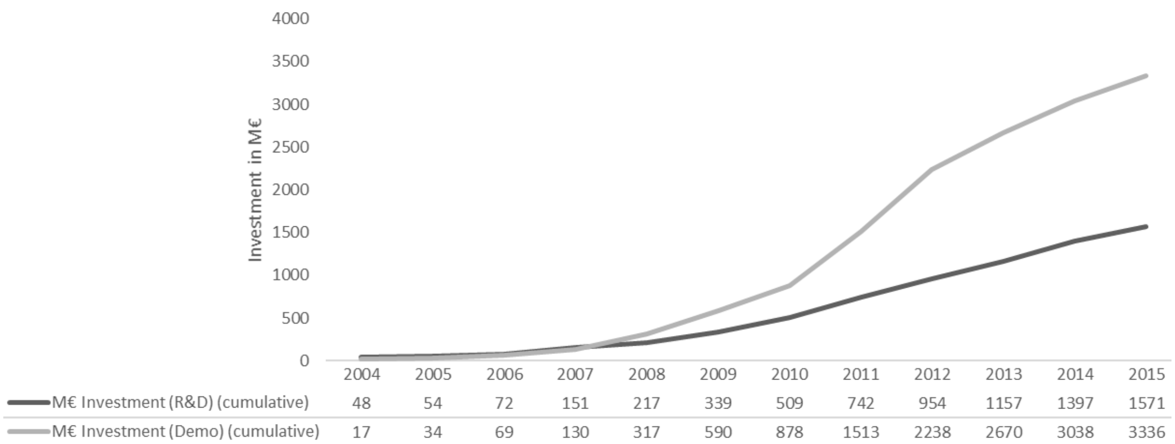

Figure 2.6 Research and development investment on smart grid projects in the EU, M€

Source: Elaboration based on Gangale et al. (2017)

In this context, DSOs invest most heavily in demonstration projects, while universities lead investment in research and development projects (Gangale et al., 2017). Figure 2.7 shows a breakdown of the cumulative investments by stakeholder and project category between 2004 and 2015.

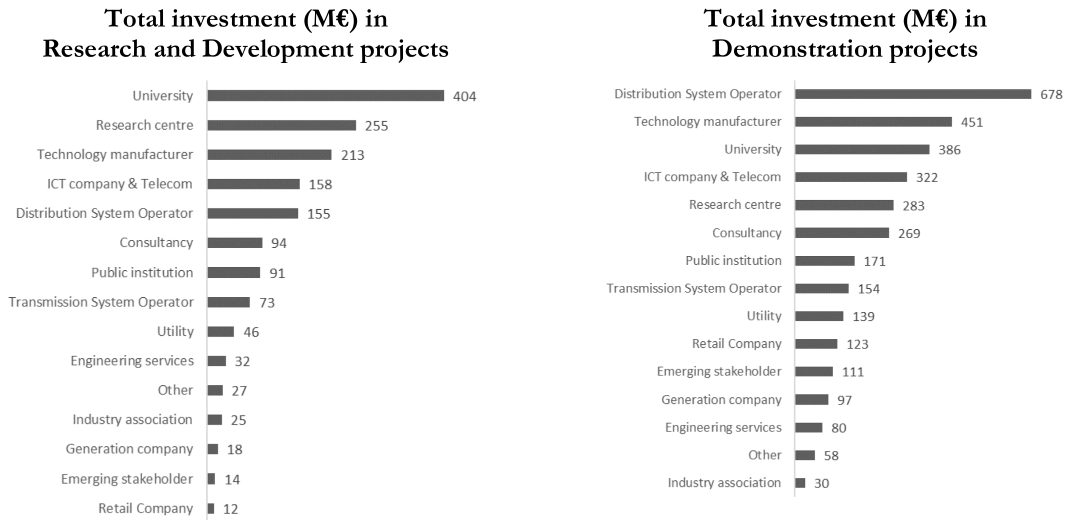

Figure 2.7 Investments by stakeholder category, M€

Source: Elaboration based on Gangale et al. (2017)

These EU projects explore smart network management; demand side management; integration of distributed generation and storage; electro mobility; integration of large scale renewable energy generation; and other applications (i.e. market and regulatory models, cybersecurity, to name a few). Figure 2.8 shows the investments in these areas between 2004 and 2015 per type of project.

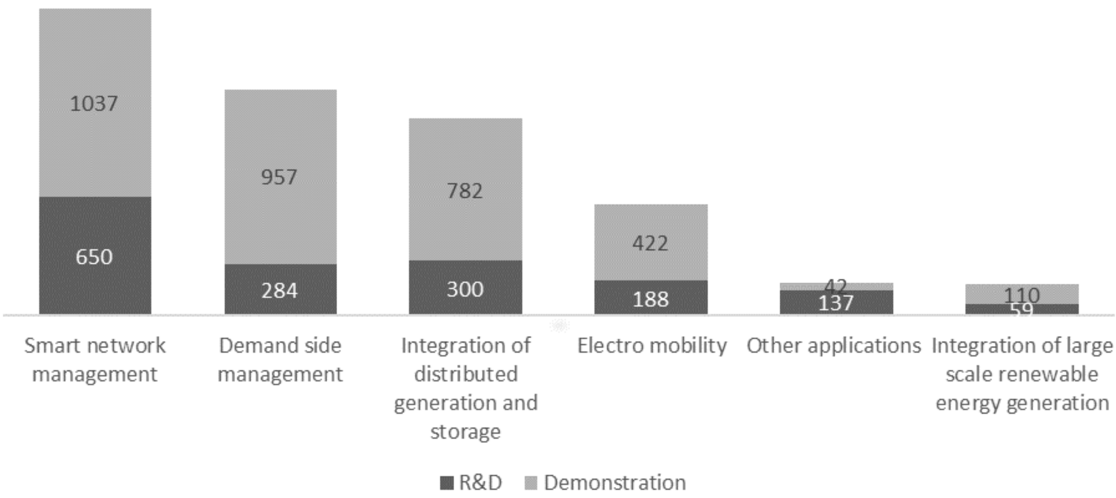

Figure 2.8 Investments by project focus area, M€
Source: Elaboration based on Gangale et al. (2017)

Notably, private funds represent the majority of EU investment in smart grid innovation, as indicated in Figure 2.9. However, European Commission and National funding, through support schemes, also play an important role. Only 15% of the 950 projects are exclusively supported through private funding. The remainder are sponsored by a combination of private, European Commission, and National funds.

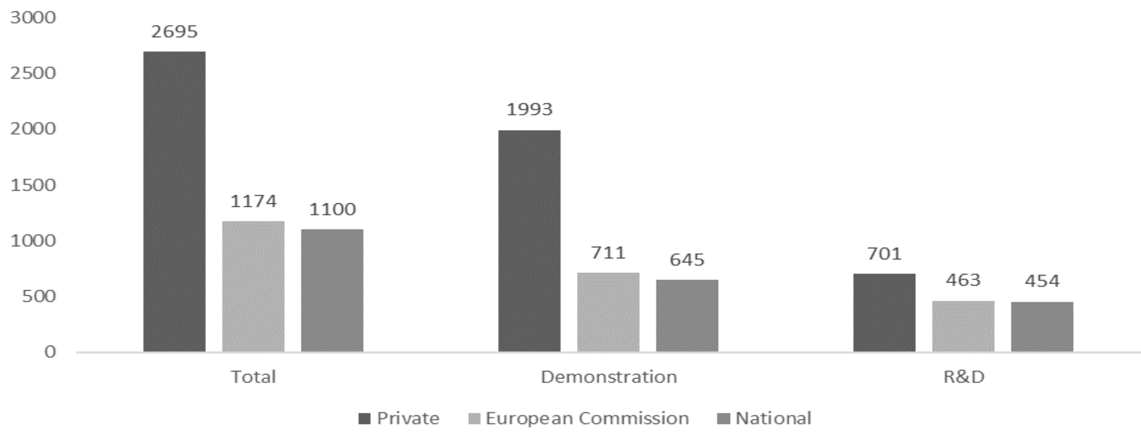

Figure 2.9 Investment funding sources, M€
Source: Elaboration based on Gangale et al. (2017)

In sum, the combination of ambitious but well-defined technological innovation plans and evidence of investment capacity necessary to advance these plans points to a positive outlook for building the future capabilities for DSOs and achieving technological adaptation.

2.5 Conclusions

This chapter discussed the smart grid and distributed generation nexus, as well as market design and technology-oriented policy efforts to transform the EU energy sector and, particularly, electricity distribution and the role of the DSO. These policy-driven changes toward a smarter and more sustainable electricity sector, along with the sector's earlier liberalization, reflect an ongoing effort to deliver secure and competitive energy to consumers (European Commission, 2015d). With this goal in mind, the Clean Energy for All Europeans package introduced a set of policy proposals for market design adjustments to enable the liberalized electricity sector to adapt (European Commission, 2016b). These proposals result from the revision of the Directive on the internal market for electricity (European Commission, 2017a), of the Regulation on the internal market for electricity (European Commission, 2017c), and of the Regulation establishing the Agency for Cooperation of Energy Regulators (ACER) (European Commission, 2017d). Combined, these policies aim to adapt the market design set by the Third Energy Package, putting more emphasis on the growth of renewable energy, decentralized generation, and technological advancement toward smarter grids. This adaptation must be achieved by ensuring renewable energy competes on an equal standing with other energy sources, and by removing existing barriers to the development of system flexibility services, such as demand response (European Commission, 2017a). These recent policy proposals suggest that DSOs procure non-frequency ancillary services in a market-based and non-discriminatory way to include different market participants, such as renewable energy generators, storage owners, aggregators, and demand-response providers.

Moreover, the proposals include provisions for the use of system flexibility, integration of electro-mobility in the network, and operation of storage. In the case of flexibility, Member States are encouraged to enable DSOs to procure flexibility services that improve system efficiency. The policy proposals guide Member States to opt for market-based approaches in the deployment, ownership, and operations of electro-mobility charging infrastructure and storage, unless no interest from other parties exists. The policy-driven evolution of electricity distribution pursued during this stage of structural change builds on the characteristics of a liberalized sector and further expands the participation of DSOs in smart grid related activities. However, the recent proposals for policy-adaptation under the Clean Energy for All Europeans package are not yet final. These proposals are currently being discussed by energy regulators (ACER and CEER, 2017b, 2017a, CEER, 2017a, 2017c) and sectoral associations for electricity distribution (CEDEC et al., 2017), all of which offer perspectives on how electricity distribution should operate in a changing electricity sector, and how DSOs should evolve in the ongoing transition.

Chapter 3

Assessment of smart and sustainable adaptation alternatives: a foresight study

3.1 Background

The EU aims to shift to an electricity sector that is sustainable, economically competitive, and affordable. This transition has contributed to a growing concern regarding how DSOs should be organized and operate electricity distribution grids (ACER, 2014). DSOs in the EU operate as natural network monopolies distributing electricity to over 260 Million connected households and businesses (Eurelectric, 2013), and are responsible for the planning, operation, maintenance, and expansion of distribution networks. However, the growing diffusion of innovative technologies connected at the distribution level are changing the way electricity is used and can impact how distribution networks are operated, and, therefore, how DSOs are organized.

The evolving technological asset base enables grids to become smarter and more sustainable, and potentially increases DSO ability to operate and manage a changing electricity distribution system (Martinot et al., 2015). However, how DSOs can (or should) adapt their participation in the electricity sector due to these changes is an open topic of discussion. The importance of understanding the role of the DSO in a smarter and more sustainable electricity sector has gained attention in the policy debate, given its impact on future policies and market design (CEER, 2014, 2015; ACER and CEER, 2017b).

This chapter examines potential development pathways for DSOs and market design alternatives to support the ongoing reform of the EU electricity sector, given the changing policies, technologies, and business models. DSO adaptation is particularly challenging due to their regulated activities, legacy technological assets, and traditional business operations. Specifically, there is the potential for conflicts of interest between the natural monopoly characteristics of electricity distribution network activities and competitive opportunities associated with the diffusion of smart grid innovations (Oosterkamp et al., 2014; Meeus & Hadush, 2016).

The assessment presented in this chapter details alternatives associated with business model innovation, technological adaptation, and market design. A foresight study focused on DSOs operating in a smarter EU electricity sector was designed and implemented through a Policy Delphi method to obtain expert knowledge. This assessment aims to further advance insights collected in previous expert consultations from the Council of European Energy Regulators and the European Commission on aspects of future market design and the role of DSOs in a changing electricity sector (CEER, 2015; European Commission, 2015c, 2015b; Tackx & Meeus, 2015). However, now with an updated perspective from European experts on policy alternatives that can contribute to the ongoing market design proposals presented in the Clean Energy for All Europeans policy package (European Commission, 2016b). This chapter combines quantitative and qualitative data, by considering both the experts' assessments to the alternatives under analysis and their perspectives, provided as complementary information.

This chapter is structured as follows: Section 3.2. describes the foresight methodology used and research design. Section 3.3 presents the results and discusses them in relation to recent policy proposals. Section 3.4 presents policy-adaptation guidelines derived from the findings. and Section 3.5 concludes by reviewing the key outcomes of the study.

3.2 Methodology

This assessment focuses on the ongoing electricity sector adaptation process and aims to contribute with a foresight-based expert assessment of alternatives for European DSOs. The method and research process design follow a Policy Delphi technique, typically used in foresight studies concerning the analysis of policy issues.

3.2.1. Policy Delphi method

The Policy Delphi method is part of the group of Delphi techniques, in which expert knowledge on a topic of interest is systematically gathered through iterative surveys combined with processes for providing structured feedback to participants (Linstone & Turoff, 2011). The knowledge collected is used to discern foresight-based assessments, increasing the accuracy of forecasts on complex issues (Linstone & Turoff, 2002; Woudenberg, 1991). The Policy Delphi was developed specifically to assess policy issues, which are defined as topics where different resolutions are being advocated, or for which guidance is sought (Turoff, 1970). Therefore, the Policy Delphi is used as a decision-facilitation tool, while conventional Delphi studies are used for decision-making (Loe, 1995). This method provides a valuable framework for this research as its approach aims to contribute to the generation of perspectives on policy issues (Loe et al., 2016). There is no standardized approach for conducting a Policy Delphi study (Gracht, 2008;

Loe et al., 2016). However, the method comprises a set of general characteristics rather than a specific series of steps:

- a group of knowledgeable experts should be engaged;
- the method runs through iterative rounds in which data is collected, evaluated, and the policy issues under analysis further structured; and
- an organized feedback process is established to feed inter-round results back to experts.

This approach offers a flexible framework for use across industries and policy topics, ranging from public health, security, strategy development, technological forecasting, climate and energy, to name a few (Loe et al., 2016; Makkonen et al., 2016). Within the sustainability and energy transition domains, recent applications of this method have contributed to insight on policy issues related to technology, business model, and social aspects. Examples include: community adaptation to climate change (Nguyen et al., 2017); suitability of indoor environmental quality standards (Alyami et al., 2013); effectiveness of community-promoted environmental policies (Hsueh, 2015); energy service companies business model viability (Pätäri et al., 2016; Patari & Sinkkonen, 2014); deployment of smart grids (Balta-Ozkan et al., 2014; Galo et al., 2014; Xenias et al., 2015); solar generation investment risk assessment (Kayser, 2016); applications and use of bioenergy technologies (Billig & Thrän, 2016; Ribeiro & Silva, 2015); community acceptance of energy technologies (Carrera & Mack, 2010); energy technology deployment forecasts (Celiktas & Kocar, 2010; Czaplicka-Kolarz et al., 2009; Liimatainen et al., 2014; Mayor et al., 2015; Schuckmann et al., 2012; Sherriff, 2014; Tuominen et al., 2014; Varho et al., 2016). This selection of studies is not an exhaustive list of Policy Delphi applications (cf. Loe et al. (2016) for a thorough review of Policy Delphi work). Instead, this selection of studies highlights the ability of this method to contribute valuable insights across policy issues. In addition, it highlights recent contributions using a methodology developed in 1970 (Turoff, 1970), thus reflecting both the maturity of the Policy Delphi method, and its current relevance for the development of foresight-based policy adaptation guidance.

3.2.2. Research design

The research process using the Policy Delphi was structured in two stages. The first stage focused on study design, while the second stage applied the iterative rounds method to obtain experts' feedback on selected DSOs policy issues. For a detailed description cf. Table 3.1 and Table 3.2.

Table 3.1 Research process description

Study stage	Activity	Description
1st stage	**Literature review**	An initial literature review evaluated the adequacy and impact of different areas of consideration previously deemed relevant to policy adaptation options and the future of electricity distribution (Pereira & Silva, 2016). These areas included organizational, technological, and institutional aspects (Dubois & Saplacan, 2010; Kiesling, 2016; Kossahl et al., 2012; Markard, 2011; Persideanu & Rascanu, 2011; Praetorius et al., 2009; Trygg et al., 2007; Tsoukas & Papoulias, 2005).
	Industry insight collection	The definition of the initial scope of topics for the Policy Delphi was supported by industry insights. This process involved four interviews with six representatives from three DSO companies, and one interview with one representative from a NRA, cf. Table 3.2 for details.
	Policy Delphi questionnaire development	Based on the perspectives gathered, the organizational dimension was further structured to focus on business model innovation. The technological dimension was developed to target technological adaptation. The institutional dimension was further specified to consider market design and policy-making. In addition, topics concerned with the role of the DSO and associated transition trajectories were identified as relevant for the study.
	Piloting and validation	A group of academic researchers and DSO representatives revised the initial draft of the questionnaire.
2nd stage	**Expert selection and invitation**	The guiding principles for expert selection included: experience in smart grids development, electricity sector, or energy policy development; and interest in the energy transition and impacts for electricity distribution and DSOs. Based on these criteria, the following communities were identified as relevant sources of experts for the study: the smart grid plus ERA-Net knowledge community (Smart Grids Plus, 2017); the European electricity grid initiative (Grid Plus, 2017); the European Commission's smart grids task force (European Commission, 2017e), national and regional smart grid initiatives in Europe (ETIP Smart Grids, 2016); and the International Conference on Electricity Distribution participants community (CIRED, 2017).
	Iterative Delphi rounds (1st and 2nd round)	The iterative rounds approach in this study was based on two consecutive surveys to experts, distributed through email and using Enuvo GmbH's online platform eSurvey Creator for expert data collection (Enuvo, 2017). Expert recruitment resulted in 207 participants for the 1st Policy Delphi survey round, of which 103 participated in the 2nd Policy Delphi survey round. The 1st survey included the initial 57 policy alternatives, while the second survey included only the statements where the expert aggregated assessment was below 70% in any of the scales used for data analysis (i.e.: a statement on Business Model Innovation – Strategy, operations, and organizational adaptation, for which aggregated expert's rating on the first-round survey is below 70% on any of the data analysis scales, would be included in the second-round survey). The use of a percentage threshold for inter-round statement selection is a commonly used technique in Policy Delphi applications (Loe et al., 2016; Ribeiro & Silva, 2015). Additionally, at the end of the study a customized report was provided to each participating expert, in which the individual assessment was presented as well as the aggregate distribution from the assessments of all the participating experts, cf. Appendix A. The study was conducted between March 2016 and April 2017.

Table 3.2 Industry experts consulted for Policy Delphi study design

Entity	No. of interviews	No. of representatives	Interview date	Region of action
NRA	1	1	Mar. 2016	Southern Europe
DSO 1	2	3	Apr. 2016, Sep. 2016	
DSO 2	1	1	May 2016	Northern Europe
DSO 3	1	2	Jun. 2016	

In this assessment, the Policy Delphi statements are the alternatives under analysis, given their ability to provide guidance for policy-adaptation actions. Policy-adaptation is considered in a broad sense here, encompassing actions from different stakeholders to facilitate the transition of the electricity distribution industry, particularly focused on the changes for DSOs. These stakeholders include: policy-makers, DSOs, industry analysts, regulators, researchers, sectoral associations, to name a few.

The questionnaires used in this study were designed for experts to evaluate alternatives using ordinal scales measuring agreement, difficulty, importance, or priority. The policy alternatives used in this analysis resulted from a literature review, complemented with insights from industry experts, cf. Table 3.1 for detailed information. Furthermore, Table 3.3 presents the structure of the questionnaire, number of statements across topics, measurement scale type, and the scale conversions used for data analysis.

Table 3.3 Questionnaire structure and measurement scales

Topic	No. of policy alternatives		Assessment scale		
			Experts questionnaire		Data analysis
	1st round	2nd round	Measure	Label	Scale conversion
Business Model Innovation					
Adaptation challenges	4	4	Difficulty [a]	1: Very difficult, 7: Very easy	1-3: Difficult, 4: Uncertain, 5-7: Easy
Strategy, operations, and organizational adaptation	5	1	Agreement [b]	1: Strongly disagree, 7: Strongly agree	1-3: Weak policy alternative 4: Uncertain policy alternative 5-7: Strong policy alternative
Activities, and responsibilities	19	6			
Technological Adaptation					
Engagement in R&D activities	3	3	Priority [c]	1: 1st priority, 2: 2nd priority, 3: 3rd priority	No scale conversion
R&D approach	1	0	Agreement [b]	1: Strongly disagree, 7: Strongly agree	1-3: Weak policy alternative 4: Uncertain policy alternative 5-7: Strong policy alternative
Electricity distribution digital capabilities	6	0	Importance [d]	1: Not at all important, 7: Extremely important	
Market Design					
EU level policy action	7	3	Importance [d]	1: Not at all important, 7: Extremely important	1-3: Weak policy alternative 4: Uncertain policy alternative 5-7: Strong policy alternative
Member State level policy action	3	1			
R&D and innovation policy action	4	0			
Electricity distribution industry transition					
Role of the DSOs in the electricity sector	3	1	Agreement [b]	1: Strongly disagree, 7: Strongly agree	1-3: Weak policy alternative 4: Uncertain policy alternative 5-7: Strong policy alternative
Electricity distribution transition trajectories	2	2	Yearly evolution [e]	1: DSOs become active network managers by 2017-2020, 2: […] by 2021-2030, 3: […] by 2031-2040, 4: […] by 2041-2050, 5: DSOs will not become active network managers	No scale conversion
Total Policy Delphi statements	57	21			

[a] Difficulty scale: 1, Very difficult; 2, Difficult; 3, Somewhat difficult; 4, Neither difficult or easy; 5, Somewhat easy; 6, Easy; and 7, Very easy.
[b] Agreement scale: 1, Strongly disagree; 2, Disagree; 3, Somewhat disagree; 4, Neither agree or disagree; 5, Somewhat agree; 6, Agree; and 7, Strongly agree.
[c] Priority scale: 1, 1st priority; 2, 2nd priority; and 3, 3rd priority.
[d] Importance scale: 1, Not at all important; 2, Low importance; 3, Slightly important; 4, Neutral; 5, Moderately important; 6, Very important; and 7, Extremely important.
[e] Yearly evolution scale: 1, DSOs become active network managers between 2017-2020; 2, DSOs become active network managers between 2021-2030; 3, DSOs become active network managers between 2031-2040; 4, DSOs become active network managers between 2041-2050; and 5, DSOs will not become active network managers.

3.3 Results and discussion

This section describes the panel of experts and presents their assessments of the alternatives regarding business model innovation, technological adaptation, market design, and electricity distribution industry transition. The results presented include a combination of quantitative assessment of future alternatives with qualitative insights resulting from expert's comments collected through the 2nd round survey. These results provide a perspective on policy alternatives related with the smart and sustainable electricity distribution transition.

3.3.1. Expert panel characterization

In terms of region of origin, the experts represented 25 countries in the 1st round, and 20 countries in the 2nd round, Table 3.4. This broad regional representation provided confidence that survey responses reflected consideration of the different electricity sector contexts across Europe.

Table 3.4 Region of origin of participating experts

Country	1st round	2nd round
Austria	14	7
Belgium	6	4
Bosnia and Herzegovina	1	1
Bulgaria	1	-
Croatia	5	4
Cyprus	1	-
Czech Republic	3	2
Denmark	2	-
Finland	8	6
France	6	-
Germany	14	3
Greece	4	3
Ireland	3	2
Italy	20	13
Latvia	1	1
Netherlands	13	4
Norway	5	1
Portugal	39	19
Romania	1	1
Slovenia	2	-
Spain	9	5
Sweden	12	5
Switzerland	3	1
Turkey	2	1
United Kingdom	11	6
Not indicated	21	14
Total	**207**	**103**

Table 3.5 Role in the electricity sector of participating experts

Role	1st round	%	2nd round	%
Distribution System Operator	85	41	38	37
Electricity Generation Companies	9	4	3	3
Electricity Retail Companies	3	1	-	-
Electricity sector associations	3	1	-	-
Industry analysts and Consultants	27	13	10	10
Policy Maker	2	1	-	-
Regulator	3	1	1	1
Researchers and Academics	57	28	32	31
Transmission System Operator	6	3	3	3
Other	12	6	16	16
Total	**207**		**103**	

Experts were also categorized according to their role in the electricity sector (cf. Table 3.5). Furthermore, the area of expertise was obtained from the experts participating in the second survey (n = 103) as an additional categorization measure. Participants backgrounds included: business and economics (n = 19); engineering and sciences (n = 79); engineering, business, and economics (n = 1), law (n = 2), and other (n = 2).

The next section shows the results from the Policy Delphi survey rounds. When a statement was included in both rounds, the final assessment from the second round is presented, and the overall variation (⊿). Despite the change in sample size from the first survey (n = 207) to the second survey (n = 103), no substantial differences in the results were identified after considering both the experts' assessments from the total number of participants for the first survey, and when only considering the returning experts. Also, no consistent differences in assessments were found across stakeholder role subgroups, and region of origin subgroups.

The results presented are for all policy alternatives included in the study, highlighting in bold the dominant position of the experts in each case. The results are based on the converted scales as shown in Table 3.3. The mean ($\bar{x}$) and median ($\tilde{x}$) from the original scale are also presented for each statement, providing measures of central tendency for each policy alternative (Loe et al., 2016).

3.3.2. Business model innovation

The business model innovation policy alternatives included in the study were intended to provide a more detailed understanding on the evolution of electricity distribution from an organizational perspective.

3.3.2.1. Adaptation challenges

These statements focused on DSO adaptation difficulties (cf. Table 3.6). The results indicate that most difficulties in DSO adaptation are expected with their integration of new technologies supporting smarter grids, their integration of new business and managerial processes, and the timeliness of their adaption. Experts were less certain about the effect of regulation on DSO adaptation. For this topic, 83.5% of the experts considered that DSOs will face difficulties in adapting their role in a timely manner. This adaptation has often been associated with the transition to smart grids (Clastres, 2011; Lund et al., 2012), and more recently to the electricity distribution industry digital transformation (ETIP SNET, 2016c; Council of the European Union, 2017d). The extent of these adaptation challenges was discussed by one expert as follows:

> "Digital transformation is more than digitalization and calls for doing different things and not just the same things in a different way. This means new skills, even at the board level, and cross sectoral knowledge (e.g. information and energy networks) that calls for a disruptive approach that is out of the DNA of most DSOs, starting by the decision-making process, usually conservative, too centralized and time consuming, not compatible with a fast-changing world." (Distribution System Operator expert, Southern Europe)

Aspects related to DSO structure and new entrants were also discussed by the experts, in this way:

> "Being (natural or not) monopolies (depending on their size), DSOs have a considerable inertia to innovate especially when compared to the fast-moving sector of ICT." (Researchers and Academics expert, Southern Europe)

The integration of new technologies to support the transition to smarter distribution grids was considered a difficult adaptation challenge by 62.1% of the experts. One of the experts connected this difficulty with the lack of incentives to do so:

> "For us this is difficult because there are no incentives today to do that." (Distribution System Operator expert, Northern Europe)

One of the study participants commented on the approach to technological evolution at the DSO level, skewed toward incremental rather than disruptive innovation:

> "DSO tend to adopt incremental rather than disruptive technologies. So, new adopted technologies will tend to be a step behind of limits or even possibilities." (Distribution System Operator expert, Southern Europe)

Additionally, one of the panelists discussed the risk of stranded investments and how these can make technological adaptation more difficult:

> "There is always a risk of making wrong technology choices leading to stranded investments. However, this should be manageable and might not affect the fundamentals of the DSOs business model. The risk of financing possible stranded investments (i.e. infrastructure that turns out not to be needed or that will be outdated

before amortization) is of regulatory (and maybe political) nature and could vary from country to country." (Researchers and Academics expert, Western Europe)

For the integration of new business processes and management practices 62.1% of participating experts considered it to be a difficult adaptation challenge. The complexity of implementing new business processes and how these may impact connected consumers was discussed by the experts:

"DSOs can adapt new processes if they are paid to do so. It is very easy to have extremely complicated processes which have very high costs for the DSO, where the benefits accrue to a small subsection of customers but where the costs are socialized over the majority. This then leads to dissatisfaction amongst the bulk of customers making further work very difficult." (Distribution System Operator expert, Western Europe)

The experts also framed this issue within the potential transition of role by the DSO and how regulation influences this, discussed as follows:

"This is what I find particularly difficult with the changing role of DSOs (from network operators to data manager, market facilitator, etc.) and this is the part most dependent on regulation." (Researchers and Academics expert, Western Europe)

Table 3.6 How do you perceive the difficulty of DSOs adaptation to a changing electricity sector?

Policy alternative	**Difficult (%)**	**Uncertain (%)**	**Easy (%)**	$\bar{x}$	$\tilde{x}$
DSOs will be able to adapt to a changing electricity sector only with adapted regulation. [a]	24.3 *(Δ -10.0)*	**42.7** ***(Δ 14.2)***	33.0 *(Δ -4.2)*	4.1 *(Δ 0.1)*	4.0 *(Δ 0.0)*
DSOs will be able to integrate new technologies to support the transition to smarter distribution grids. [a]	**62.1** ***(Δ 10.4)***	19.4 *(Δ 3.0)*	18.4 *(Δ -13.4)*	3.5 *(Δ -0.3)*	3.0 *(Δ 0.0)*
DSOs will be able to integrate new business processes and management practices. [a]	**62.1** ***(Δ 10.9)***	20.4 *(Δ 1.1)*	17.5 *(Δ -12.0)*	3.4 *(Δ -0.2)*	3.0 *(Δ 0.0)*
DSOs will be able to adapt their role in a timely manner. [a]	**83.5** ***(Δ 17.8)***	12.6 *(Δ -4.8)*	3.9 *(Δ -13.0)*	2.9 *(Δ -0.4)*	3.0 *(Δ 0.0)*

[a] Statement included in the first and second round

These results emphasize the importance of developing a DSO transition framework to ease existing difficulties. Moreover, it is relevant to note that, despite the agreement amongst policy makers on the importance of improving the existing regulatory framework to facilitate DSOs adaptation (Ruester et al., 2014; CEER, 2015; EDSO, 2015), a significant share of experts question the role of regulation in facilitating this transition process.

3.3.2.2. Strategy, operations, and organizational adaptation

Statements included in this topic aimed at shedding light on how DSOs should reconfigure their business strategy, and operations (cf. Table 3.7). Strong policy alternatives include adapting DSO organizational structures to take advantage of the opportunities arising from a smarter grid scenario. Such adaptation can include efforts to improve skills, create or restructure teams, redefine responsibilities and create new internal roles, as well as ensuring that existing departments, strategy, and resource allocation practices are aligned with the challenges and opportunities of the energy transition (Eurelectric, 2016). The Delphi experts also agreed on the need for innovative system services that contribute to the creation of new sources of revenue, and the need to test new business models and strategies that challenge the current industry framework. The importance of exploring new business models is evident from the cases of Uber, Airbnb, Lyft, eBay, Amazon, Tesla, Google, which have transformed traditional industry practices in transportation, accommodation, communication, and commerce, often by overriding market rules and conventional mindsets. More limited DSO adaptation, such as focusing only on grid operation and maintenance, and limiting business strategy to the possibilities created by current regulations, were considered weak alternatives by the Delphi experts. The following panelist remark corroborates this:

> "Current regulation is very conservative and might be limiting new market developments. One of the associated risks is related with separating the costs and benefits of the new market opportunities. Conservative regulations might concentrate all costs for DSO's whereas new start-up companies can reap in the profits by providing innovative services." (Distribution System Operator expert, Western Europe)

Adding to the perspective on the limitations of existing regulation, one expert argued in favor of DSOs internal capabilities and how these can support them in redirecting their business strategy into new fields, as follows:

> "DSOs have good capabilities to perform tasks around flexibility services, energy storage and electric vehicle charging infrastructure. Even though the European Commission does not like to see DSOs actively acting and owning these kinds of units they are best equipped for it." [Distribution System Operator expert, Northern Europe]

In line with this, the panel emphasized the need for DSOs to contribute to a regulatory framework that supports changes in business strategy and is ready for a more flexible distribution system, as observed in the following remark:

> "DSO should seek to influence regulators options by stating their points of view according to the strategy they find more correct, both from the perspective of the company's health, which is of public interest, and from the perspective of society at large and consumers." (Researchers and Academics expert, Southern Europe)

Table 3.7 How should DSOs position themselves regarding business model and organizational innovation?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
DSOs should focus on adapting their organizational structure to be ready for the opportunities resulting from a fully deployed smart grid.	3.9	2.4	**93.7**	6.2	6.0
DSOs should provide innovative system services allowing for new sources of revenue.	9.7	3.9	**86.5**	5.7	6.0
DSOs should test business models and strategies that challenge the current regulation and disrupt the market	22.2	7.7	**70.0**	5.0	6.0
DSOs should focus only on grid operation and maintenance, planning and expansion, and quality of service.	**70.5**	6.3	23.2	3.1	3.0
DSOs should limit their business strategy to the possibilities allowed by existing regulations. [a]	**81.6** ***(Δ 14.4)***	1.0 *(Δ -3.4)*	17.5 *(Δ -11.0)*	2.6 *(Δ -0.5)*	2.0 *(Δ -1.0)*

[a] Statement included in the first and second round

These expert assessments emphasize the need for DSOs to expand their operations beyond core electricity distribution services and explore new possibilities. This could be accomplished through internal changes, such as business strategy reconfiguration, and innovative service experimentation

3.3.2.3. Activities and responsibilities

This topic examined current and potential DSO responsibilities. Unsurprisingly, most experts advocated for DSOs to continue performing core electricity distribution functions of grid management and planning. However, they also considered smart meter deployment, data collection, and the integration of distributed generation technologies into electricity distribution operations as a good fit for DSOs. On the contrary, they did not recommend DSO involvement in Electricity retail, cf. Table 3.8 for detailed results. In this context, smart meter ownership was considered a strong policy alternative by 70.9% of the experts. This result is emphasized by the following comment:

> "Supplier switching is much easier when the DSO owns the smart meter, given its neutral market facilitation role. Also, the DSOs need the smart meters data to optimize the grid." (Distribution System Operators expert, Northern Europe)

The following feedback provides an additional perspective on the consumer as a possible smart meter owner:

> "The owner of the smart meter should be either the DSO or the client. In any case, the client should be the owner of the measurements and the DSO should be allowed to read aggregated values for billing purposes and check detailed values for fraud prevention." (Researchers and Academics expert, Southern Europe)

Resulting from the increased diffusion of smart meters, in combination with more sensors connected to electricity distribution grids, the resulting data could be leveraged toward the development of added value services by other market players (Oosterkamp et al., 2014). Having DSOs as managers of a data marketplace platform was considered a strong policy alternative by 75.7% of the experts'. The experts supported this position through the following:

> "Acting as data hubs DSO are in the best position to assure compliance with the European General Data Protection Regulation in terms of data privacy." (Distribution System Operator expert, Southern Europe)

In line with the previous comment, the following remark further emphasized the role of DSOs in enabling new markets players:

> "This is a role which is more appropriate for DSOs. They might be better off as enablers of other market players which are entering the distribution services market." (Industry analysts and Consultants expert, Eastern Europe)

Energy efficiency and energy savings are an important pillar of the European electricity sector sustainability transition (European Commission, 2015a, 2016a). In this regard, 67% of the experts expressed that DSOs should provide energy efficiency and energy savings advice to end-users. Despite the general position of the panel on the relevance of DSOs as promoters of energy efficiency, the following comments indicate the importance of this type of activity being performed by other market players:

> "A DSO should not be involved in this area. It should simply provide a platform (i.e.: network) on which others will operate a market for such services. There is no reason a DSO will have better skills in this area than others, so why would it find it attractive?" (Distribution System Operator expert, Western Europe)

The growing attractiveness and diffusion of electric vehicles creates the need to deploy electric vehicle charging infrastructure that can support existing electric vehicle owners. The panel considered that DSOs should be electric vehicle infrastructure owners, with 45.6% of support as a strong policy alternative. For this policy issue the experts expressed the following views:

> "DSOs should own the cables and wires to the chargers, but the chargers should be leased to EV charge companies on a franchise/license basis. This allows technological competition at charging point level. This leads also to reduced entry barriers as DSOs make the initial investments." (Distribution System Operator expert, Western Europe)

The following expert view brings to the discussion the possible complementarities between DSOs, electric vehicle loads, and electric vehicle charging infrastructure operators:

> "DSOs may foster the deployment but not the competition toward the best electric vehicles charging infrastructure. Electric vehicles for rent, autonomous driving e-Cabs, etc., (basically any EV-infrastructure you can think of) shall be offered by independent competing companies/enterprises, i.e., customers of DSOs. However, DSOs shall be allowed to use EV batteries and EV charging facilities for grid stabilizing (smart charging), paying an appropriate compensation to the EV infrastructure owner, which shall explicitly include the option to fund the charging hardware (i.e. buffer batteries)." (Anonymous expert, Stakeholder category: n.a.)

Distributed electricity generation units connected to the grid are also increasing, and their adequate integration in the electricity system calls for changes on how infrastructure is planned and operated (ETIP SNET, 2016b). In line with this 73.8% of the experts considered the management of distributed generation units by DSOs, as a strong policy alternative. A perspective on when DSOs should manage distributed generation is expressed in the expert comment below:

> "DSOs should manage distributed generation as much as TSOs manage transmission-level generation. The main driver for distributed generation management should be local markets, but DSOs should guarantee the correct operation of the system, which implies having a certain degree of control on all producers and consumers connected to the corresponding distribution network." (Researchers and Academics expert, Southern Europe)

Separation of electricity distribution and electricity retail activities took place as part of the market restructuring process leading to liberalization (European Union, 1996, 2003, 2009b). As a result, electricity retail is forbidden for unbundled DSOs, which have to operate as neutral market facilitators. Nonetheless, this activity was presented to the experts as a future possibility to understand the panels' perspectives in having distribution and retail combined. 81.6% of the experts considered this a weak policy alternative. The following comment corroborates this:

> "There is no need for DSOs to be involved in this area. Electricity retail is more of a fast-moving consumer good with short timescales, low skills base and small profit margin. DSO is 40-year time scale, higher margin, higher risk and much higher skill base." (Distribution System Operator expert, Western Europe)

Table 3.8 In the future DSOs should be involved in the following activities?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
Grid management (i.e. operation and maintenance).	1.9	1.0	**97.1**	6.5	7.0
Grid planning (i.e. expansion and reinforcement).	1.4	0.5	**98.1**	6.5	7.0
Smart meter deployment.	6.3	5.3	**88.4**	6.1	6.0
Data gathering.	6.3	9.2	**84.5**	5.9	6.0
Integration of distributed generation technologies.	7.7	3.4	**88.9**	5.7	6.0
Smart meter ownership. [a]	10.7 *(Δ -1.9)*	18.4 *(Δ -2.3)*	**70.9** ***(Δ 4.2)***	5.6 *(Δ 0.2)*	6.0 *(Δ 0.0)*
Neutral market facilitation (i.e. avoiding interference with competitive market activities).	9.2	14.0	**76.8**	5.6	6.0
Integration of electricity storage technologies.	8.7	6.8	**84.5**	5.6	6.0
Data storage and management	12.6	12.6	**74.9**	5.5	6.0
Providing flexibility services to end-users (i.e. demand response, flexible consumption, flexible production, flexible storage).	14.0	7.7	**78.3**	5.4	6.0
Managing a data marketplace (i.e. to enable the development of added value services by other market players). [a]	12.6 *(Δ -5.7)*	11.7 *(Δ -5.3)*	**75.7** ***(Δ 11.0)***	5.4 *(Δ 0.4)*	6.0 *(Δ 0.0)*
Electric vehicle infrastructure deployment.	13.5	10.6	**75.8**	5.3	6.0
Indirect grid balancing (i.e. through price signals to other relevant market players, therefore participating in procuring flexibility).	13.0	9.2	**77.8**	5.3	6.0
Direct grid balancing (i.e. connecting and disconnecting consumers from the grid).	17.4	8.2	**74.4**	5.3	6.0
Management of electricity storage technologies.	16.4	7.7	**75.8**	5.2	6.0
Management of distributed generation technologies. [a]	16.5 *(Δ -7.6)*	9.7 *(Δ -0.9)*	**73.8** ***(Δ 8.6)***	5.2 *(Δ 0.3)*	6.0 *(Δ 1.0)*
Provide energy efficiency and energy savings advise to end-users. [a]	18.4 *(Δ 1.1)*	14.6 *(Δ -0.4)*	**67.0** ***(Δ -0.6)***	5.1 *(Δ 0.1)*	6.0 *(Δ 1.0)*
Electric vehicle infrastructure ownership. [a]	35.0 *(Δ 6.0)*	19.4 *(Δ -7.6)*	**45.6** ***(Δ 1.7)***	4.2 *(Δ 0.0)*	4.0 *(Δ 0.0)*
Electricity retail. [a]	**81.6** ***(Δ 21.7)***	10.7 *(Δ -2.4)*	7.8 *(Δ -19.3)*	2.0 *(Δ -1.1)*	1.0 *(Δ -1.0)*

[a] Statement included in the first and second round

The expert perspectives match the current market structure in which DSOs are expected to operate as neutral market facilitators, supporting competitive market players, but without actively participating in the competitive segments of retail and generation (CEER, 2014, 2015; ACER and CEER, 2017b). Nonetheless, the expert assessments also offer insight on the importance of pursuing new activities and increasing smart grid related responsibilities for DSOs. For instance, they recommend that DSOs take responsibility for the integration and management of electricity storage facilities. This differs from the recent proposals, in the Clean

Energy for All policy package (ACER and CEER, 2017b; European Commission, 2017a), that DSOs should only engage in storage ownership, development, management, or operation, when no other parties are interested.

3.3.3. Technological adaptation

Given the technical intensity of electricity distribution operations, it is important to understand technological adaptation needed to combine legacy technologies with smart grid innovations. The experts assessed the appropriateness of different R&D activities and digital capabilities for DSOs.

3.3.3.1. Engagement and approach to R&D activities

The examination of DSO engagement in R&D activities (cf. Table 3.9) aimed at understanding which technology readiness level should be the priority for DSOs in a changing electricity sector (EARTO, 2014; European Commission, 2014d). The results indicate that nearly 40% of the experts prioritized DSO engagement in piloting and demonstrating emerging technologies. Just over a third prioritized DSO exploitation of tested and proven technologies, while nearly a quarter recommended that DSOs engage first in exploratory R&D. The different policy alternatives have similar levels of expert support, however, highlighting the importance of DSOs being engaged at all stages of technology R&D.

Table 3.9 How should DSOs position themselves for technological innovation and research and development (R&D) activities?

Level of technological development	**Policy alternative**	**1st Priority (%)**	**Rank**	$\overline{x}$	$\overline{x}$
Basic technology research Research to prove feasibility	DSOs should conduct exploratory R&D activities for new technologies and innovative applications. [a]	23.3 *(⊿ -3.3)*	3	2.2 *(⊿ 0.0)*	2.0 *(⊿ 0.0)*
Technology development Technology demonstration	DSOs should pilot and demonstrate the potential and impact of emerging technologies. [a]	39.8 *(⊿ 1.2)*	1	1.7 *(⊿ -0.1)*	2.0 *(⊿ 0.0)*
System commissioning System operations	DSOs should exploit proven technologies, deploying external R&D results from universities, ICT firms, and other DSOs. [a]	36.9 *(⊿ 0.2)*	2	2.1 *(⊿ 0.1)*	2.0 *(⊿ 0.0)*

[a] Statement included in the first and second round

The results suggest expert preference for DSOs engaging in R&D activities that are closer to deployment versus early exploratory developments. The former can contribute to faster results, and possibly more rapid delivery of benefits, whilst also bearing fewer risks than exploratory research. Experts also strongly favored a research approach in which DSOs develop R&D in cooperation with external entities (cf. Table 3.10).

Jointly, these expert assessments suggest that DSOs can best manage and minimize technological adaptation risks by developing R&D in collaboration with entities providing complementary capabilities.

Table 3.10 How should DSOs develop R&D activities?

Policy alternative	**Weak policy alternative (%)**	**Uncertain policy alternative (%)**	**Strong policy alternative (%)**	$\bar{x}$	$\tilde{x}$
DSOs should explore technological innovation in partnership with external entities such as universities, ICT firms, and other DSOs.	1.0	1.9	**97.1**	6.4	7.0

These expert assessments of R&D approaches offer additional insight into how the research and innovation roadmap, as described in ETIP SNET, could be implemented (ETIP SNET, 2016b; European Commission, 2016c).

3.3.3.2. Electricity distribution digital capabilities

Electricity distribution operations are becoming increasingly digital (EDSO, 2016; ETIP SNET, 2016b; European Commission, 2016b). The alternatives included on this issue analyzed the importance of different digital capabilities to deal with growing quantities of data (cf. Table 3.11). Experts were almost unanimous in their assessment that DSOs should be capable of data collection from all connected distribution networks and devices, such as distributed generation, smart meters, electric vehicle infrastructure, network monitoring points, substation monitoring. They also agreed that most other digital activities, such as data validation, analysis and interpretation will be important capabilities needed by DSOs. Data analysis and interpretation can directly contribute to increasing the efficiency and quality of service by supporting the definition of flexibility schedules, and forecasting network expansion and reinforcement needs.

Table 3.11 What is the importance of the following digital capabilities for DSOs new roles?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
Collection of data	3.4	3.4	**93.2**	6.1	6.0
Validation and quality certification of data	3.9	5.3	**90.8**	6.0	6.0
Analysis and interpretation of data	5.8	4.3	**89.9**	6.0	6.0
Aggregation of data (e.g. from a diversity of sources to obtain meaningful decision-support information).	4.3	4.3	**91.3**	5.9	6.0
Automation	7.7	7.2	**85.0**	5.8	6.0
Communication of data to other market participants.	8.2	14.5	**77.3**	5.4	6.0

These assessments underline the need for digital capabilities at the DSO level. Only after data is appropriately collected, validated, analyzed, and aggregated, should DSOs use it to increase automation or share data with other market participants. Nevertheless, digital automation is expected to become a critical DSO capability, in which previously gathered data supports the design and implementation of distributed generation, flexibility management algorithms, and automatic storage coordination algorithms.

These results foresee a central role for DSOs in data management and support the Clean Energy for All Europeans policy package, which recommends that DSOs should enable data access in a non-discriminatory way to all eligible parties (European Commission, 2017a).

3.3.4. Market design

In addition to business model innovation, and technological adaptation, market design issues are also paramount in a changing electricity sector due to the policy-driven nature of the electricity distribution industry. Given this, the assessment included also alternatives addressing both EU and Member States level policy actions, as well as R&D and innovation policies.

3.3.4.1. EU-level policy actions

Experts assessed the importance of various EU-level market design policies (cf. Table 3.12). There was strong expert consensus favoring the definition of a common vision for DSO role. Experts also largely agreed on the importance of defining common rules for DSO-TSO data management and exchange standards, which aligns with the proposals presented by the European Commission (European Commission, 2017c). Moreover, experts agreed on the need for the Digital Single Market strategy to provide guidance on the roles of DSOs as these become increasingly interconnected and data-driven. The experts also supported the development of a specific electricity distribution EU-directive and the development of a regulatory body facilitating DSO transition. EU-level actions in line with these policy alternatives are currently being pursued. The proposals for the new electricity directive released with the Clean Energy for All Europeans package establish a framework for DSOs operations in a smarter electricity sector, providing guidance on electricity storage, data handling, electric vehicle charging infrastructure, and system flexibility issues (European Commission, 2017a). Moreover, the European Commission has also proposed the creation of a EU-level DSO Entity to provide support for the adaptation of the electricity distribution industry (Eurelectric, 2017; European Commission, 2017c).

The experts were divided on the value of redefining the 100 000 connected consumers unbundling rule. In line with this, recent policy proposals maintain this threshold (European Commission, 2017a). This alternative was evaluated by 49.5% of the experts as an uncertain policy alternative). One of the experts mentioned the need to remove this threshold and unbundle all DSOs:

> "In my opinion the threshold should be removed, and the unbundling requirements should be applied on all DSOs." (Distribution System Operators expert, Northern Europe)

The following expert comment refers to the quality of applying a quantity-based criterion:

> "Numbers are never a good separation criterion; any number is equally poor." (Anonymous expert, Stakeholder category: n.a.)

The transition toward smart distribution grids encompasses new technologies, new processes, and the need for new regulatory approaches. Considering this the panel was presented with an alternative regarding if a new regulatory body should be established focusing on the transition to a smarter grid framework, with a strategy and incentives for DSOs to innovate. This was referred to as a strong policy alternative by 62.1% of the experts. The following comment discusses the importance of innovation supportive regulation, and the possibilities for expanding existing regulators roles, rather than establishing a new stakeholder:

> "Regulation establishing a strategy for DSOs is important and may need incentives for fulfilling its objectives. Perhaps it is not necessary to establish a new regulatory body, and this can be done by existing entities." (Researchers and Academics experts, Southern Europe)

Table 3.12 How important are the following EU level policy-oriented actions in the ongoing DSOs transition?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
DSOs should follow a common-vision of their most effective role in the electricity value chain, to support and strengthen the development of the EU internal electricity market.	7.2	9.2	**83.6**	5.4	6.0
The DSOs and Transmission System Operators (TSOs) data management and exchange standards should be defined at the EU-level.	11.6	18.4	**70.0**	5.2	6.0
The EU strategy toward a Digital Single Market should provide guidance on the role of DSOs as these become more interconnected and data driven.	12.1	15.5	**72.5**	5.2	6.0
DSOs should have a specific EU-level directive, focusing on the operation of the distribution network in a smarter grid framework.	12.1	13.5	**74.4**	5.1	5.0
The DSOs and TSOs congestion management and balancing responsibilities should be defined at the EU-level. [a]	10.7 *(Δ -3.3)*	19.4 *(Δ -0.4)*	**69.9** ***(Δ 3.7)***	5.0 *(Δ -0.4)*	5.0 *(Δ -1.0)*
A new regulatory body should be established focusing on the transition to a smarter grid framework, with a strategy and incentives for DSOs to innovate. [a]	28.2 *(Δ 0.6)*	9.7 *(Δ -2.4)*	**62.1** ***(Δ 1.7)***	4.5 *(Δ -1.1)*	5.0 *(Δ -1.0)*
The unbundling threshold currently set to DSOs with 100 000 connected consumers should be re-considered as it can challenge the adaptation and innovation potential of DSOs. [a]	12.6 *(Δ -3.8)*	**49.5** ***(Δ 17.6)***	37.9 *(Δ -13.8)*	4.3 *(Δ 0.3)*	4.0 *(Δ 0.0)*

[a] Statement included in the first and second round

3.3.4.2. Member state level policy actions

Experts were asked to assess policy alternatives at the Member State level (cf. Table 3.13). Experts largely agreed on the importance of having Member States encourage DSO experimentation with new technologies and services. Experts also favored developing national strategies for smart grid deployment in the form of National Smart Grid Action Plans. They disagreed on whether the role of DSOs should be solely defined at the Member State level; over 40% of the experts indicated this was important while nearly 40% indicated the opposite. Experts pointed to the local and national role of DSOs in supporting this policy alternative.

Building on this perspective, one panelist expanded on this policy alternative indicating the need to establish DSOs roles at the EU level:

> "This is important; however, it should not be limited at the Member State level only. Harmonization of the DSO's role at EU level should exist and it will prove necessary in the (near) future, particularly with the advent of even more increasing distributed energy resources, electric vehicles, and active consumers and prosumers." (Researchers and Academics expert, Western Europe)

Table 3.13 How important are the following Member State level policy-oriented actions in the ongoing DSOs transition?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
Member States should encourage DSOs to experiment with new services, technologies, business models and market designs, even if it requires overriding current regulations.	11.6	11.1	**77.3**	6.0	6.0
Member States should develop a National Smart Grid Action Plan to provide a deployment roadmap and the roles of actors in this context.	7.2	13.0	**79.7**	4.6	5.0
The role of the DSOs should only be specified at the Member State level, allowing each country to establish its role to fit the specific context. [a]	36.9 *(Δ -5.1)*	20.4 *(Δ 4.9)*	**42.7** ***(Δ 0.2)***	4.0 *(Δ -0.5)*	4.0 *(Δ -1.0)*

[a] Statement included in the first and second round

These results can inform Member State efforts supporting the electricity distribution industry transition and complement the ongoing EU-level restructuring efforts.

3.3.4.3. R&D and innovation policy action

Finally, R&D and innovation policies were examined that affect market design (cf. Table 3.14). The redesign of the electricity market calls for a coordinated R&D and innovation policy framework facilitating the introduction of new technologies, processes, and practices underpinning innovative roles and services. The experts strongly supported the existence of specific support programs for technological innovation at the DSO level. They also favored developing a flexibility market governance model and programs to support DSO business model innovation. Such programs could facilitate the establishment of new departments for smart grid operations, the integration of new processes for asset management, or new skills development. The experts overwhelmingly agreed on the importance of having a regulatory framework supportive of innovation and investment in smart grids.

Table 3.14 How important are the following R&D and innovation policy-oriented actions in the ongoing DSOs transition?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
There should be specific support programs for technological innovation at the DSOs level.	7.7	9.7	**82.6**	5.4	6.0
A flexibility market governance model should be implemented to ensure the adequate intervention of different actors.	6.3	15.0	**78.7**	5.4	6.0
There should be specific support programs for business model innovation at the DSOs level.	11.1	9.2	**79.7**	5.2	5.0
DSOs regulation should be designed to facilitate innovation and investments in smart grid technologies.	3.4	2.4	**94.2**	5.0	5.0

These assessments align with recent policy efforts to support DSO innovations. Such efforts include the recent Smart Networks for Energy Innovation R&D and innovation roadmap with a specific set of objectives for electricity distribution, estimating the need for 1 475 Million Euros to develop the proposed activities (ETIP SNET, 2016b). European regulators and DSOs are also exploring ways to encourage innovation at the distribution level by adapting regulatory frameworks (Eurelectric, 2016; CEER, 2017b).

3.3.5. Electricity distribution industry transition

The extent to which the electricity distribution industry shifts toward new roles and activities can impact the overall diffusion of smart grid related technologies, and the pace at which potential benefits are transferred to connected grid users. Experts were presented with alternatives related to future roles for DSOs as well as the timeframe for this transition.

3.3.5.1. Role of the DSOs in the electricity sector

DSO roles in the electricity sector were presented within three archetypes: passive network managers, active network managers, or reactive network managers (Oosterkamp et al., 2014; Martinot et al., 2015). Experts suggest that DSOs will become active network managers (cf. Table 3.15) or, alternatively, become reactive network managers. Conversely, most experts did not foresee DSOs acting as passive network managers in the future, a pattern consistent with more traditional electricity distribution designs.

Table 3.15 What's the future of DSOs in the electricity sector?

Policy alternative	Weak policy alternative (%)	Uncertain policy alternative (%)	Strong policy alternative (%)	$\bar{x}$	$\tilde{x}$
DSOs as active network managers DSOs will incorporate the full spectrum of smart grid capabilities, managing system flexibility as part of its operations, operating as active network managers.	9.2	6.3	**84.5**	5.7	6.0
DSOs as reactive network managers DSOs will incorporate some additional coordination capabilities, handling congestions and other grid related issues at the operation stage, by restricting load and generation, operating as reactive network managers.	18.4	9.2	**72.5**	5.1	6.0
DSOs as passive network managers DSOs will continue with their traditional activities, solving most of the grid related issues at the planning stage, operating as passive network managers. [a]	**77.7** ***(Δ 21.6)***	2.9 *(Δ -3.9)*	19.4 *(Δ -17.8)*	2.7 *(Δ -0.8)*	2.0 *(Δ -1.0)*

[a] Statement included in the first and second round

These expert assessments reinforce current policy actions to support the establishment of smarter and more sustainable electricity networks, which will require new capabilities and more active system management (ACER and CEER, 2017a).

3.3.5.2. Transition trajectories

The ongoing advances in policy and technology toward a smarter and more sustainable electricity sector enable DSOs to assume more responsibility in facilitating system flexibility, consistent with more active network management. Expert consensus suggests that most DSOs will be operating as active network managers by 2021 – 2031 (cf. Table 3.16).

Table 3.16 When will DSOs fully evolve toward active network managers, procuring flexibility services?

Policy alternative	DSOs become active network managers…				DSOs will not become active network managers (%)	$\bar{x}$	$\tilde{x}$
	between 2017-2020 (%)	between 2021-2030 (%)	between 2031-2040 (%)	between 2041-2050 (%)			
Small DSOs (Less than 100 000 connected consumers) [a]	3.9 *(Δ -6.3)*	**76.7** ***(Δ 24.0)***	16.5 *(Δ -6.2)*	0.0 *(Δ -2.9)*	2.9 *(Δ -8.7)*	2.2 *(Δ -0.3)*	2.0 *(Δ 0.0)*
Large DSOs (Unbundled, with 100 000 or more connected consumers) [a]	10.7 *(Δ -3.8)*	**76.7** ***(Δ 14.9)***	10.7 *(Δ -6.2)*	1.9 *(Δ -1.0)*	0.0 *(Δ -3.9)*	2.0 *(Δ -0.2)*	2.0 *(Δ 0.0)*

[a] Statement included in the first and second round

Because the electricity distribution industry in the EU consists of a significant number of DSOs of varying sizes (Eurelectric, 2013), the possible impact of DSO size on adaptation patterns was also considered when analyzing the Policy Delphi outcomes. The results obtained indicate that size is not perceived as differentiating factor, as both large and small DSOs are expected to become more active network managers within the same time period. This finding is further developed through the qualitative insights obtained across topics regarding the extent to which DSO size influences their ability to adapt and transition to new roles. Table 3.17 provides a synthesis of the panel perspectives from which adaptation challenges are observed across DSOs scales.

Table 3.17 Adaptation and DSO scale

Adaptation	DSO Scale			
	Small DSO (under 100 000 connected consumers)		Large DSO (above 100 000 consumers)	
	Weaker adaptation challenges	Stronger adaptation challenges	Weaker adaptation challenges	Stronger adaptation challenges
General adaptation		"Adaptation will be difficult for the small electricity distributors." (Transmission System Operator expert, Southern Europe)		"DSOs are big and slow rather that small and fast market participants, and as such they cannot adapt quickly, if they can at all. And if they should at all. Newcomers from the IT sector will enter the distribution services market much faster and much more interested in providing new and additional services than DSOs." (Distribution System Operator expert, Eastern Europe)
Technological adaptation	"It may be easier for smaller DSOs operating on newly constructed networks." (Researchers and Academics expert, Southern Europe)		"There are no real problems for larger, often technically outstanding DSOs, but most DSOs are not like that." (Distribution System Operators expert, Southern Europe)	"It would be much complex for larger DSOs. It is also a matter of voltage level: the transition to smarter distribution grids is easier in Medium Voltage networks but is quite challenging for Low Voltage networks." (Researchers and Academics expert, Southern Europe)
New business processes	"This is less technology-dependent, smaller DSOs can be more than capable of adaptation, possibly even better than large DSOs." (Distribution System Operator expert, Southern Europe)			
Transition to active network managers	"Some small are quite innovative and they can make money given current regulation." (Anonymous expert, Stakeholder category: n.a.) "Small are more agile and can adopt, but evidently there will be laggards among them." (Anonymous expert, Stakeholder category: n.a.)	"Small DSOs need to be better considered by the regulation from now on and will be ready in a few years to become active network managers." (Researchers and Academics, Southern Europe)		

3.4 Policy-adaptation guidelines

From the results obtained a set of policy-adaptation guidelines were structured, aimed at supporting the electricity distribution industry transition. These result from the consideration of the study findings, in combination with ongoing policy debates, as discussed in the previous section

Regarding business model innovation:

- The European Commission and European energy regulators should consider the strong support for policy alternatives associated with evolution and exploration of new possibilities in electricity distribution business models, and the provision of innovative services. While the ongoing transition to a smarter and more sustainable electricity sector strives to build on a liberalized market structure, the analysis of future roles, activities, and responsibilities, should consider disruptive approaches that include all possible future scenarios. This "open-mind" approach to electricity sector restructuring could contribute to the identification of alternatives that might go unnoticed in focusing only on options adjacent to the present market structure.
- Policy-makers and DSOs alike should reconsider the allocation of responsibilities, considering expert support for integration, ownership, and management of electricity storage by DSOs, which differs from the recent proposals in the Clean Energy for All Europeans package.

Regarding technological adaptation:

- The European Commission and the European Technology and Innovation Platform on Smart Networks for Energy Transition (ETIP SNET) should consider the assessments on R&D engagement and reflect on whether DSOs should be encouraged to achieve specific technology readiness levels. Such decisions might affect the Integrated Strategic Energy Technology Plan, as well as the ETIP SNET Research and Innovation roadmap for electricity distribution, and the more recent implementation plan being discussed for the period between 2017-2020 (ETIP SNET, 2017a).
- DSOs should consider the importance of data-related capabilities underpinning industry digitalization and assess whether they meet the demands of a data intensive smart grid framework. While DSOs have been largely responsible for data management in the past, significant growth in data volumes and data sources may require new data governance models, new operational capabilities, and new market participants in the industry.

Regarding market design:

- The European Commission, European regulators and National Regulatory Authorities should consider assessments pointing to the relevance of R&D and innovation support policies and define how these can be fostered at the levels of both the EU and individual Member States. In addition, they should focus on how regulatory frameworks, innovation incentives and market design can be combined into an effective policy package.
- The European Commission should consider how it could implement a flexibility market governance model for DSOs.
- Member States governments, and National Regulatory Authorities should consider developing National Smart Grid Actions Plans (i.e.: comparable to the previously mandated National Energy Efficiency Actions Plans, and Renewable Energy Action Plans) to guide the development of new roles, markets, and the delivery of smart grid related societal benefits.

3.5 Conclusions

The adaptation of the electricity distribution industry to a smarter and more sustainable electricity sector requires organizational, technological, and institutional changes, which will influence the role and operations of DSOs. The assessment presented in this chapter, obtained through a foresight study, focused on these aspects to inform the ongoing policy-adaptation process underway in the EU.

This contributed to the identification of challenges for both technological and business model adaptation by DSOs. These challenges are intensified by uncertainty about the role of regulation in facilitating change. However, the experts confirm the importance of expanding DSO strategy, from a focus on core electricity distribution activities, toward the introduction of innovative system services. Such a shift in strategy must be supported by disruptive business models and underpinned by changes in current organizational structures, skills, capabilities, and internal processes.

The results obtained also validate the importance of DSO engagement in all stages of R&D, with a slight preference for piloting and demonstrating proven technologies, and the value of collaborative R&D approaches was also highlighted. In addition, the expert assessments emphasize the value of DSO data management capabilities as the distribution industry becomes more digital. Specifically, experts expect benefits from DSOs developing capabilities in data collection, validation, analysis, aggregation, and dissemination to other market participants.

Additionally, the importance of a EU vision for DSOs is confirmed, as well as common rules for TSO-DSO interaction, in addition to the need for a specific EU-level policy and support body. These EU-level elements are complemented by the relevance of policy actions at the Member State level that support planning (i.e., through the development of National Smart Grid Action Plans) and experimentation of new approaches (i.e., services, technologies, business models, and market designs). Furthermore, underpinning both the EU and Member States policy options, the R&D and innovation policy alternatives highlight the importance of support for technological and business model innovation, as well as the need of a market governance model for flexibility.

This chapter presented the results of a foresight assessment on the future of the electricity distribution industry in the EU, and consequently on the role of DSOs. The size and demographics of the Policy Delphi expert panel are a key strength of this study. The 1st round included 207 experts, while 103 returned in the 2nd round. Additionally, these experts represented a diversity of regions, educational backgrounds, and sector roles, contributing diverse perspectives on DSO-related policy adaptation. Future work might focus on adapting this EU-level foresight study for the national level. While the recent market redesign proposals evolve into final policies at the EU level, further information will be needed to inform policy making at the level of Member States.

Chapter 4

Assessment of adaptation challenges and opportunities: a case study approach

4.1 Background

The transition towards a low-carbon energy sector is currently a priority in most countries, recently reinforced through the Paris agreement signed in 2015 at the 21st Conference of the Parties (COP 21). Many European countries have set targets for the share of renewable energy: Germany, for example, aims to reach a share of 35% renewable energy by 2020, while Denmark and Sweden have set 50% as a target (Anaya & Pollitt, 2015). Commonly envisioned transition paths include the integration of the heating and mobility sector into the electricity sector on the consumption side (sector coupling). The generation of electricity is expected to gradually shift from centralized thermal power plants to distributed energy resources (DER), which either feature high energy efficiency levels, due to combined heat and power generation, or are based on renewable energies, and thus carbon-free during operation, such as wind turbines and solar photovoltaic modules (Palensky & Dietrich, 2011; Castro & Dantas, 2017; Pereira & Silva, 2017).

Smart grids will play a key role in integrating these distributed energy resources and their associated flexibilities, increase energy and economic efficiency, and empower customers (European Commission, 2012a), which is why the European Union (EU) prompted its Member States to ensure the rollout of intelligent metering systems (European Union, 2009b). These developments can be expected to strongly impact electricity distribution system operators (DSOs), their grid operations, and the role of network infrastructure in the future (Lavrijssen et al., 2016; Pereira et al., 2018a).

While there has been some general discussion on challenges and opportunities for DSOs in a smart grid future (Droste-Franke et al., 2012; BMWi, 2014; Siano, 2014; Lavrijssen et al., 2016), few insights on recent developments and on how DSOs face this transition can be found in the literature (Pereira et al., 2018b).

This chapter presents empirical insights on the challenges and opportunities that the sociotechnical transition towards smart grids and distributed energy resources represent for DSOs, and for the transformation of the electricity distribution industry in the European Union. The findings presented result from a series of nine multi-stakeholder workshops, conducted in 2016 and 2017, engaging experts in the field, in Germany and Portugal, as two representative EU member countries. Participating stakeholders include experts from research, academia, and industry exposed to both the national and European context on the energy transition.

In the EU, security of energy supply, sustainability, and competitiveness were defined as the main goals for the energy market (European Commission, 2010, 2015a). The introduction of competition was identified as a key element for achieving these and was gradually implemented through the EC energy packages (1996, 2003, and 2009) that pushed for the liberalization of the electricity market and the unbundling of the vertically integrated electric utilities (European Commission, 2016b; Ringel & Knodt, 2018). A second important aspect of European legislation is the guaranteed grid access for electricity from renewable assets (European Union, 2009a). For grid operators this implies that they must adjust and expand their grid according to the ongoing diffusion of renewable energy generation, potentially causing significant costs. Since grid operators function as natural monopolies, countries have had to find ways in their national legislation to incentivize grid operators' minimization of expenditures for grid operation and expansion. In Germany, with around 880 DSOs, an incentive regulation method was enacted in 2007, and applied since 2009, which simulates competition between grid operators through the comparison of key performance indicators, thus promoting efficiency (Deutscher Bundestag, 2007; BNetzA, 2014). Conversely, Portugal, with one dominant DSO, while being focused on measures to increase operational efficiency as well, also gives attention to find new ways to incentivize innovation activities (Eurelectric, 2016).

Smart grids can contribute to reduce the need for grid expansion and consequently to lower or postpone costs (Pudjianto et al., 2007; Siano, 2014; Lavrijssen et al., 2016). An essential element for reaping this benefit are smart meters since they allow for an active management of the devices behind the meter (cf. McHenry (2013) for further discussion). Considering this, the EU requested cost-benefit analyses of smart meter rollouts in their Member States in 2009 and compared the insights gained in 2014. While 16 states decided to go for a comprehensive rollout until 2020, 7 states, including Germany and Portugal, remained skeptical (BMWi, 2013; European Commission, 2014c). While German policy-makers finally agreed to a moderate rollout until 2032 in the "Act on the Digitization of the Energy Transition" endorsed in 2016, no national legislation for a rollout exists in Portugal until today.

From an operational perspective, in the past, DSOs mostly received electricity from the upstream transmission system, which was then delivered to the local customers. With the diffusion of small-scale generation assets on the distribution grid level more electricity has now to be fed back to the higher voltage levels. This excess of local production can lead to limitations in the thermal capacity of the local grid infrastructure or violations of the permitted voltage band (Pepermans et al., 2005; Veldman et al., 2013). These limitations and violations can be mitigated in different ways, including a reinforcement of the local power lines, adjustable local power transformers, provision of reactive power, electricity storage devices as local buffers, re-dispatching of distributed generation assets and others, all having their specific individual pros and cons (Lopes et al., 2007). Figure 4.1 shows the recent evolution of the share of wind and solar in the total electricity generation, from 2004 to 2016, of which up to 90% is estimated to be connected to DSO networks, directly impacting grid operations (European Commission, 2017b). A similar topic is the one of grid stability and ancillary services where DSOs at present rely on conventional, centralized power plants. With those fading, renewable energy assets have to become better integrated, as the DSOs have to manage their grids in a much more active and “smarter” manner than in the past (Lopes et al., 2007; Ipakchi & Albuyeh, 2009; Reddy et al., 2014; Anaya & Pollitt, 2015; Martinot, 2016).

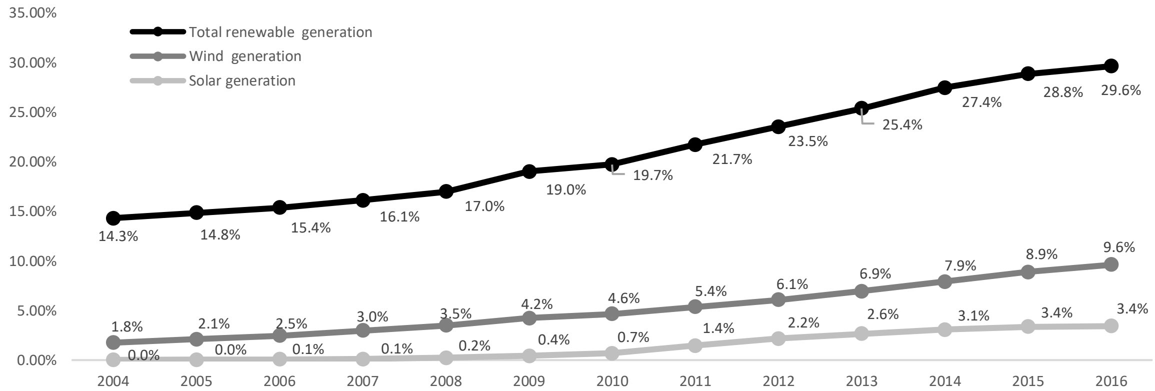

Figure 4.1 Share of renewables on total electricity generation for the EU 28, 2004 – 2016
Source: Elaboration based on Eurostat (2018)

One popular form often mentioned is the grid-friendly operation of local flexible assets such as electric vehicles in the form of demand side management, as investigated by Dallinger et al. (2013) for California and Germany. Table 4.1 shows the evolution of electric vehicles and charging infrastructure in the EU 28, from 2010 to 2017.

Table 4.1 Electric vehicles and charging stations evolution for the EU 28, 2010 – 2017

	2010	2011	2012	2013	2014	2015	2016	2017
Electric vehicles on the road								
Battery electric vehicles	700	9 787	23 919	47 702	85 413	143 811	207 239	328 351
Plug-in hybrid electric vehicles	n.a.	336	9 350	35 228	68 627	158 550	252 735	349 084
Total electric vehicles on the road	**700**	**10 123**	**33 269**	**82 930**	**15 4040**	**302 361**	**459 974**	**677 435**
Available charging stations								
Normal charging	n.a.	3 882	13 054	22 528	32 099	52 960	82 958	101 947
High speed charging	n.a.	13	296	1 013	2 349	6 262	9 775	14 824
Total charging stations available	**n.a.**	**3 895**	**13 350**	**23 541**	**34 448**	**59 222**	**92 733**	**116 771**

n.a.: no information available.
Source: Elaboration based on EEA (2016) and EAFO (2018)

This might turn out to be important since increasing production and consumption peaks could potentially impose massive costs for grid expansions unless a way is found to operate these assets in a grid-friendly manner (Palensky & Dietrich, 2011; Wood & Funk, 2017). However, this path to smart grids requires smart meters as a key element, as mentioned above. The rollout of these smart meters goes along with new challenges for DSOs, who often find themselves in the role of meter operators, in terms of safe digital communication, data property and privacy issues, and new technological specifications, e.g., in terms of installation and calibration (Depuru et al., 2011; Yan et al., 2013).

The assessment conducted encompasses technology, business model, and market design aspects, for existing contributions in the literature often focus on the specificities of a single dimension. By doing so, this study aims to provide a complementary perspective to the following areas of action focused on the electricity distribution industry adaptation dynamics. Firstly, the growing discussion on the regulatory models to be applied on DSOs in the future (CEER, 2014, 2015; ACER and CEER, 2017b), as well as the ongoing discussion on the most adequate electricity market design for the EU as part of the Clean Energy for All Europeans policy proposals (European Commission, 2016b; Council of the European Union, 2017a, 2017b, 2017c). Secondly, the efforts in understanding the role of smart grid and distributed generation technologies in a changing electricity system and the opportunities and benefits these represent (Giordano & Fulli, 2011; Giordano et al., 2011, 2013; Krishnamurti et al., 2012; Hall & Foxon, 2014; Ruiz-Romero et al., 2014; Gangale et al., 2017). Lastly, the importance of identifying the most adequate business model innovation approach and capabilities needed to realize the added value possible from new technologies and enabling policies (Nisar et al., 2013; Helms, 2016; Reuver et al., 2016; Shomali & Pinkse, 2016).

This chapter is structured as follows: Section 4.2 describes the research design implemented and characterizes Germany and Portugal as representative case studies. Section 4.3 presents and discusses the findings. A summary of the main challenges and opportunities identified is presented in Section 4.4, followed by a conclusion in Section 4.5.

4.2 Methodology

This section focuses on the methodology implemented for this assessment. Section 4.2.1 describes the use of a case study approach to study the transition in DSOs. Section 4.2.2 presents the steps taken for the implementation of this approach and detailed characteristics of Portugal, Germany, and selected stakeholders.

4.2.1. Case study methodology

The analysis of the adaptation dynamics of electricity distribution towards smart grids in the EU is conducted following a case study methodology, which supports the development of empirical insights through interaction with electricity distribution stakeholders by collecting data related to their real-world contextual setting (Dul & Hak, 2008; Krivokapic-Skoko & O'neill, 2011). This approach facilitates insight collection from stakeholders and contributes to the identification of existing and emerging challenges and opportunities. Moreover, it provides a flexible method through which multiple perspectives can be obtained (Yin, 2011). A case study research design supports an empirical approach aimed at gaining a better understanding of the sociotechnical transition of the electricity distribution industry. On the scope of transition studies', a case study approach contributes to understand actor's perspectives and perceptions as shifts and adaptation occur, often considering their technological, organizational, and cultural aspects. Notwithstanding the context-rich insights attainable through this approach, it faces also the possible challenges of a bounded perception of the stakeholders engaged, limited by their immediate situation. However, this limitation is counterbalanced by the value of a detailed understanding of how transitions impact actors (Schot & Geels, 2008), which can contribute to adjustments to policies and incentives, or the identification of new priorities for DSO adaptation.

4.2.2. Implementation and cases characterization

The research design was implemented through nine multi-stakeholder workshops conducted between May 2016 and October 2017. Multi-stakeholder workshops represent an action-based participatory element in this research (Kindon et al., 2007), due to their ability to generate discussion and facilitate insight collection across heterogeneous participants (Schut et al., 2015; Mahroum et al., 2016). A questionnaire with open questions was designed to facilitate discussion during the workshops. Table 4.2 presents the covered dimensions, topics, and open questions of the analysis (Sreejesh et al., 2014). The questions selected for use during the workshops reflect the focus of the analysis to encompass business model, legislative, and technology aspects related to the adaptation of the electricity distribution industry. Figure 4.4 details the research design process.

Table 4.2 Open questions for workshops

Analysis dimension	Topic	Questions
Business model and organizational issues	Strategy and operations	What is your perspective in terms of the activities presented recently as grey areas to be performed by DSOs? i.e.: electric mobility infrastructure, smart metering equipment installation and maintenance, energy efficiency services, data management, and integration of distributed energy resources. What are the main drivers for operational efficiency improvements? What is the value of flexibility for DSOs? Do you outsource any business activities? Which ones? How engaged are you in the energy transition and DSO role adaptation? Is the operation of small isolated areas a challenge for DSOs?
	Organizational change	What are the main drivers for engaging in research and development projects? Have any new business units or departments been created because of the changes in the power sector?
Technological adaptation	Technology and innovation	What are your means to increase the service availability and quality of service levels? How does the DSO handle the connection of new distributed energy resources to the distribution grid? What forecasting techniques are applied for renewable energy plants connected to the distribution grid?
Market design and regulation	Regulatory framework and policy aspects	What is the impact of the regulatory framework in the business operations? Does the 100 000 customers rule for unbundling result in an advantage or a disadvantage for DSOs?
	Market design	What is your perspective on the appearance of new market players in the electricity sector in the future? What is your perspective on electricity distribution market structure?

The data collected through the workshops was coded, resulting in several topics within the broader categories considered in the questionnaire with open questions: (1) business model and organizational issues; (2) operations, technology, and asset management; and (3) market design and regulation. Participating stakeholders represent two groups: stakeholders active in the electricity supply chain and stakeholders outside the electricity supply chain. The participants in the workshops are located in Germany (DE) and Portugal (PT) as two representative cases of the diverse dynamics of the electricity distribution in the EU (Eurelectric, 2013, 2016). Figure 4.2 and Figure 4.3 contrast trends in the EU 28 with the cases of Germany and Portugal as indicative evidence of the representativeness of these case studies in the general EU context by looking at the evolution of renewables shares and the electric vehicle market, as proxies for the distributed energy resources diffusion.

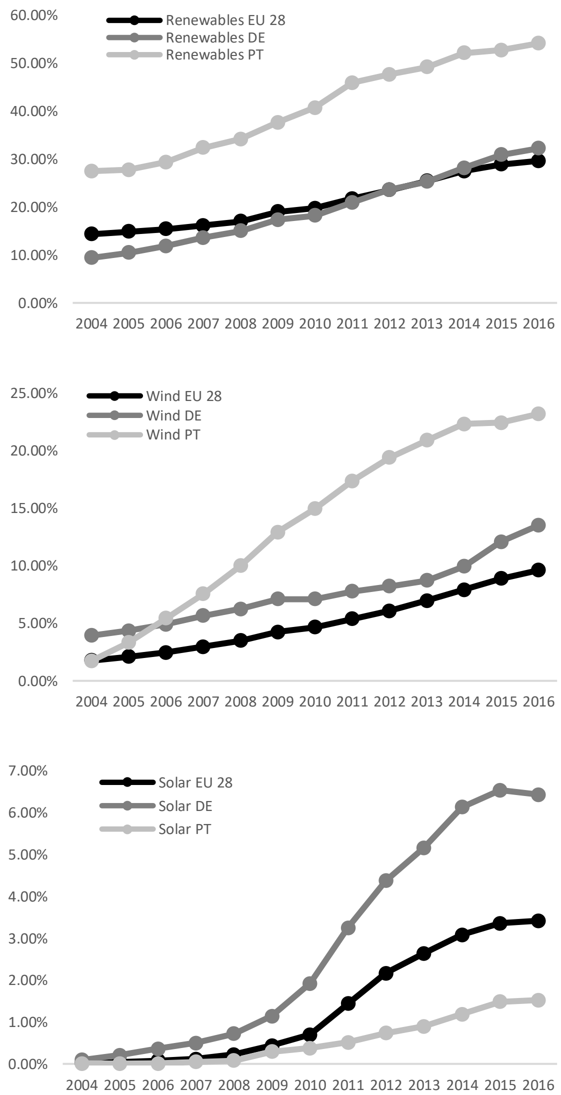

Figure 4.2 Share of total renewables, wind, and solar in total electricity generation for PT, DE, and EU 28
Source: Elaboration based on Eurostat (2018)

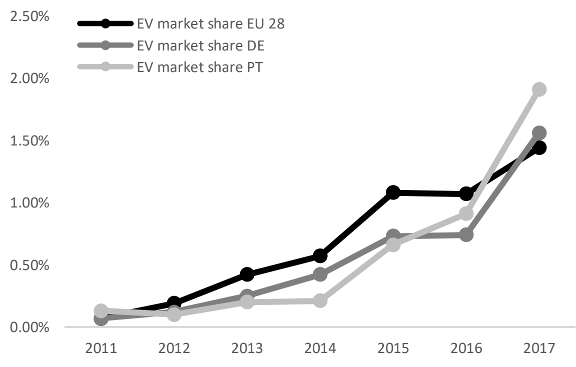

Figure 4.3 Electric vehicles' market share for PT, DE, and EU 28
Source: Elaboration based on EAFO (2018)

Table 4.3 provides additional details on the German and Portuguese electricity distribution industry characteristics through a set of indicators of industry structure, evolution, and infrastructure characteristics.

Table 4.3 Electricity distribution characterization for Germany and Portugal

Electricity distribution characterization		Germany	Portugal	EU 28
Distribution industry structure				
Distribution sector concentration		Low	Medium	
Regulatory mechanism		Incentive	Hybrid	
Innovation support mechanism		None	Enhanced rate of return	
DSO Ownership		Largely public	Largely private	
DSOs with > 100 000 consumers		75	3	190 [a]
Connected consumers		49 294 962	6 137 611	263 370 337 [a]
Distributed power (TWh/Year)		511	52	2 581 [a]
Industry evolution				
No. of DSOs [c]	**in 1997**	1 000	13	2 553 [a]
	in 2003	900	13	1 762 [a]
	in 2010	880	13	2 335 [a]
Infrastructure characteristics				
Distribution line voltage (% of total distribution infrastructure)	**< 1 KV**	65%	62%	60% [b]
	1 – 100 KV	30%	38%	37% [b]
	> 100 KV	5%	-	3% [b]
Grid length and components	**Line density (km lines/km ^{2})**	5	2.4	2.7 [b]
	Overall line length (km)	1 772 696	222 627	9 952 844 [a]
	No. of MV and LV transformers	461 900	64 458	3 918 178 [a]
Smart grid development	**Smart grid investments (€/Million €/GDP $_{2015}$)**	267.08	495.81	379.32 [b]
	Smart grid investments (€/Capita)	9.86	8.61	13.01 [b]
	Smart meter rollout	The German government expects a rollout of 30% of smart meters (15.8 Million meters) by 3032	No nationwide rollout mandated. Several pilot projects are under way.	

[a] EU 28 total; [b] EU 28 average, [c] Based on estimates from Eurelectric (2013).
Source: Elaboration based on Eurelectric (2013); Cambini et al. (2016); Gangale et al. (2017); My Smart Energy (2018a, 2018b)

The findings are anonymized. However, background information on the participating stakeholders is provided. In terms of stakeholders active along the electricity supply chain, 4 distribution system operators participated in the workshops, operating under different structural and regulatory frameworks. The participating delegates from DSOs represent a heterogeneous group, which contributes to obtaining complementary perspectives on adaptation issues towards smarter grids. Table 4.4 provides information regarding their scale in terms of connected consumers, the degree of separation of electricity distribution activities from other activities through unbundling, as well as the regulatory framework and market structure and operational characteristics [4] [5] [6]. The stakeholders outside the electricity supply chain include the research group conducting the study, a research center focused on smart grids, and the innovation unit of an electric utility group holding (cf. Table 4.4).

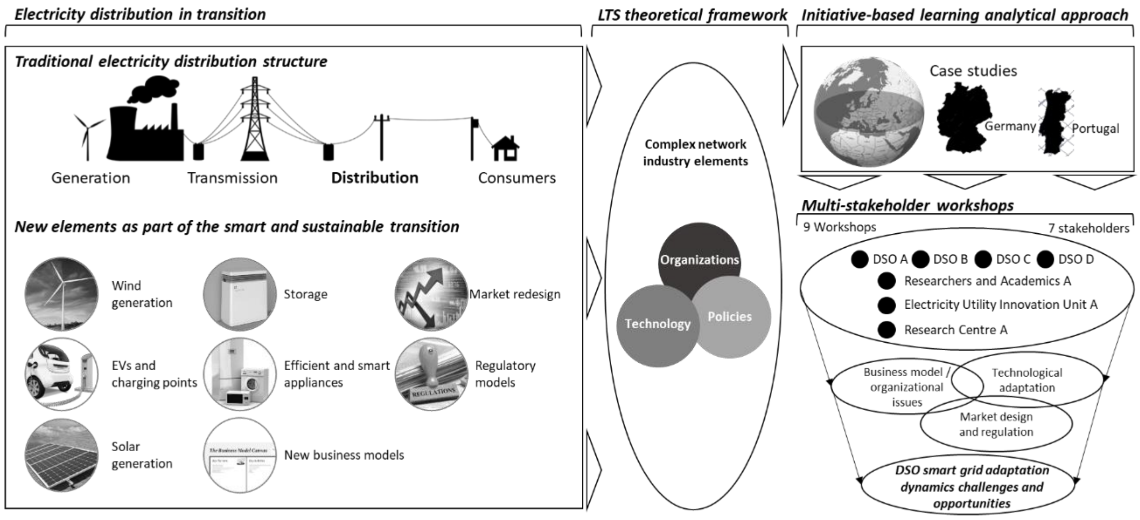

Figure 4.4 Research design

[4] Regarding the regulatory framework characteristics our participants are subject to either incentive-based or hybrid approaches. An incentive-based approach offers possibilities for DSOs to increase their financial earnings if certain efficiency improvement targets are met (Cambini et al., 2016). A hybrid approach is based on a combination of cost- and incentive-based approaches often using a cost-based approach on capital expenditures and an incentive-based approach on operational expenditures. Cost-based regulation enables DSOs to recover their investments plus a set rate of return (Eurelectric, 2014; Cambini et al., 2016).

[5] Innovation incentives can include access to a higher rate of return for innovation-related investments, as well as a specific mechanism to adjust revenues throughout the regulatory period for research and development-related costs (Eurelectric, 2016).

[6] For a detailed description of market concentration cf. Section 2.3.

Table 4.4 Stakeholder description

Stakeholders within the electricity sector supply chain.

Stakeholder	Unbundled	Connected consumers (approx.)	Operations		Regulatory framework		Market structure	
			Distributed electricity (GWh/year)	Total grid length (KM)	Regulatory approach	Innovation incentives	DSO Concentration	Ownership
DSO A	Yes	4 000 000	16 428	182 461	Incentive	No	Low	Largely public, municipal ownership
DSO B	Yes	100 000	2 681	3 366	Incentive	No	Low	Largely public, municipal ownership
DSO C	Yes	5 000 000	44 599	225 422	Hybrid	Yes	Medium	Largely private
DSO D	No	15 000	5.9	321.3	Incentive	No	Low	Largely public, municipal ownership

Stakeholders outside the electricity sector supply chain.

Stakeholder	Description
Researchers and Academics A	This research group includes academics from the University of Coimbra, Coimbra, Portugal and from RWTH Aachen University, Aachen, Germany.
Electricity Utility Innovation Unit A	The electric utility company represented by this stakeholder owns distribution systems in Southern America and Southern Europe, as well as other supply chain activities. The innovation unit is responsible for driving disruptive change for the group of companies owned.
Research Center A	This research center focuses on power systems and power economics research, with a specific focus on smart grids and new electricity sector market design.

Table 4.5 provides details on the workshops, stakeholder groups represented and number of participants, workshop goals, as well as dates (month and year) they were conducted.

Table 4.5 Research workshop details

Workshop no.	Stakeholders group and participants	Workshop goals	Workshop date
1	Researchers and Academics A (n=4)	Establish research framework	May 2016
2	Researchers and Academics A (n=5), DSO A (n=1)	Semi-structured interviews, and data collection	May 2016
3	Researchers and Academics A (n=4), DSO B (n=2)	Semi-structured interviews, and data collection	Jun. 2016
4	Researchers and Academics A (n=5)	Data analysis, and refine research framework	Sep. 2016
5	Researchers and Academics A (n=5), DSO C (n=2)	Semi-structured interviews, and data collection	Sep. 2016
6	Researchers and Academics A (n=5), Electricity Utility Innovation Unit A (n=1)	Semi-structured interviews, and data collection	Sep. 2017
7	Researchers and Academics A (n=5), DSO D (n=2)	Semi-structured interviews, and data collection	Sep. 2017
8	Researchers and Academics A (n=4), Research Centre A (n=1)	Semi-structured interviews, and data collection	Oct. 2017
9	Researchers and Academics A (n=4)	Data analysis, and discussion of results	Oct. 2017

4.3 Results and discussion

This section presents the results obtained through the multi-stakeholder workshops. The findings presented are structured into three main topics. Section 4.3.1 presents and discusses the findings associated with operations, technology, and asset management. Section 4.3.2 focuses on the business model and organizational issues identified. Lastly, Section 4.3.3 discusses the regulatory and market design adaptation dynamics for DSOs.

4.3.1. Operations, technology, and asset management

This section focuses on the operations, technology, and asset management dynamics for DSOs. Section 4.3.1.1 presents the results for the integration of distributed energy resources and distributed generation. Section 4.3.1.2 discusses operational and maintenance related issues. Smart grid technologies are covered in Section 4.3.1.3, followed by smart meter technologies in Section 4.3.1.4. The results associated with legacy technologies are presented in Section 4.3.1.5.

4.3.1.1. Integration of distributed energy resources and distributed generation

The increase of distributed generation units connected to distribution grids is contributing to a more decentralized electricity system. Their integration on traditional distribution operations is a challenge for DSOs, with wind power generation being the most challenging technology. *"The* *biggest challenge in terms of integration of renewables are wind farms, however we must also consider smaller scale technologies such as PV and the impacts these might have."* (representative DSO B). The extent of these challenges is stronger in rural areas, where more opportunities to deploy distributed generation exist, particularly wind, given land availability, as opposed to urban areas[7] where deployed capacity is generally lower, and mostly solar PV. *"The integration of renewable energy generation at the distribution level is particularly challenging, considering that in some areas production is between 15 and 50 times higher than consumption. This is often the case in rural areas, which require expensive grid expansion to handle the increased distributed generation."* (representative DSO A). Regarding distribution infrastructure, increases in distributed generation will impact mostly the low- and medium-voltage segments of the grid. As described in the background section 4.1, the growing share of distributed generation connected to the networks challenges also the traditional configuration and use of upstream electricity infrastructure. This was confirmed by the experts who also observed an impact on network stability and a rapid increase in investments needs. "*We have to improve transformers capacity in several districts very quickly even though such measures are time- and capital-intensive. Several solutions exist, but the costs will be very high."* (representative DSO B).

4.3.1.2. Operations and maintenance

Changes on how electricity is distributed to consumers requires adaptation in terms of operation and maintenance of the grids. An exploitation of flexibility potentials within the distribution grid is one possible way to meet the upcoming challenges of a distributed energy system and could potentially reduce the need for investments related to grid expansion. *"We have some flexibility management possibilities, but these are very limited. Flexibility management can be a solution instead of grid expansion."* (representative DSO B).

Furthermore, distributed generation can contribute to significant changes in infrastructure usage in isolated areas, where consumption remains unaltered while electricity generation increases. Larger DSOs do not consider the operations and maintenance in these areas as challenging. *"Operating and maintaining small isolated areas is not a challenge, it is in fact okay, and is a good business."* (representative DSO A). Conversely, small DSOs have a different perception, considering this as a challenge. *"Small isolated areas sometimes can be challenging from an operational perspective."* (representative DSO B). These different insights call for more attention regarding the impact of DSO size in distribution network operation and maintenance.

[7] *"This is not a significant challenge for us. We have no wind power generation connected to the grid, and only a small share of PV. This is related to the fact that our distribution operations concentrate in an urban area."* (representative DSO D)

Redesigning the operations of distribution networks will benefit from a clearer understanding of the role of the DSO in the future. Managing system flexibility and enabling flexibilities from distributed generation, electricity storage, and demand response can contribute to value creation (Damsgaard et al., 2015). However, a consistent legislative framework is needed to settle the options and duties of (monopolistic) DSOs.

4.3.1.3. Smart grid technologies

Smart grid technologies were discussed as enabling components to facilitate the adaptation of distribution operations. Smart grid technologies can include monitoring and automation components that increase access to grid data and control capabilities. Moreover, these can include components that enable the integration and interaction with distributed generation and distributed energy resources. For instance, electric vehicles and the associated charging infrastructure were indicated as having the potential to bring disruption to the electricity distribution sector. However, DSOs are not certain regarding the most adequate implementation plan. "*In the current context electric mobility can be a game changer. However, we need to understand if there will be charging stations at home, if charging stations are stranded capital, and if there should be a subsidy for charging stations?"* (representative DSO A). Moreover, electricity storage represents also an interesting future option, for which a supportive regulatory framework should be established. *"In addition, storage is also seen as an opportunity for disruption. Regulation should be revised to set the right incentives."* (representative DSO A).

Smart grid technologies are expected to enable new services and contribute to increased consumer management capabilities. *"Our smart grid projects focus on either smart metering or distribution automation applications. The type of remote services possible for the DSO as a smart meter operator are for instance to connect a consumer, disconnect a consumer due to a non-payment, automated billing, etc."* (representative DSO C). The added value resulting from evolving towards smart grids relates to the possibilities to access new data. *"Much of the value that can be created comes from data currently collected, and data that can be collected in the future through more sensors, smart meter deployment, and partnerships with external data providers."* (representative Electricity Utility Innovation Unit A).

Standardization is essential for a successful adaptation of DSOs given the increasing deployment of smart meters, grid automation technologies, control devices, and other smart grid technologies (representative Research Centre A, representative DSO C). Moreover, the ability of DSOs to adopt smart grid technologies is influenced by their scale. Smaller DSOs notice greater challenges for rolling out innovative technologies *"The rollout of smart grid technology, in this case smart meters, is challenging for small DSOs."* (representative DSO D).

4.3.1.4. Smart meter technologies

Smart meters provide remote measurement and communication of electricity usage in smart grids, and are often referred to as the initial step to take in a smart grid deployment plan (Sharma & Saini, 2015; Kabalci, 2016). The added value of smart meters rests on their ability to provide more granular information about grid usage, as well as increased fault location capabilities. "*From a grid expansion perspective, having more data, through more monitoring points can help understanding the network better.*" (representative DSO D). Moreover, smart meters support observability, and can contribute to improvements in network congestion management (representative Research Centre A). However, the potential for smart meters is lowered without dynamic pricing of electricity. *"Smart meters can provide better information about the grid. However, these have little potential in a one-tariff system. Tariffs should be dynamic for smart metering to be attractive"* (representative DSO A). Nonetheless, while smart metering technologies are perceived as important and of added value, the stakeholders did not consider it necessary to have a smart meter at every end-point and mentioned that having data from smart meters collected from only 10% to 15% of the end-points would be sufficient[8].

These insights provide a valuable perspective on the DSOs perception on their benefits related to large-scale rollouts of smart meters. To estimate the value of a rollout on a macroeconomic scale, these benefits have to be contrasted with the associated costs. Therefore, the EU requested the Member States to conduct a cost-benefit analysis in its Third Energy Package, setting a target of 80% of smart meters installed by 2020 whenever this cost-benefit analysis is positive (European Union, 2009b; European Commission, 2014b). As described in the background section 4.1, this cost-benefit analysis in Germany turned out negative, with smart meters being feasible only above a certain consumption threshold (BMWi, 2013). For Portugal, a first study indicated positive results, however, due to severe economic challenges, Portugal decided to review the original findings and considered the analysis inconclusive, also refraining from the ambitious 80% target of the EU (ICCS-NTUA & AF Mercados EMI, 2015). The observed position across DSOs can offer new possibilities for other players to support the deployment of smart meters in the EU. Despite this insight on the perceived value of smart

[8] "*We don't see the need for a smart meter in every end-point. If 10% of the homes have a smart meter in a specific area it is enough to provide the necessary information on the status of the grid.*" (representative DSO A, representatives of DSO B, DSO C, and DSO D presented agreeing views).
"Smart meters could help DSOs to support the observability of the grid and contribute to better congestion management." (Research Center A)

meters the responsible party for implementation and ownership across the EU are mainly DSOs (European Commission, 2014c, 2017f).

Connected to the perception of limited added value from a full rollout of smart meters, alternative technology options are being considered to support DSO adaptation. The need for information on every end-point of the grid is perceived as limited. *"We are not sure if a smart meter is the right device to provide us with the information we need from the network. The interest in more information regarding the current grid conditions is rather small. We see no need for smart metering for real-time consumption measurement. Metering of only certain parts of the grids is sufficient to reveal enough information about distributed generation."* (representative DSO B).

Also, the rollout of smart meters encompasses technical and economic challenges. Technical challenges are related with the complexity around data management and cybersecurity. Economic issues are related with the potentially shorter lifespan of smart meters, in comparison to its electromechanical predecessors. *"The deployment of smart metering can increase complexity around data collection and cybersecurity issues. Moreover, the possible provision of new services and functionalities adds to the concerns associated with hacking. This adds to the challenges associated with costs, and cost allocation for consumers, Traditional meters have had a lifetime of 16 years. Smart meters have an expected lifetime of 8 years, with possibilities to last up to 13 years."* (representative DSO D). Standardization is also an important aspect when it comes to smart meter technologies' adaptation and adoption by DSOs. *"Right now, DSOs are analyzing communication protocols and how these can be standardized."* (representative DSO D).

4.3.1.5. Legacy technologies

Adapting electricity distribution networks has been generally discussed around the importance of innovative technologies and approaches to network operations. However, legacy technologies are also a relevant element in supporting DSOs adaptation. These represent existing technologies, which have been incrementally improving and are perceived as low-cost and low-risk options. *"In addition to the disruptive technology options there are also low-cost legacy technologies that when implemented result in significant efficiency increases for the DSOs. These include controllable low voltage transformers, and standardized automated controls."* (representative DSO A). The following example on the relevance of legacy technologies was provided: *"Our substations are quite old but the automation present in them from the 1980s works well enough."* (representative DSO C).

Grid expansion is mostly within the scope of legacy technologies and has always been part of DSOs operations. Despite their historical experience, grid expansion is an increasingly challenging task due to location constraints for both transformer stations and lines. *"We have* *clear plans for grid expansion and we plan to pursue them. These expansion plans are mostly related with building new lines. This brings challenges related to the fact that it is not easy to find places to build new transformer stations, as well as the fact that most of the lines must be planned as underground lines being costlier and less durable."* (representative DSO B). Despite the challenges, grid expansion is a priority for DSOs. *"At present we are concerned with the building and maintenance of the grid."* (representative DSO B).

4.3.2. Business model and organizational issues

This section focuses on the business model and organizational issues impacting DSOs through the energy transition. Section 4.3.2.1 presents the results related to the existing business model for electricity distribution. Section 4.3.2.2 discusses the role of business restructuring, demergers, and acquisitions. Section 4.3.2.3 presents findings related to innovation. Lastly, Section 4.3.2.4 provides a forward-looking discussion by focusing on future business model possibilities.

4.3.2.1. Prevailing business model

The significant changes in the technology and regulatory environment (cf. section 4.1) suggest that also the underlying business model for electricity distribution and the value creation approach might have to be adapted or even completely redeveloped. *"Our current business model is hardly profitable, and we expect legislative changes in the future. Still, we are not taking an active role in contributing to shape these future regulations."* (representative DSO A). Despite the challenges resulting from existing business models, electricity distribution is an interesting business, which can benefit from timely adaptation to the changes in technologies and policies. This adaptation requires understanding the role of DSOs in providing or facilitating new services. *"Being a network company only (unbundled) is a good place to be, there are good chances to do new tasks in the future. What is important is to start these new tasks."* (representative DSO B).

4.3.2.2. Business restructuring and mergers

Adaptation of the electricity distribution industry is intertwined with an adaptation of the entire electricity sector supply chain. Changes in the electricity sector have resulted in restructuring and mergers across utilities, aimed at increasing economic performance and improving their position to engage in new business areas. *"Due to financial turmoil our mother company is splitting into two companies to capture capital from the markets. One of the companies will keep all the generation and trading-related activities. A new company will keep the distribution network, renewable energy, and retail-related activities, as the more profitable business areas."* (representative DSO A).

An example of these restructuring efforts has been observed in two German utilities, E.ON and RWE. In 2016, E.ON's restructuring approach was based on a demerger that resulted in the creation of a spin-off company, Uniper, covering the unregulated business activities. RWE, following a different strategy, also demerged, but retained its unregulated activities, and created a spin-off company, innogy, for distribution grids, retail, and renewables (Zank et al., 2016). After this demerger actions, in 2018 E.ON presented a takeover offer over the newly created innogy, with the goal to create two more stable players, one focusing on networks and retail activities – the New E.ON, and one focusing on generation and trading – the New RWE. This restructuring aims to contribute to simplify the two utilities' corporate structures, making them more transparent and easier to valuate. Moreover, this merger can reduce the risk of acquisitions by foreign investors (E.ON, 2018; E.ON and RWE, 2018; Zank, 2018). Figure 4.5 describes the evolution through demergers and mergers and acquisitions for these two utilities.

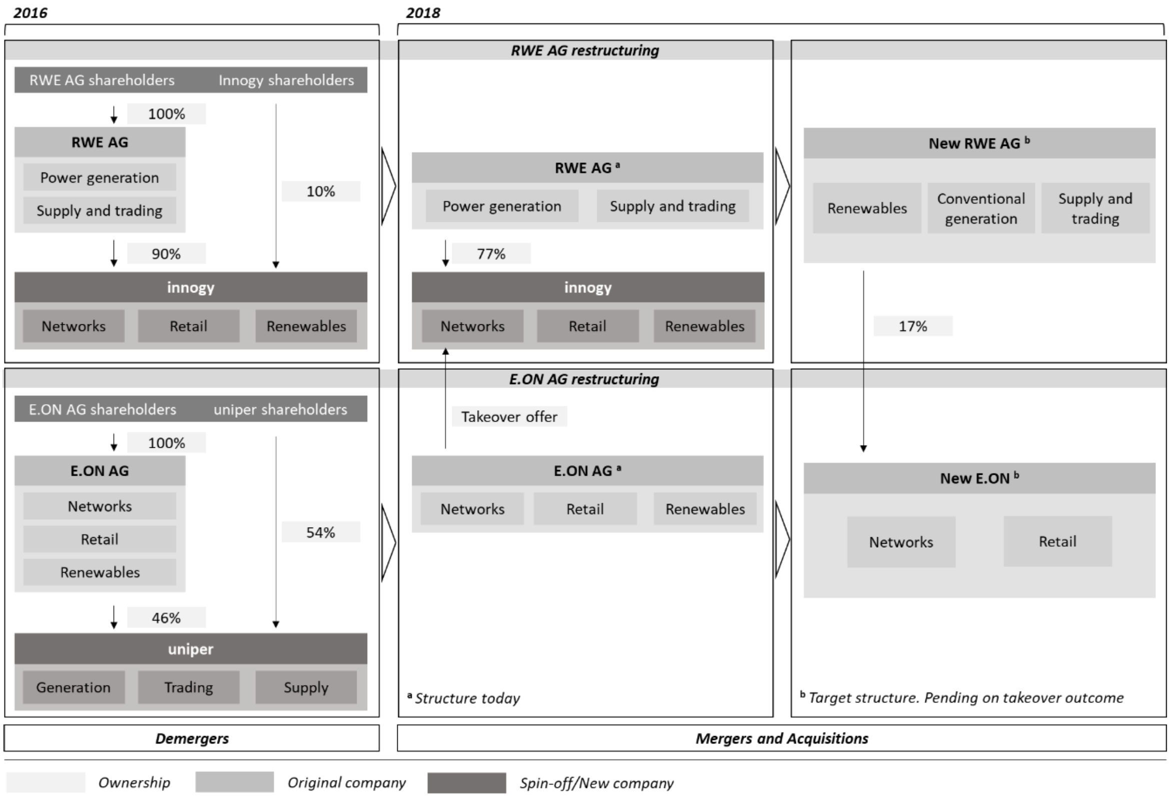

Figure 4.5 RWE and E.ON restructuring

Source: Elaboration based on Zank et al. (2016); E.ON (2018); E.ON and RWE (2018); Zank (2018)

Mergers are considered an opportunity by small DSOs, which are looking for ways to reach greater economies of scale. "*Right now, we are considering merging with another DSO. This merger is needed because we are constantly being pushed to reduce our operational costs in order to improve our efficiency factor. Because of this, more than 50% of our employees had to be fired in recent years. In line with this, we* *estimate the best conditions for medium/big DSO players in the future"* (representative DSO B). Moreover, collaboration across smaller-scale DSOs has been considered as an option to overcome challenges for technology acquisition. *"We joined 7 other DSOs, servicing altogether a consumer population of some 200 000, to achieve greater economies of scale for acquiring technology."* (representative DSO D). However, the experts from academia pointed out that there are also several cases where big DSOs lost concessions when the municipalities decided to found and own a local energy supplier/grid operator.

4.3.2.3. Innovation

Collaborative innovation efforts through Research and Development (R&D) projects are being pursued by DSOs as a source of knowledge and capability development for integrating and operating new technologies. DSOs are engaged in exploring new grid technologies and services. *"We are participating in innovation projects and R&D in partnership with academic institutions. Our projects include advanced usage of smart meters, central battery storage and intelligent control of the systems."* (representative DSO A). In terms of their approach to innovation, DSOs are interested in both exploitation and exploration. Exploration activities are concerned with understanding how new technologies and processes can be part of the electricity distribution industry. These include projects focusing on smart meter integration, storage integration, and intelligent control of systems. Also, through the development of virtual power plants, integration of solar photovoltaic (PV) systems. Exploitation activities focus on more traditional aspects of the electricity distribution operations. These include improvements in asset management, as well as innovations in business processes. *"Complementing our more disruptive applications, we develop internal projects to support the innovation in asset management and business processes."* (representative DSO C).

While being engaged in innovation-driving efforts is an important aspect, this activity is still challenged by a corporate culture with considerable levels of inertia to changes that embody unfamiliar technologies, processes, and stakeholders. "*As the electricity sector has been to a large extent tied to stringent regulations and legacy technologies, certain innovation proposals are hard to pass through. Here, having an internal innovation unit enables greater levels of confidence and buy-in from internal decision makers, that external players with disruptive ideas and proposals would not have."* (representative Utility Innovation Unit A).

Concrete examples of the existing inertia to engage in disruptive transformation processes were discussed. For instance, the creation of an innovation hub to mobilize disruptive innovation efforts was considered as unacceptable on the scope of the DSO strategy. *"Our unit proposed the creation of a digital energy disruptor hub outside of the company, which would foster disruptive ideas for the* *electricity sector. The executive board and internal decision makers annihilated the idea, claiming it would cannibalize our business."* (representative Utility Innovation Unit A). Another example was associated with a proposal to submit the DSOs' smart meters to an ethical hacking group, in order to better understand the extent of the DSOs cybersecurity vulnerabilities. *"We as innovation unit proposed to our DSO that the smart meters being deployed would go through an ethical hacking consulting firm to understand the extent of cybersecurity threats. The board did not feel comfortable with the idea and rejected it."* (representative Utility Innovation Unit A). This gives a sense that there are things that should rather remain unknown, and that maybe research must be conducted outside the companies themselves.

4.3.2.4. Future business model

The future business model for DSOs is expected to enable value creation and capture through flexibility management services. DSOs are willing to provide new services and integrate new technologies, therefore expanding the scope of their activities and responsibilities. *"The future of our business requires operating flexibility to reduce the network operational costs and make the most of distributed energy resources and flexible demand. Moreover, we see a future in which we include new smart elements to operate our networks, such as new transformers, and where we are responsible for the coordination of the ancillary services for the system."* (representative DSO A). Managing electricity storage units is considered as one of the opportunities within flexibility services. *"We want to be able to contract storage to use it for grid balancing. We see a future in which one of our roles is to provide ancillary grid services."* (representative DSO B).

In addition to the emphasis on system flexibility management, creating value from data is one of the opportunities considered promising in a more digital electricity system. These opportunities result from the direct access to new data that DSOs benefit when integrating smart meters and sensors as part of grid modernization actions. Moreover, access to data from third parties can contribute to creating data-driven services. However, delivering these benefits from data will only be possible through a shift in DSOs' conservative culture regarding data access and sharing. *"However, while data represents significant opportunities for new service development, it is still difficult to get buy in from decision-makers on matters that involve sharing data or using it in new ways. Previous attempts to implement ideas that require data sharing from the DSO to other partners resulted in reactions such as: 'That is not what we do', 'We are a regulated business, we are not supposed to share data', and 'That is not part of our operations'.* (representative Electricity Utility Innovation Unit A). The possible business model changes around data do not necessarily indicate that DSOs will become actively engaged in delivering new services for electricity consumers. This may be a more suitable role for other market players. Nonetheless, DSOs can play an important role in facilitating those market players that have the capabilities to deliver innovative services. Future business models around data and digitalization can benefit from blockchain technology (Aitzhan & Svetinovic, 2016; Mengelkamp, Notheisen, et al., 2017; Knirsch et al., 2018), similar to the approach being followed by LO3Energy in Brooklyn, New York (Mengelkamp, Gärttner, et al., 2017). While blockchain and the possibilities for introducing smart contracts seem attractive, it is possible to do similar things without any blockchain technology. However, at least both big DSOs (A and C) indicated that they would like to be perceived as pro-actively considering innovative and potentially disruptive technologies such as blockchain in their future operations.

Beyond the complexities of technological adaptation, introducing new services in electricity distribution requires additional resources and capabilities that are not part of the DSOs' existing operations. DSOs are assessing their future needs to better understand how to adapt. *"From a capability perspective, we are now looking at the resources we have available and how these can support the challenges brought by the energy transition. Soon, we expect to have a clearer idea about whether our technical and human resources are adequate for the digitalization of electricity distribution."* (representative DSO D)

Moving toward new business models requires detailed planning and consideration for the necessary investments and changes to be implemented. However, these plans are challenged by the need for DSOs to react to changes in the distribution network, such as the growth of connected distributed generation units. *"The choice to pursue new business opportunities, and associated investments, faces a barrier related with the limited planning horizon. Plans are basically made as a reaction to new surges in connected distributed generation units."* (representative DSO B). The need to continuously improve operational efficiency contributes also to the challenges of implementing strategic changes in the business model. This often results in preference being given to reactive measures such as outsourcing of activities and staff reductions. *"Considering our challenging operational framework, we see outsourcing of business activities and staff reduction as options for the future."* (representative DSO B). The characteristics of future business models can also be understood by considering the possible changes across core electricity distribution activities (cf. Table 4.6).

Table 4.6 Evolution of DSO activities (DSO A)

Activity	Traditional	Today	Future
Electricity management	Load management	Grid stability control with increasing shares of distributed generation	Flexibility management
Operation	Static load flow calculation	Monitoring and control based on additional measurements	Automated operational control
Asset management	Standardized equipment	Integration of novel technologies	Operation and control of smart equipment
Communication	Exchange of aggregated values, mostly for billing	Immediate, transparent, and non-discriminatory data transfer	Operation of a data platform
System reliability	Local voltage quality	Introduction of ancillary services	Provision of ancillary services via distribution system

Source: Elaboration based on DSO A (2016)

4.3.3. Market design and regulation

This section presents the results related to market design and regulation. Section 4.3.3.1 focuses on market structure characteristics and how these influence DSOs' adaptation. Section 4.3.3.2 discusses the results on regulatory frameworks and their importance in the ongoing smart and sustainable electricity sector transition.

4.3.3.1. Market structure

Market structure is a relevant aspect when considering adapting market designs and existing regulatory frameworks. The electricity distribution industry across the EU presents a heterogeneous concentration, which is mostly the result of the historical and cultural perception of the interaction between communities and their electricity infrastructure. *"DSO market concentration is mostly related to the fact that local communities wanted to have some control over their energy infrastructure. Therefore, patchy structures are a result of every community wanting to own their grid."* (representative DSO A).

The attractiveness of electricity distribution as a business creates possibilities for changes in market structure. Municipalities are becoming increasingly interested in operating their local electricity distribution grids. This can result in a shift in ownership from larger, integrated DSOs that operate distribution grids through concessions with municipalities, to ownership by municipalities. *"For instance, we have had contracts with the municipalities for 20 years regarding the operation of their local grid, however, we note an increase in municipalities' willingness to operate their grid by themselves, given that grid operation is a good business."* (representative DSO A). This shift was observed in Hamburg, Germany, when the incumbent utility Vattenfall lost the grid operation concession to a municipality (representative Research Centre A). This structural change was the result of a referendum for the remunicipalization of energy networks held in 2013 (Wagner & Berlo, 2015).

Changes in market structure can also result from different adaptation capabilities across different DSO scales. In this context, larger DSOs seem to be better prepared to adapt to technological changes, given their ability to capture greater economies of scale because of their larger consumer base. *"Larger DSOs have an easier time rolling out smart meters, and other smart grid-related technology."* (representative DSO D).

Electricity sector reforms impact also the distribution market structure. Market liberalization was introduced as a driver for more affordable, higher quality electricity services. However, having an integrated view of the electricity supply chain, which was a possibility in vertically integrated utilities, can also be beneficial in times of disruptive change in the electricity sector. When pushing for innovation it does help to look at the entire electricity supply chain.

4.3.3.2. Regulatory aspects

The regulatory framework in each country was presented as important to incentivize DSOs in the rollout of new technologies. To this end, existing market designs focusing on operational efficiency improvements represent a sensible approach for a traditional electricity distribution industry. However, it is less compatible with a changing electricity sector in which new technologies are being integrated across the electricity supply chain, which impact electricity distribution. This hinders the engagement of DSOs in smart grid developments. *"This is bad news for smart grid-related projects that often reduce the operational efficiency and harm revenue collection capability. This regulatory approach creates barriers on the business strategy DSOs pursue. This results in a preference for grid expansion instead of smart grid investments, since a smart grid would increase the operational costs, where a grid expansion increases the capital costs and thus increase the efficiency factor."* (representative DSO A). This insight highlights the importance to reevaluate and adjust how cost structures are regulated as distribution networks become smarter and integrate greater levels of distributed energy resources. Regulatory models that support innovation and the transition to smart grids must consider a new balance between operational expenditures (OPEX) and capital expenditures (CAPEX). For instance, managing and coordinating higher shares of distributed generation can result in increased OPEX while supporting CAPEX containment or deferment, which challenge the traditional CAPEX bias. Despite the importance of rethinking cost structures only Finland, France, Ireland, and the United Kingdom have implemented incentives for OPEX associated to innovation activities (Eurelectric, 2016).

Regarding the investment needs to adapt to a changing electricity sector it is important to highlight that financial resources are not a significant barrier; the real barrier is obtaining business plan approval. *"For all these future activities we need to be able to get the money, but this is not difficult; what is difficult is obtaining an approved business model by the regulator for these investments."* (representative DSO B). Efforts to adjust existing market design and regulations have benefited from the growing resources dedicated to advancing the energy transition. *"The energy transition is supporting an increased attention to topics related to the changing role of DSOs."* (representative DSO A).

While Germany and Portugal are lagging in terms of legislation mandating large-scale smart meter rollouts, consequently impacting the transition to smart grids, other EU member countries present more prominent outlooks. These differences across Member States are partly due to differences in innovation and adaptation support of each country's regulatory framework. In Germany, only a limited number of innovative projects are approved by the regulators for DSO development. The scheme defined in Portugal provides DSOs with additional revenue for certain smart grid investments, usually associated with smart grid development. To be qualified as eligible for this incentive, innovative investments must be submitted to the approval of the Portuguese NRA and the DSO must demonstrate its benefits to consumers and the system. These benefits are then shared with consumers, with the additional income for DSOs being distributed over 6 years, capped at 1.5% of the investment value (ERSE, 2017). The regulatory frameworks in both Portugal and Germany exclude large-scale pilots or innovative technology rollouts, and are considered as presenting some degree of regulatory hurdles to innovation (Eurelectric, 2014). Concurrently, regulatory approaches implemented in Italy, Norway, and the United Kingdom, have been presented as best practices. The Italian regulator has been increasingly supporting the transition to smart grids since 2010 and has approved several pilot projects which receive a 2% bonus to the rate of return for a 12-year period, providing DSOs with long-term positive economic signals to engage in smart grids diffusion. The Norwegian regulator allows DSOs to recover innovation costs directly through tariffs, capped at 0.3% of their grid asset value. In the United Kingdom, the regulator has established an innovation stimulus package to support innovation. The package includes 'The Network Innovation Competition', in which DSOs compete for funding sources; the 'Network Innovation Alliance', through which DSOs receive an allowance based on their innovation strategy; and the 'Innovation Rollout Mechanism', which allows DSOs to request additional funding for innovative activities to be implemented in the regulatory period (Eurelectric, 2014, 2016).

In addition to regulatory aspects, the acceptance of new technologies also plays a critical role, such as smart meter acceptance by the households, which is closely related to data protection issues and cybersecurity concerns. The importance of these two aspects is widely accepted by all the interviewed experts and corroborated by the experiences in other countries. In the Netherlands, for instance as one of the early movers regarding smart metering, an insufficient consideration of privacy issues led to a significant loss in acceptance and delayed the rollout by several years (Hoenkamp et al., 2011). The UK, on the other hand, deliberately promoted their rollout and set up the Smart Metering Early Learning Project to investigate how to best engage customers in the rollout process. As a result, about 73% of smart meter owners would recommend it to others, with only 3% being skeptical. In this case, of those who still have an old meter, 48% would like to get a smart meter soon (Smart Energy GB, 2018).

4.4 Synopsis of challenges and opportunities

The insights obtained from the multi-stakeholder workshops are classified into challenges and opportunities for electricity distribution (companies' and system's/technologies') adaptation needs. This provides an updated perspective on what is hindering the adaptation of electricity distribution, as well as on which future opportunities are being considered. In terms of operations, technology, and asset management (cf. Table 4.7) challenges are perceived when it comes to both smart grid, and smart meter technologies, as well as legacy technologies. Future opportunities include flexibility management from distributed energy resources, and more access to data as a new source of added value.

Table 4.7 Operations, technology, and asset management

Topic	Challenges	Opportunities
Integration of distributed energy resources and distributed generation	Operations at the medium and low voltage segments of the grid. Surge of distributed generation in rural areas. Time and capital-intensive investments required. Network stability.	Increase system flexibility on low-voltage levels.
Operation and maintenance	Peak loads, both in consumption and production.	Flexibility management.
Smart grid technologies	Identify the best approach to integrate electric mobility in electricity distribution grids. Regulatory framework and incentives for electricity storage. Standardization of technologies for seamless integration.	Electric mobility. Electricity storage. Smart metering. Distribution automation. Data-driven innovations. Partnerships with external data providers.
Smart meter technologies	One-tariff system that hinders smart meters potential to send economic signals. Uncertainty if smart meters are the best technology for DSOs data needs. Increased complexity in data collection Cybersecurity and hacking concerns. Investment and cost allocation. Shorter life span of the technology. Standardization of communication protocols.	More information about the grid. Fault location capabilities. Observability. Network congestion management.

Topic	Challenges	Opportunities
Legacy technologies	Finding new places to build new transformer stations. Obtaining permits for underground lines.	Low-cost legacy technologies that increase efficiency (Low voltage transformers, standardized automated control devices)

Business models and organizational challenges (cf. Table 4.8) include strategic restructuring, which has been pursued through demergers, creation of new companies to support reallocation of assets and operations, and more recently mergers and acquisitions. While innovation is being pursued and is considered a source of knowledge for expanding service offering, the inertia associated with DSOs' traditional business culture challenges the adoption of innovative technologies and hinders the possibilities for disruptive ideas to be considered. Opportunities encompass integration and adaptation of distributed energy resources, and the facilitation of data-intensive services.

Table 4.8 Business model and organizational issues

Topic	Challenges	Opportunities
Business restructuring and mergers	Separating the more profitable from the less profitable segments of the value chain.	Use mergers to boost scale-effects. Use partnerships to share development costs and risks.
Innovation	Electricity sector historically tied to regulations and legacy technologies. Innovation proposals are hard to pass through. Decision-makers adversity to disruptive ideas from external stakeholders (e.g. from start-ups).	Advanced use of smart metering. Battery storage. Intelligent systems control. Virtual power plants. Integration of solar PV. Participation in R&D projects with universities and external partners at the national and European level. Technology exploration and exploitation. Improve asset management. Business process improvement. Internal innovation initiatives.
Future business model	Decision-makers adversity to using data for service innovation. Understanding the technical and human resources needed. Difficulty to establish future development plans, which are mostly driven by distributed generation diffusion.	Expand service offering. Integrate new technologies. Develop new capabilities. Operate system flexibility. Provide ancillary services. Data-driven business models. Increase data collection through more sensors. Partner with external data providers for new service offerings. Outsource business activities. Staff reductions.

Regarding market design and regulation (cf. Table 4.9) challenges are associated with the possible limitations of a liberalized market structure when considering disruptive changes. Moreover, pursuing operational efficiency can act as a barrier on smart grid investments, as well as result in job losses in the industry.

Table 4.9 Market design and regulation

Topic	Challenges	Opportunities
Market structure	Liberalized market structure can result in a siloed view of the different segments of the supply chain. Focus on operational efficiency compromises smart grid investments.	Considering the entire electricity sector supply chain, and how innovation can improve it, beyond current market structures.
Regulatory aspects	Continuous efficiency improvements Obtain regulatory approval for new business models.	Increasingly engage in innovation activities that support smart grid diffusion and create knowledge to adapt the regulatory framework.

Further, adaptation challenges were identified that are perceived to impact DSOs differently, depending on their scale (cf. Figure 4.6).

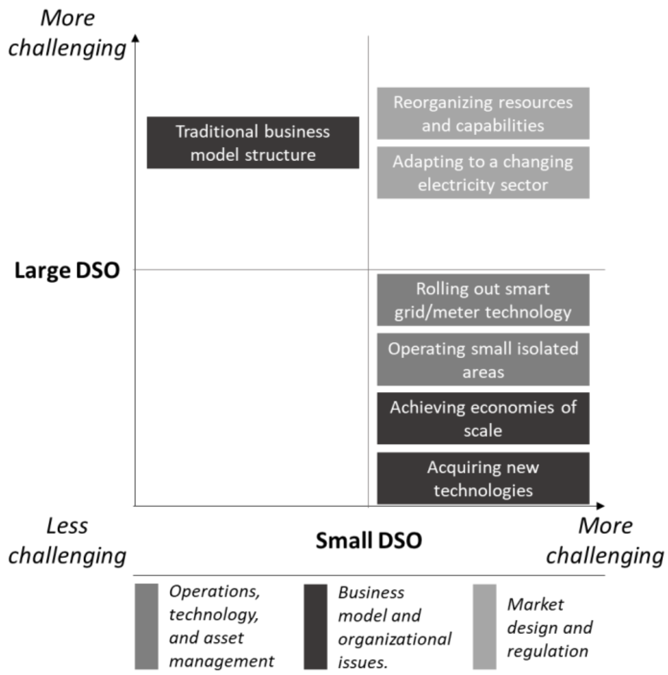

Figure 4.6 DSOs' scale and associated challenges

4.5 Conclusions

This chapter provided insights on challenges and opportunities for DSOs regarding technology, business models, and market design in the EU. Through a series of nine multi-stakeholder workshops in two representative EU Member States, Germany and Portugal, qualitative up-to-date perspectives on how DSOs are facing and accommodating the shift to a smarter, more decentralized, and sustainable electricity sector were collected. As the debate on the digitalization of the electricity system evolves, these findings reveal uncertainty regarding the value of full-scale rollouts of smart meters by DSOs. Policy makers should consider how this influences future expectations regarding large-scale diffusion of smart metering technology and should ensure that all potential benefits actually become exploited.

Adapting operations for the provision or facilitation of these new value-added services, such as flexibility management, is considered a promising opportunity. However, a corporate culture with high levels of inertia to change is observed. Future policies should consider the impacts of inertia to change in the deployment of innovative technologies and adoption of new business processes. Evolving toward smart grid technologies and processes can be challenging with a regulatory framework focused on continuous improvement of operational efficiency. The results obtained also indicate that while operational efficiency is important, it may result in job losses in the quest for cost reductions, as well as motivate outsourcing of core business activities, leading to loss of internal knowledge and technical capabilities. Policy makers should consider these impacts when designing regulation to support smart grid investments and capability development by DSOs.

The results further provide a recent guiding reference on the challenges and opportunities impacting the electricity distribution industry in the EU, helping to pave the way for future research and considerations. Other countries are well advised to learn from experiences made in the investigated countries. In Portugal, the DSOs agreed with the regulator on a voluntary rollout without a legislative mandate and with the primary goal of value maximization. In Germany, in contrast, the economic incentives for DSOs were apparently insufficient to ensure a quick diffusion on their own. Furthermore, the data protection and cybersecurity requirements have not yet been finalized. This is problematic both because it does not really contribute to dispel concerns and acts as an additional hurdle preventing a quick rollout even after a law mandating that the general rollout-process must be enacted. Future work includes collecting more insights to understand how existing policies contribute to more adaptable DSOs across the EU, and DSOs' capabilities in delivering new business models.

Chapter 5

Assessment of business model innovation and adaptation: a capabilities approach

5.1 Background

The sociotechnical sustainability transition is transforming the electricity sector. Traditionally, incumbent utilities, as is the case of DSOs, operated in a stable policy, technological, and economic environment, now challenged in a rapidly changing electricity sector. These changes result from the growing share of decentralized, low-carbon generation, and the growing interconnectedness of energy infrastructure and information networks, paralleled by changing customer behaviors, now able to control their energy consumption, support part of their power needs through local generation, and organize in local energy communities and markets (IEA, 2017).

Amidst these shifts there is a growing demand to apprehend changes in the role of critical electricity sector infrastructure and consequently what to expect from utilities in the future. As a result, a growing body of knowledge has emerged focusing on the future of utilities and critical power sector infrastructure (Pérez-Arriaga et al., 2013; Ruester et al., 2014; Pérez Arriaga & Knittel, 2016; Meeus & Glachant, 2018). Focusing on the framework conditions in which utilities operate – external factors, Pérez-Arriaga et al. (2013), Pérez-Arriaga & Knittel (2016), and Meeus & Glachant (2018) have analyzed the impact of regulation and possible adjustments to support a transition in distribution networks with increased shares of distributed energy resources. Also, focusing on external factors Jansen et al. (2012) studied sustainable innovations in technologies and processes, and their impact for the electricity sector and utilities. On the other hand, with a stronger emphasis on utilities firm-level aspects – internal factors, Fox (2016) analyzed utilities adaptation to a more sustainable business, comprising the consideration of renewables integration, customers and stakeholders' engagement, and managing environmental impacts. Consequently, awareness on utilities business models, and its innovation has also increased, given its ability to establish a link between internal and external factors and utilities transformation amidst change (Sioshansi, 2012; Lehr, 2013; Newcomb, Lacy, & Hansen, 2013; Newcomb, Lacy, Hansen, et al., 2013; Cross-call et al., 2018).

This chapter provides an assessment of business model innovation and adaptation in DSOs through a capability approach. Using the business model innovation as a conceptual framework. It provides a firm-level perspective on the adaptation of DSOs as a key actor in a larger technical system – the electricity system. Analyzing business model innovation through a capability approach supports the development of knowledge on utilities adaptability to reorganize and implement new business models. All things considered, the assessment herein presented does not aim to identify the business model of the future, rather to understand the extent to which utilities capabilities enable innovative business models.

The role of capabilities on business model innovation is explored through a Structural Equations Modelling (SEM) approach, which enables the assessment of causal relationships between variables that cannot be directly measured – latent variables, suitable for studying the role of capabilities. This assessment is based on primary data from 129 DSOs operating in 27 different EU countries, collected in 2017.

Increasing awareness on utilities adaptability, here analyzed by focusing on incumbent network utilities, contributes with valuable insights for both the utility sector, and policy makers, which will gain a more detailed perspective on the ability of incumbents to react to the changing industry dynamics and adjust their value capture and creation processes. The assessment resulting from this research benefits the ongoing smart and sustainable energy transition by unveiling governance-relevant indicators on how likely the utility sector is to redesign its value creation processes and implement innovative business models.

This chapter is structured as follows: Section 5.2 provides a literature background on business model, business model innovation and adaptation, and the relevance of business models as analytical frameworks to study sociotechnical sustainability transitions impacting the electricity sector. Section 5.3 provides a description of the methodology and research design. Section 5.4 described the findings obtained through SEM modelling. Section 5.5 presents a discussion of the results obtained. Conclusions are presented in Section 5.6.

5.2 Business models' adaptation

This section provides a conceptual framework on business models. Section 5.2.1 presents the business model concept, reviews existing literature on business model adaptation, and on business model innovation. Section 5.2.2 emphasizes the relevance of the business model within sustainability transitions. Lastly, Section 5.2.3 presents a review of exiting studies applying a business model analytical lens to the electricity sector sustainability transition.

5.2.1. Business model innovation

Conceptually, a business model unveils the processes through which firms organize and combine internal factors, such as assets, financial resources, talent, with external factors, such as customer needs, policy developments and technology shifts, for value capture and creation, (Baden-Fuller & Haefliger, 2013; Cosenz & Noto, 2018). Moreover, it provides a link between a firm and its characteristics, and the wider production and consumption chain where it operates, providing a system perspective of evolution (Boons et al., 2013). Generally, it includes: a value proposition, a supply chain, a customer interface, and a financial model (Osterwalder, 2004; Doganova & Eyquem-Renault, 2009).

Evolving firm-level and framework conditions influence the business model design and value creation processes in place, consequentially driving adjustments and business model innovation (Teece, 2010; Halecker & Hartmann, 2013). Business model innovations can support either the creation of a new market, or the creation of new opportunities within an existing market. The adjustments need not be complete overhauls, as incremental business model innovation can redefine firms and industries in the long-term, and contribute to change supply and demand dynamics over time (Amit & Zott, 2012). Business model innovation requires adjustments on how firms define and combine performed activities, which can include: adding or removing activities, resulting in content innovation; organizing activities in new ways, resulting in structure innovation; and changing the responsible party for an activity, resulting in governance innovation (Amit & Zott, 2012; Bolton & Hannon, 2016). Therefore, business model innovation becomes essential to create new opportunities, and also to reduce lock-in and path dependencies in firms that have been operating under the same business model for an extended period of time (Achtenhagen et al., 2013). Innovations in business models require firm' level adaptation and an ability to lead efforts towards the identification, design and implementation of change (Saebi et al., 2017).

Business model innovation and adaptation are influenced by firm's capabilities (Teece, 2017). Capabilities, as a combination of competences and resources at the firm-level, have been increasingly presented as an important building block for business model innovation and as a source of evidence on what enables firms adaptation (Achtenhagen et al., 2013). Firm-level capabilities result from the combination of competences and resources. For instance, creating a product or a service by combining assets and individuals represents a capability, as a distinctive activity developed within the firm, such as a specific routine or process.

Capabilities can be categorized as being either 'operational' or 'dynamic' capabilities (Teece & Pisano, 1994; Teece et al., 1997; Teece, 2007, 2018). Operational capabilities are the fundamental competences needed to perform the firm's core business activities; these are the competences the firm requires to operate with its existing resources and provide its products and services. Dynamic capabilities represent the firm's adaptability to a rapidly changing market and reflect their ability to integrate, assemble, and transform its competences, therefore these reflect the ability of firms to adapt and innovate, these provide strategic guidance to the firm (Teece et al., 1997; Eisenhardt & Martin, 2000; DaSilva & Trkman, 2014). Dynamic capabilities include the capacity to sense, seize and transform the business model as a response to policy, technology and market changes (Teece, 2007; Achtenhagen et al., 2013), therefore impacting how firms create and capture value (Katkalo et al., 2010; Leih et al., 2015).

5.2.2. Sociotechnical sustainability transitions

Sociotechnical sustainability transitions encompass complex interactions between actors including governments, researchers and academia, and firms, among others, to support progress in sustainable development (Farla et al., 2012). Governments, alongside policy makers, are tasked with understanding the impacts of transitions on institutional frameworks and identify the necessary policy adjustments. Researchers and academia expand the state of the art on science, technology, and its relationship with society to tackle exiting challenges. Firms navigate the changing framework conditions, driven by the implementation of new policies and technologies, in combination with their internal knowledge, resources, and understand how to act upon external shifts to remain competitive, and become more sustainable while creating value.

Against this backdrop, business models have become more relevant given their ability to translate how efforts towards advancing sociotechnical sustainability transitions are integrated by firms to create value (Boons & Lüdeke-Freund, 2013; França et al., 2017). Therefore, the use of the business model as a conceptual framework allows to bridge the gap between the potential benefits resulting from the development of a new technology, a new regulation, or a new service design – the invention, and the actual delivery of the benefits and value of that invention to society – the innovation (Chesbrough, 2010; Bolton & Hannon, 2016). Furthermore, business models are valuable because they symbolize the activities in which firms engage to create and capture value, which go beyond the firm itself, and interact with external stakeholders as part of an integrated system (Zott et al., 2011; Bolton & Hannon, 2016). This characteristic of business models positions them as a useful analytical tool in sustainability transitions, by proving a firm-level perspective of the complex interlinks associated with sociotechnical change.

5.2.3. Existing applications on the electricity sector

A growing body of knowledge has been analyzing the electricity sector sustainability transition through a business model lens, motivated by the importance of understanding how new technologies, regulations, processes, stakeholders, and customer behaviors, impact the value creation process in the electricity sector. Existing studies fall into three main approaches: 'retrospective', 'prospective', and 'emergent' business model innovation assessments.

'Retrospective' business model assessments focus on studying business model designs already implemented and analyze their impact on utilities and other electricity sector firms, implementations of this approach include: Richter (2013a) on business model options for the deployment of renewable energy technologies in general, and for solar PV in particular in Richter (2013b). Behrangrad (2015) reviewed and analyzed the key characteristics of existing business model designs for demand side management focusing on the energy efficiency and demand response services. Gabriel & Kirkwood (2016) on renewable energy firms' business models in developing countries to identify what impacts the choice of business model design. Karakaya et al. (2016) on solar PV firms business model challenges resulting from regulatory and policy adjustments to renewable energy incentives. Wainstein & Bumpus (2016) on business models for electricity sector incumbents and new entrants. Burger & Luke (2017) on firms operating in the distributed energy resources sector to identify the most common business models related with solar PV, electricity and thermal storage, demand response, and energy management systems.

'Prospective' business model assessments are future-oriented and focus on identifying, conceptualizing, and proposing suitable business model designs according to ongoing electricity sector trends. Implementations of this approach include: Fox-Penner (2014) on utility business model innovation pathways as evolving into either smart integrators, or service-oriented utilities. Oosterkamp et al. (2014) and Puente et al. (2014) studied the feasibility of integrating new activities in electricity distribution business operations as a result of smart grids and renewable energy diffusion. PwC (2014) conceptualized business model alternatives across the electricity sector value chain. Hall & Roelich (2016) on business model's innovation alternatives for local electricity retail firms. Hamwi & Lizarralde (2017) on service-oriented business models alternatives for the electricity sector. Taminiau et al. (2017) on the characteristics of sustainable business models for utilities. Cross-call et al. (2018) devised possible business model innovation pathways in electricity distribution considering alternatives for utilities, and third-party operators. Jamasb et al. (2018) proposed a business model alternative for electricity distribution utilities in developing countries.

'Emergent' business model assessments focus on the possibilities for business model innovation, rather than on a specific business model design, these studies focus on the ability to take the necessary actions that will drive adaptation. This approach provides valuable insights on transitions governance as this information can then be combined with ongoing discussions on technological and policy innovation, relevant to understand if the potential business model innovations are achievable. Studies following this approach include: Shah et al. (2013) and Nisar et al. (2013) analyzed the processes of renewable energy technology adoption by utilities as a source of insight on business model innovation. Worch et al. (2013) studied the impact of capabilities on utilities performance and emphasized their importance in supporting business model adaptation amidst changes in regulatory frameworks. Tackx & Meeus (2015) assessed ongoing pressures impacting the business model in electricity distribution and identified future trends in adaptation. Helms (2016) studied the current challenges of utilities asset transformation and transition to a service-oriented business model. Tayal & Rauland (2017) on the feasibility of business model innovations for utilities.

Among the identified approaches, 'retrospective' assessments concentrate on business model innovation mostly by considering technological shifts, such as diffusion of renewable energy technology, or demand response services. 'Prospective' assessments provide a broader perspective on the business model design and source of value creation, such as a shift to a more service-oriented business model in utilities. 'Emergent' assessments present a variety of approaches to understand business model innovation processes, informing how and under which circumstances business models are evolving.

While the concept and importance of business model innovation are well defined in the literature, as a process of continued adaptation for value creation, less attention has been given to support how these adaptations occur and how firms adjust their processes and activities when pursuing business model innovations (Achtenhagen et al., 2013). Additionally, despite the generalized agreement that adapting business models is the sensible action to take by firms to continuously create value amidst internal and external changes, less theoretical and empirical evidence on what supports such adaptation exists (Achtenhagen et al., 2013).

Applying a business model innovation conceptual framework to study DSOs adaptation amidst the ongoing smart and sustainable transition provides an analytical framework to evaluate their ability to transform their value creation processes. DSOs have predominantly created value by distributing electricity from large generation centers to consumers. However, growing diffusion of smart grids and renewable energy create framework conditions in which DSOs can expand or adjust their value creation model, with new possibilities associated to flexibility management, data analytics, and growing local energy markets.

5.3 Methodology

This section focuses on the methodology applied for this assessment. Section 5.3.1 describes the capabilities approach implemented. Section 5.3.2 presents the data characteristics. Lastly, Section 5.3.3 details the application of SEM as a causal relationship modelling method.

5.3.1. Capabilities approach implementation

This study contributes to the literature on utility business model innovation through a capability approach and aims to provide a better understanding on DSO adaptation in a rapidly changing electricity sector, driven by the ongoing smart and sustainability transition. The relevance of capabilities goes beyond their role in supporting business model innovation (Teece, 2017), (cf. section 5.2), as capabilities have gained relevance within sociotechnical transition studies, assumed their ability to assess the ability to convert resources towards sustainable development and value creation (Rauschmayer et al., 2015).

This assessment is supported by a conceptual model, which specifies the causal relationships considered to analyze the role of capabilities on business model innovation and adaptation, cf. Figure 5.1. The conceptual model developed hypothesizes an indirect relationship between dynamic capabilities and firms' performance, following theoretical and empirical findings from previous studies (Wang & Ahmed, 2007; Ambrosini & Bowman, 2009; Barreto, 2010; Zheng et al., 2011; Protogerou et al., 2012; Arifin & Frmanzah, 2015). DSOs dynamic capabilities, as a proxy of their ability to adapt to a rapidly changing market, are considered as encompassing: change foresight, learning and transformation capabilities. Operational capabilities include aspects related to both core electricity distribution operations, as well as smart grid distribution operations. In terms of performance, aspects related to: operational, innovation, and smart grid diffusion are considered.

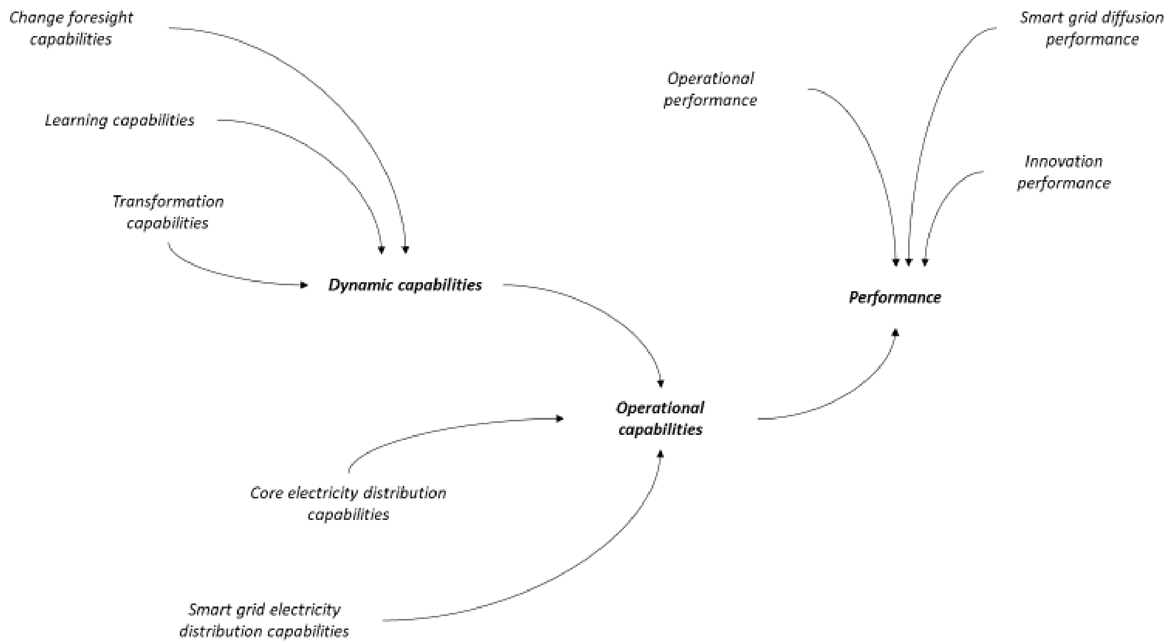

Figure 5.1 Capabilities assessment conceptual model

The conceptual model presented in Figure 5.1 is a general specification of the scope of the capabilities approach. The estimation of the hypothesized relationships was conducted using four models, which differ in terms of the performance measure considered, and are further described in the results section, cf. Section 5.4. Model 1 includes only electricity distribution operational performance. Model 2 includes only innovation performance. Model 3 includes only smart grid diffusion performance. Lastly, Model 4 synthesizes operational, innovation, and smart grid performance metrics into a business model innovation and adaptation performance measure.

The capabilities approach is implemented through a questionnaire designed to measure dynamic capabilities, operational capabilities, and performance of EU DSOs. Questionnaires are a common tool for data collection in capability assessments. The questionnaire applied in this study draws on a review of the literature on studies measuring firms' capabilities and studying their role in supporting adaptation and performance. Given that most studies using questionnaire approaches to measure capabilities have been developed without a specific industry focus, as is the case of this assessment focusing on DSOs, the proposed questionnaire was piloted and validated by a group of experts to strengthen its adequacy. Questionnaire piloting involved experts in energy policy and smart grids from academia and the electricity sector. Experts contributed improvements in wording and scope resulting in an adjusted final questionnaire. Appendix B provides detailed information on the questionnaire applied.

In terms of sample, this study aimed to engage all the electricity distribution companies in the EU, approximately 2 400 according to Eurelectric (2013). Firstly, each country NRA was contacted to obtain its list of DSOs. The information provided was used for desk-based research for DSO representatives and respective contact information. A novel database was generated that included 1 733 electricity distribution companies, with contact information for 3 860 DSO representatives. Multiple contacts were collected when available, to support a higher participation rate. The roles of the representatives for which contact information was collected included: chief executive officers (n = 583), network managers (n = 548), marketing executives (n = 100), and technology specialists (n = 78), among others. DSOs invitations for study participation and data collection ran between May 2017 and December 2017, via email using the communication platform MailChimp (Mailchimp, 2017). The questionnaire was distributed in electronic format using Qualtrics online service (Qualtrics, 2017).

5.3.2. Data characteristics

The questionnaire included measurement items for capabilities, both dynamic and operational, as well as operational performance, innovation performance and smart grid diffusion performance. The measurements used to collect data on dynamic capabilities were designed to assess DSOs ability to foresee change, learn, and transform their business model, cf. Table 5.1. These draw on dynamic capabilities literature (Teece & Pisano, 1994; Panda & Ramanathan, 1996; Teece, 2007; Rush et al., 2007; Alegre & Chiva, 2008; Fosfuri & Tribo, 2008; Guifu & Hongjia, 2009; Protogerou et al., 2012; Clausen, 2013; Janssen et al., 2016) but are particularly detailed for the changes impacting the electricity sector. To ensure these measurements reflected the ongoing sustainability transition each dimension (i.e.: change foresight, learning, and transformation) was structured to include aspects related to technology, policy, and business aspects associated to adaptation, as key components of transitions.

Table 5.1 Dynamic capabilities measurements

Change foresight capability [a]	
Technological	Identify technologies to improve the quality and efficiency of our operations Identify new technologies (e.g. smart metering, electric vehicle charging infrastructure, flexibility management, etc.)
Policy	Identify changes in policies and regulation to ensure the adequacy of our business strategy Influence policies and regulation to be aligned with our business strategy
Business model	Identify system changes (e.g. understanding the impact of distributed generation, the impact of the current DSO-TSO relationship, etc.) Identify the changing needs of grid users (e.g. accommodating the increasing number of smart homes, residential storage units, electric vehicles, etc.)
Learning capability [a]	
Technological	Understand the implications of smart grid technologies Learn to integrate new technologies
Policy	Understand the impact of policy and regulatory changes on our business Identify ways to adapt our business strategy to fit policy and regulatory requirements
Business model	Identify the resources needed to adapt our business strategy Identify the business areas that require adaptation
Transformation capability [a]	
Technological	Adapt our organization to use new technologies (e.g. teams, responsibilities, departments, strategy, resource allocation, etc.) Change our business to use new technologies
Policy	Adapt our activities and responsibilities given policy and regulatory changes Implement business changes to explore opportunities from policy and regulatory changes
Business model	Systematically analyze future strategies as we move toward a smarter grid environment Develop flexible organizational practices that adapt to our business model and strategy

[a] Measured through a 6-point Likert scale: (1) Not capable at all, (2) Slightly capable, (3) Moderately capable, (4) Capable, (5) Very capable, (6) Extremely capable

The measurements used to collect data on operational capabilities were designed to assess both DSOs core capabilities, and smart gird capabilities, cf. Table 5.2. The indicators used draw on general measures of firms' operational capabilities from the literature (Panda & Ramanathan, 1996; Wang et al., 2006; Ortega, 2010; Su et al., 2010; Hao & Yu, 2012; Reichert & Zawislak, 2014), further specified for electricity distribution operations. The ongoing transition of electricity distribution toward smart grids further enhanced the need to understand the extent to which DSOs have developed capabilities in this domain, in addition to its more traditional network operation, maintenance, and expansion capabilities, which motivated the development of both core and smart grid capability measurements for this study.

Table 5.2 Operational capabilities measurements

Core electricity distribution capabilities [a]
Operate our grid to provide an efficient and reliable service
Monitor our grid and detect faults
Conduct grid maintenance to avoid or solve faults
Provide high quality service to all grid users
Reinforce and expand our grid infrastructure in a timely manner
Smart grid electricity distribution capabilities [a]
Integrate distributed generation technologies (e.g. solar PV and wind)
Integrate DSO-owned electricity storage technologies for grid management
Integrate grid user-owned electricity storage technology for grid management
Integrate electric vehicles charging infrastructure
Own electric vehicles charging infrastructure
Manage or facilitate system flexibility by coordinating distributed generation
Manage or facilitate system flexibility by triggering demand response actions
Manage or facilitate system flexibility by coordinating distributed electricity storage
Deploy smart meters for all connected consumers
Own smart meter infrastructure
Conduct planning and asset management adequate for a smarter grid future

[a] Measured through a 6-point Likert scale: (1) Not capable at all, (2) Slightly capable, (3) Moderately capable, (4) Capable, (5) Very capable, (6) Extremely capable.

The measurements related to performance were designed to collect data on operational, innovation, and smart grid diffusion engagement related performance. Operational performance indicators focus on electricity distribution service operations. Innovation performance indicators measure the firms' engagement in innovation activities. Smart grid diffusion indicators measure the level of engagement in smart grid deployment.

Table 5.3 Operational, innovation, and smart grid performance measurements

Operational performance [a]
Improved cost efficiency
Improved service quality and reliability indicators (e.g. SAIFI, SAIDI)
Improved general performance across departments

[a] Measured through a 6-point Likert scale: (1) Strongly disagree, (2) Disagree, (3) Somewhat disagree, (4) Somewhat agree, (5) Agree, (6) Strongly agree

Innovation performance [a]	
Explorative innovation	Introduced technologies, processes or practices that are new to the electricity distribution sector Started experimenting with innovative technologies in our operations
Exploitative innovation	Improved our ability to increase quality of service Improved our ability to increase cost efficiency of our operations

[a] Measured through a 6-point Likert scale: (1) Strongly disagree, (2) Disagree, (3) Somewhat disagree, (4) Somewhat agree, (5) Agree, (6) Strongly agree

Smart grid diffusion performance	
We solve most of the grid challenges	(1) at the planning stage (2) at the operational stage (3) across planning and operational stages
Our main grid management practice is to	(1) plan sufficient grid capacity to deal with changing system demands (2) restrict distributed generation injections to manage grid congestion (3) manage distribution system flexibilities
Considering smarter distribution operations	(1) we are aware of the opportunities (2) we are experimenting with new processes, technologies, and practices (3) we have integrated smart grid technologies (e.g. smart meters, electric vehicle charging infrastructure, distributed generation, automation devices)
In terms of engagement in smart grids diffusion	(1) we consider the possibilities for becoming more engaged in the deployment of smart grids (2) we observed operational improvements from deploying a smarter distribution grid (3) our processes, technologies, and practices reflect an extensive engagement in the deployment and facilitation of smart grids
Our investments in a smarter distribution grid are	(1) residual (2) moderate (3) substantial

In addition to the measurements on dynamic capabilities, operational capabilities, and performance, characteristics of the participating DSOs were also obtained, including operational and regulatory characteristics, Table 5.4.

Table 5.4 Operational and regulatory framework measurements

<table>
<tr><th colspan="2">Indicator</th><th colspan="2">Measurement</th></tr>
<tr><td colspan="4">Electricity distribution operations</td></tr>
<tr><td>Connected consumers in 2016</td><td>(1) 1 to 50 000
(2) 50 000 to 150 000
(3) 150 000 to 350 000
(4) 350 000 to 1 000 000
(5) 1 000 000 to 2 000 000
(6) 2 000 000 to 5 000 000
(7) Over 5 000 000</td><td>Years' operating in the electricity distribution sector</td><td>(1) Up to 5
(2) 5 to 20
(3) 20 to 50
(4) Over 50</td></tr>
<tr><td colspan="4">Regulatory environment</td></tr>
<tr><td colspan="2">Allows us to perform new roles
Allows for new investments to be conducted to explore new roles
Encourages innovation
We find it easy to adapt to the demands of the regulatory framework</td><td colspan="2">(1) Strongly disagree
(2) Disagree
(3) Somewhat disagree
(4) Somewhat agree
(5) Agree
(6) Strongly agree</td></tr>
</table>

5.3.3. Modelling method

The conceptual model developed for this study, Figure 5.1, was analyzed using Structural Equations Modelling (SEM), which encompasses a set of statistical methods to study causal effects, applicable to theory and empirically derived models (Hayduk et al., 2007). As a causal inference method, SEM can be characterized through its main inputs and outputs (Kline, 2015). The inputs include: a theory or empirically derived assessment model of causal relationships to be tested with data; and a set of questions regarding the causal relationships between the variables included in the conceptual model. The outputs include: quantitative estimates of the model relationships; and measures to evaluate the quality of the model given the input data. The specification of the direction of relationships between variables in the models positions SEM mainly as a confirmatory method, for which there is some flexibility in cases when various models can be drawn from theory or empirical evidence, making it also suitable for exploratory studies. SEM supports the use of observed and latent variables. Observed variables represent those for which data can be directly collected. Latent variables represent those for which a direct measurement is not possible, and that require a series of measurements to obtain an approximate measurement (Hoyle, 1995; Kline, 2015). This study benefits from this method as the capabilities and performance data used represent latent variables[9].

[9] Model estimation was conducted using the R package 'lavaan' (Rosseel, 2012). The 'lavaan' package is a bundle of tools for latent variable statistical analyses, which combines the capabilities of commercial software, such as LISREL, Mplus, EQS, and AMOS, in an open-source environment.

A structural equations model includes two components: a measurement model, representing the relationships between measured variables and the associated latent variables these measured variables aim to represent; and a structural relationships model, representing the causal relationships hypothesized to be estimated.

As a statistical toolkit to explore the relationship between variables SEM is related with other well established statistical analysis methods, namely, exploratory and confirmatory factor analysis (EFA and CFA), analysis of variance (ANOVA), and multiple regression analysis (Hoyle, 2012), as a SEM model can be used to conduct any of these. The advantages of using SEM are related to its integrated approach to these individual statistical tools. In addition, SEM extends the possibilities to establish causal relationships when estimating a model, more limited in ANOVA and multiple regression analyses.

Model representation in SEM can be carried with path diagrams, as presented in Figure 5.2, which depicts the main components of a SEM model as specified in Hoyle (2012: 6). In this model Y is an outcome of X. Y and X are latent variables, in which Y is defined by the measured variables y_1, y_2, and y_3, and X is defined by the measured variables x_1, x_2, x_3, and x_4. The measured variables, x1 to x4, and y1 to y3, can result from the implementation of questionnaires, behavioral observations, physical aspects, to name a few, all of which are assumed to reflect the latent variables X and Y respectively.

The regression part of the model involves only the unobserved latent variables, represented by circle shapes, and often referred to as factors. The latent variables represent the commonality among the measured variables, represented by square shapes. The variance of each measured variable, the indicators, results in one hand from the latent variable to which it is associated, and on the other hand from the measured variable uniqueness, represented by small circle shapes. One-headed arrows indicate the model's directional effects, and double headed arrows indicate the model's variances. The star symbols are the parameters to be estimated during the modelling process, these include the regression coefficient from X to Y, the factor loadings from the indicator variables to the factors, the uniqueness of each indicator variable, and the error of the regression at Y.

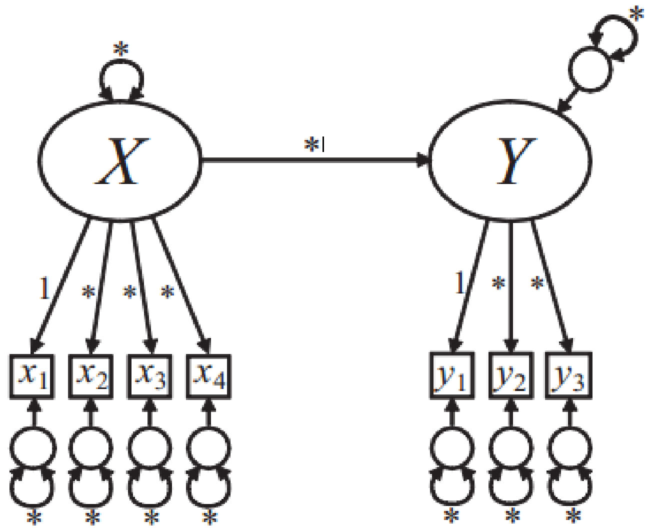

Figure 5.2 SEM model path diagram

Source: (Hoyle, 2012: 6)

For this study the implementation of this modelling framework follows the steps presented in Figure 5.3. Model specification resulted in the conceptual model presented in Figure 5.1. Data was collected through self-reporting questionnaires including the measurements described in section 5.3.2. The data collection in this study involved an intense effort with over 40 000 contacts made with the DSO representatives identified to participate in this study. A sample of n = 129 DSO responses was obtained, which falls within the minimum sample sizes observed in the literature, with samples ranging n = 125 to 200 in a review conducted by Shah & Goldstein (2006), and minimum samples sizes indicated in the order of n = 100 (Kline, 2015). While larger samples are encouraged for SEM analyses, modelling with n < 200 cases has been supported for cases in which access to the study's population, or the population size itself is restricted to the hundreds or thousands cases, as is the case of the electricity distribution firms' population in which this assessment focuses (Gignac, 2006; Barrett, 2007; Hair et al., 2014).

The impact of sample size on model fit and estimation results has been considered in simulation studies, which have indicated small samples only adequate for models with low complexity, also suggesting that studies with small samples can benefit from increased number of observed variables in the estimated models (Wolf et al., 2013). As SEM practice evolves the possibilities for using SEM with smaller samples are further being considered and new modelling tools developed (Jiang & Yuan, 2017).

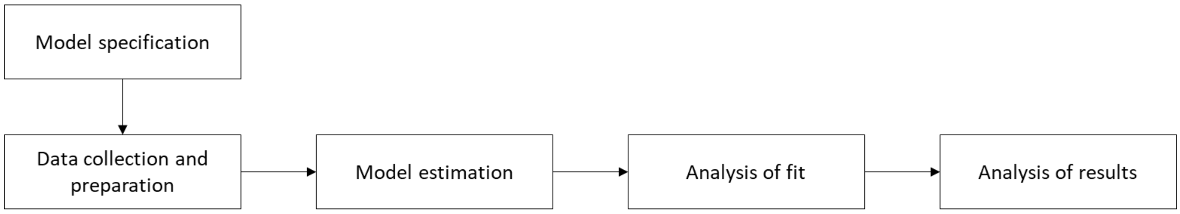

Figure 5.3 Modelling implementation steps
Source: Elaboration based on Hoyle (2012)

Estimation through Path Analysis was considered as an alternative approach to estimate the conceptualized causal relationships in the specified models, given its ability to deal with smaller samples. However, while this study is based on recent literature on the role of capabilities on business model innovation and could be regarded as a confirmatory approach, it is also an electricity distribution industry specific exploratory application. Therefore, a SEM model with latent variables allows to incorporate the possible imperfection of the measurements used to assess capabilities and performance constructs in the electricity sector.

An important aspect in SEM modelling is model fit evaluation, which indicates the extent to which the hypothesized causal relationships is supported by the data. The assessment of model fit in SEM is done through model test statistics and approximate fit indexes. This study reports on the following fit measures as guidance to model evaluation, Table 5.5. A model presenting fit indexes out of the presented cut-off criteria is recommended to be rejected, due to a poor fit of the hypothesized model to the data being used. However, the literature on the assessment of model fit through fit indexes is diverse and includes different suggestions on cut-off ranges. Considering that fit indices can be biased by sample sizes, data characteristics, and model specification, this study presents fit indices for both the original sample and fit indices resulting from Bollen-Stein bootstrapped samples, which has been found to reduce false model rejection (Hoyle, 2012), and has been applied in studies with small samples (Nevitt & Hancock, 2001; Ievers-Landis et al., 2011; Kim & Millsap, 2014). Additionally, a growing understanding in the SEM community suggests that theory needs to be the main driver of SEM models, and not the search for perfect fit indices, as models with good fit may be of small value to advance knowledge, and models with modest fit may result in relevant insights for developing theory and practice (Beaujean, 2014; Kline, 2015).

Table 5.5 Model fit assessment

χ^2	χ^2/df	**Comparative Fit Index (CFI)**	**Tucker-Lewis Index (TLI)**	**Incremental Fix Index (IFI)**	**Root Mean Square Error of Approximation (RMSEA)**	**Standardized Root Mean Error of Approximation (SRMR)**
P-value >0.05	>5 Poor,]2; 5] Acceptable]1; 2] Good ~1 Excellent	<0.8 Poor [0.80;0.90[Acceptable [0.90;0.95[Good ≥0.95 Excellent			>0.1 Poor]0.05;0.10] Good ≤0.05 Excellent	≤.06 Excellent ≤.08 Good ≤.1 Acceptable ≥.1 Bad

Source: Elaborated based on Hu & Bentler (1999); McDonald & Ho (2002); Schreiber et al. (2006); Hooper et al. (2008); and Hoyle (2012)

Robust Maximum Likelihood estimation with Satorra-Bentler correction was used for model estimation, providing an adjusted Chi-square (χ^2) statistic and robust standard errors, recommended for ordinal observed variables and also suitable in studies with small samples (Bentler & Yuan, 1999; Hu & Bentler, 1999; Hoyle, 2012; Li, 2016). This type of estimation has been found to minimize biased chi-square statistics, factor loadings, and standard errors, given that it is less dependent on the assumption of multivariate normal distribution (Beaujean, 2014; Li, 2016).

5.4 Results

This section presents the results obtained. The measurement model section presents the reliability analysis and provides information on the individual and composite reliability of the measurements used. The structural model section presents the results for the estimations resulting from the conceptual models proposed.

The 129 DSO responses obtained represent 27 EU countries (Table 5.6).

Table 5.6 DSOs region and country

Region	n	%	Country	n
Eastern Europe	19	15%	Bulgaria	3
			Croatia	1
			Czech Republic	2
			Hungary	1
			Poland	3
			Romania	4
			Slovakia	1
			Slovenia	4
Northern Europe	49	38%	Denmark	2
			Estonia	3
			Finland	28
			Latvia	2
			Lithuania	1
			Sweden	13
Southern Europe	15	12%	Greece	1
			Italy	3
			Malta	1
			Portugal	1
			Spain	9
Western Europe	41	32%	Austria	4
			Belgium	2
			France	4
			Germany	13
			Ireland	1
			Luxembourg	1
			Netherlands	7
			United Kingdom	9
Other	5	4%	Other	5
		Total		**129**

In addition to the regional diversity of the participating DSOs Table 5.7 presents the sample distribution in terms of connected consumers and years' operating in the electricity sector.

Table 5.7 DSOs operational characteristics

Connected consumers	n	%
1 to below 50 000	27	21%
50 000 to below 150 000	10	8%
150 000 to below 350 000	8	6%
350 000 to below 1 000 000	53	41%
1 000 000 to below 2 000 000	7	5%
2 000 000 to below 5 000 000	11	9%
Over 5 000 000	13	10%
Total	**129**	

Years' operating in the electricity sector	n	%
Up to 5	-	-
5 to below 20	11	9%
20 to below 50	11	9%
Over 50	107	83%
Total	**129**	

5.4.1. Measurement model

The measurement model corresponds to the relationship between the measured data and the latent variables these represent. Confirmatory Factor Analysis (CFA) was used to estimate the quality of the measurements used in this study. CFA was conducted for the dynamic capability measurements: change foresight capability, learning capability, and transformation capability; operational capability measurements: core electricity distribution capabilities, and smart grid electricity distribution capabilities; and performance measurements: operational performance, innovation performance, and smart grid diffusion performance. CFA was also conducted for the control variable: regulatory framework.

The measurements used to collect data on smart grid electricity capabilities were developed specifically for this study and tested with industry and academic experts, however the measurements did not represent a single smart grid capability dimension as initially hypothesized. Given this and to understand the underlying structure of the variables the measurements were analyzed with Exploratory Factor Analysis (EFA), cf. Table 5.8, from which three distinct factors were identified, and according to the measurements associated named as: smart grid management (Factor 1), smart grid integration (Factor 2), and smart grid deployment (Factor 3). The identified factor structure is valuable as it provides a more detailed structure of smart grid capabilities to be considered in this assessment.

Table 5.8 Exploratory factor analysis on operational capabilities: smart grid electricity capabilities

Measured item	Factor		
	1	2	3
Integrate DSO-owned electricity storage technologies for grid management	0.70		
Integrate grid user-owned electricity storage technology for grid management	0.59		
Manage or facilitate system flexibility by coordinating distributed generation	0.71		
Manage or facilitate system flexibility by triggering demand response actions	0.73		
Manage or facilitate system flexibility by coordinating distributed electricity storage	0.92		
Conduct planning and asset management adequate for a smarter grid future	0.45		
Integrate distributed generation technologies (e.g. solar PV and wind)		0.78	
Integrate electric vehicles charging infrastructure		0.76	
Own electric vehicles charging infrastructure		0.64	
Deploy smart meters for all connected consumers			0.77
Own smart meter infrastructure			0.96
Cumulative explained variance	28.96	46.48	62.8
Eigenvalue	4.71	1.73	1.41

Estimation: Maximum Likelihood, Rotation: Varimax, Factor retention criterion: Eigenvalue > 1

Table 5.9 shows the results of the individual-item reliability analysis: factor loadings, and the communality (R^2) of each measured variable to the respective latent variable. Factor loadings range between 0.43 and 0.95, above the cut-off of 0.4 applied in the literature (Walker & Maddan, 2009). The communalities represent the amount of variance shared across variables, the communalities for the measurements in this study range between 0.19 and 0.91, communalities above 0.5 are recommended (Kline, 2015), and communalities above 0.25 are considered acceptable. One of the variables related to the regulatory environment does not meet the cut-off limit, however it was retained and used as a control variable in analyses.

Table 5.9 Confirmatory factor analysis results

Measured item	Factor loading	R^2
Dynamic capabilities		
Change foresight capability		
Identify technologies to improve the quality and efficiency of our operations	0.75 [a]	0.57
Identify new technologies (e.g. smart metering, electric vehicle charging, flexibility management, etc.)	0.77	0.60
Identify changes in policies and regulation to ensure the adequacy of our business strategy	0.81	0.65
Influence policies and regulation to be aligned with our business strategy	0.64	0.40
Identify system changes (e.g. understanding the impact of distributed generation, DSO-TSO relationship, etc.)	0.79	0.63
Identify the changing needs of grid users (e.g. accommodating smart homes, residential storage, electric vehicles.)	0.83	0.68
Learning capability		
Understand the implications of smart grid technologies	0.76 [a]	0.58
Learn to integrate new technologies	0.73	0.54
Understand the impact of policy and regulatory changes on our business	0.82	0.68
Identify ways to adapt our business strategy to fit policy and regulatory requirements	0.84	0.70
Identify the resources needed to adapt our business strategy	0.88	0.77
Identify the business areas that require adaptation	0.82	0.68
Transformation capability		
Adapt our organisation to use new technologies (e.g. teams, responsibilities, strategy, resource allocation, etc.)	0.87 [a]	0.73
Change our business to use new technologies	0.84	0.71
Adapt our activities and responsibilities given policy and regulatory changes	0.77	0.60
Implement business changes to explore opportunities from policy and regulatory changes	0.87	0.76
Systematically analyse future strategies as we move toward a smarter grid environment	0.78	0.60
Develop flexible organisational practices that adapt to our business model and strategy	0.83	0.69
Operational capabilities		
Core capabilities		
Operate our grid to provide an efficient and reliable service	0.79 [a]	0.63
Monitor our grid and detect faults	0.54	0.29
Conduct grid maintenance to avoid or solve faults	0.67	0.45
Provide high quality service to all grid users	0.74	0.55
Reinforce and expand our grid infrastructure in a timely manner	0.72	0.52
Smarter distribution grid capabilities		
Smart grid management		
Integrate DSO-owned electricity storage technologies for grid management	0.71 [a]	0.45
Integrate grid user-owned electricity storage technology for grid management	0.68	0.47
Manage or facilitate system flexibility by coordinating distributed generation	0.77	0.59
Manage or facilitate system flexibility by triggering demand response actions	0.78	0.61
Manage or facilitate system flexibility by coordinating distributed electricity storage	0.89	0.79
Conduct planning and asset management adequate for a smarter grid future	0.53	0.28

Measured item	Factor loading	R^2
Smart grid integration		
Integrate distributed generation technologies (e.g. solar PV and wind)	0.69 [a]	0.47
Integrate electric vehicles charging infrastructure	0.92	0.84
Own electric vehicles charging infrastructure	0.71	0.51
Smart grid deployment		
Deploy smart meters for all connected consumers	0.92 [a]	0.85
Own smart meter infrastructure	0.84 [a]	0.70
Performance		
Electricity distribution operational performance		
Improved cost efficiency	0.78 [a]	0.60
Improved service quality and reliability indicators (e.g. SAIFI, SAIDI)	0.73 [a]	0.53
Improved general performance across departments	0.69	0.47
Innovation performance		
Innovation exploration		
Introduced technologies, processes or practices that are new to the electricity distribution sector	0.95 [a]	0.91
Started experimenting with innovative technologies in our operations	0.79 [a]	0.64
Innovation exploitation		
Improved our ability to increase quality of service	0.87 [a]	0.76
Improved our ability to increase cost efficiency of our operations	0.91 [a]	0.81
Smart grid diffusion performance		
Smarter distribution operations	0.59 [a]	0.35
Engagement in smart grids diffusion	0.57 [a]	0.33
Investments in a smarter distribution grid	0.76 [a]	0.58
Control		
Regulatory environment		
Allows us to perform new roles	0.91 [a]	0.84
Allows for new investments to be conducted to explore new roles	0.87 [a]	0.75
Encourages innovation	0.43	0.19

[a] Marker variable.

Table 5.10 presents the results of the composite reliability analysis for the latent variables, and indicates the latent variables used in each model. The model Cronbach α is 0.95, above the 0.7 recommended value, and the Average Variance Extracted is 0.6, above the 0.5 value recommended in the literature (Hair et al., 2014).

Table 5.10 Composite reliability of the latent variables

Latent variable	Cronbach α	Average Variance Extracted	Used in Model			
			1	2	3	4
Change capability	0.90	0.58	✓	✓	✓	✓
Learn capability	0.93	0.65	✓	✓	✓	✓
Transformation capability	0.93	0.68	✓	✓	✓	✓
Core distribution capability	0.82	0.49	✓	✓	✓	✓
Smart grid deployment	0.87	0.77	✓	✓	✓	✓
Smart grid integration	0.80	0.60	✓	✓	✓	✓
Smart grid management	0.87	0.55	✓	✓	✓	✓
Distribution performance	0.78	0.54	✓			✓
Innovation exploration performance	0.86	0.74		✓		✓
Innovation exploitation performance	0.88	0.79		✓		✓
Smart grid diffusion performance	0.66	0.39			✓	✓
Regulatory environment	0.76	0.57	✓	✓	✓	✓
Total	**0.95**	**0.60**				

Discriminant validity was also analyzed for the latent variables used in the model, which aims at validating the significance of adding each latent variable for model estimation. Hair et al. (2014) indicates that when two or more latent variables have correlations above 0.90 these represent significantly overlapping constructs and consequently multicollinearity. High correlations, > 0.9, were identified between the latent variables related to dynamic capabilities, Table 5.11.

Table 5.11 Correlation matrix between dynamic capability latent variables

	Change capability	Learn capability	Transformation capability
Change capability	1.00		
Learn capability	0.96	1.00	
Transformation capability	0.90	0.97	1.00

As the highly correlated latent variables were theoretically derived and designed to measure dynamic capabilities, a second order latent was implemented to represent: change, learn, and transformation capabilities. Factor loadings for the second order construct implemented were:

0.91 for change capability, 0.99 for learning capability, and 0.94 for transformation capability. Following a similar approach, a second-order latent variable is implemented to be used in Model 4, which hypothesizes the role of capabilities for business model innovation and adaptation. Business model innovation and adaptation is implemented as a second-order latent to represent: distribution performance, innovation exploration performance, innovation exploitation performance, and smart grid diffusion performance. Factor loadings for the second order construct implemented were: 0.7 for distribution performance, 0.83 for innovation exploration performance, 0.89 for innovation exploitation performance, and 0.69 for smart grid diffusion performance. After considering both dynamic capabilities and business model innovation as second-order latent variables the correlations among latent variables range between -0.16 and 0.75, indicating the added value of each individual latent variable being considered in this study.

Preceding model estimation with the hypothesized causal relationships, full confirmatory factor analyses where conducted for each model. In these analyses all the latent variables considered in each model are included in a confirmatory factor analysis were no causal relationships between the latent variables are considered.

Table 5.12 Model fit statistics for full confirmatory factor analyses

Model	**(χ^2) (df)**	**χ^2/df**	**CFI**	**TLI**	**IFI**	**RMSEA**	**SRMR**
1	1147.95*** (710)	1.62	0.867	0.854	0.849	0.069 [a]	0.085
2	1197.09*** (743)	1.61	0.868	0.854	0.85	0.069 [b]	0.084
3	1151.79*** (711)	1.62	0.866	0.853	0.85	0.069 [c]	0.085
4	1535.89*** (1004)	1.53	0.857	0.847	0.834	0.064 [d]	0.086

*** p < 0.001, ** p < 0.05 **, * p < 0.1

[a] 90% CI [0.062, 0.076], [b] 90% CI [0.062, 0.075], [c] 90% CI [0.062, 0.076], [d] 90% CI [0.058, 0.070]

The resulting fit statistics for the four models being considered indicate a general adequate model fit, Table 5.12. An insignificant χ^2 test statistic (p >.0.05) is suggested as necessary to accept the model fit, this is not obtained in the models being tested, however this measure of fit has been found to be biased to small sample sizes, and it is recommended to be considered among other fit metrics. Conversely, the normed χ^2/df presents values < 2 indicating adequate model fit (Hoyle, 2012; Kline, 2015).

5.4.2. Structural model

This section presents the results for the causal relationship estimations for the four hypothesized models. The general conceptual model previously presented is now specified considering the latent variables and causal relationships being analyzed in each model, Figure 5.4. The four models have in common the causal paths hypothesizing a positive relationship between dynamic capabilities and operational capabilities (i.e.: core capabilities, smart grid deployment, smart grid integration, and smart grid management), hypotheses $(H1a_{M1\ to\ M4})$ to $(H1d_{M1\ to\ M4})$. The difference between the models is related to the different outcome latent variable being considered in each case. Model 1 hypothesizes positive relationships between operational capabilities and operational performance, hypotheses $(H2a_{M1})$ to $(H2d_{M1})$. Model 2 hypothesizes positive relationships between operational capabilities and innovation approaches, measured through innovation exploration, hypotheses $(H2a1_{M2})$ to $(H2d1_{M2})$, and innovation exploitation, hypotheses $(H2a2_{M2})$ to $(H2d2_{M2})$,. Model 3 hypothesizes positive relationships between operational capabilities and smart grid diffusion performance, hypotheses $(H2a_{M3})$ to $(H2d_{M3})$. Lastly, Model 4 combines the outcome variables used in Model 1, Model 2 and Model 3 and synthesizes it in a latent variable as a representative measure of business model innovation and adaptation, for which a positive relationship between operational capabilities and business model innovation is hypothesized, $(H2a_{M4})$ to $(H2d_{M4})$.

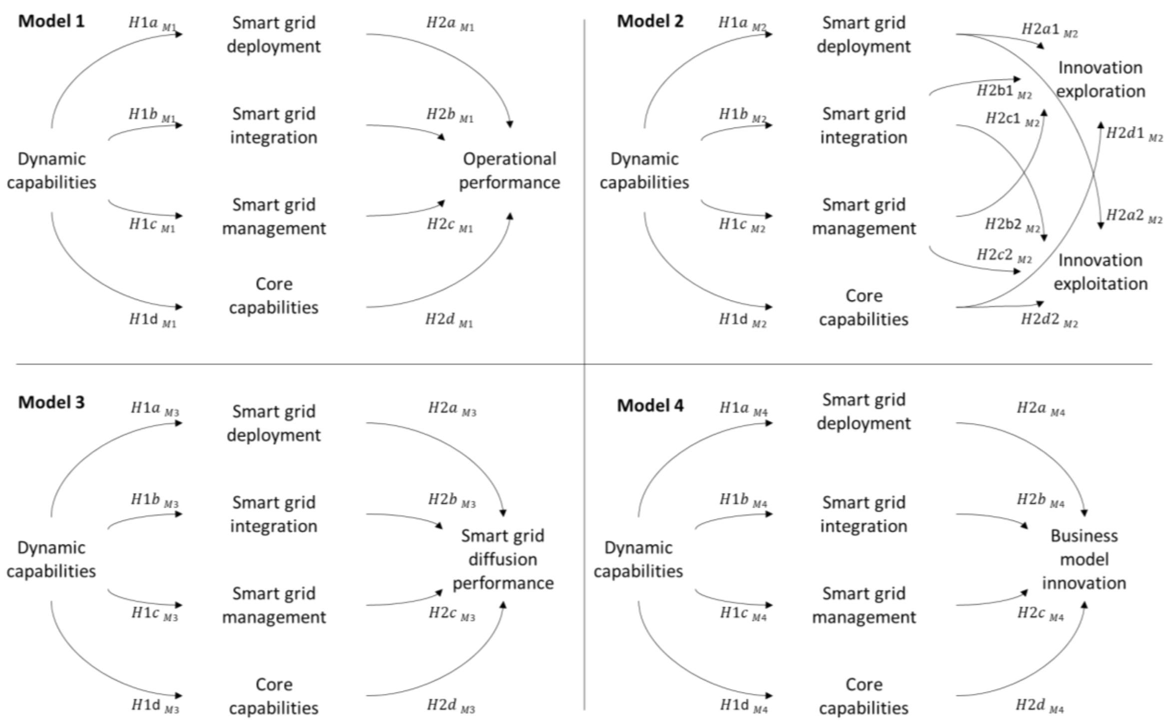

Figure 5.4 Structural equation models

The fit indexes resulting from the structural model estimation indicate an adequate fit of the four models to the data. Table 5.13 presents the fit indexes obtained from the original sample, and fit indexes obtained using the Bollen-Stein bootstrap method, using 250 bootstrapped samples, indicated as sufficient by Nevitt & Hancock (2001).

Table 5.13 Model fit statistics for structural models

M	Sample	(χ^2) (df)	χ^2/df	CFI	TLI	IFI	RMSEA	SRMR
1	Original sample	1283.159***(799)	1.61	0.857	0.846	0.837	0.069 [b]	0.105
	Bootstrapped samples[a]	1094.170**(808)	1.35	0.918	0.913	0.920	0.050	0.062
2	Original sample	1342.598***(833)	1.61	0.85	0.837	0.837	0.069 [c]	0.105
	Bootstrapped samples	1150.10**(833)	1.38	0.920	0.913	0.921	0.051	0.062
3	Original sample	1299.079***(800)	1.62	0.853	0.842	0.837	0.070 [d]	0.101
	Bootstrapped samples	1073.76*(800)	1.34	0.924	0.919	0.926	0.048	0.063
4	Original sample	1724.481***(1107)	1.56	0.837	0.827	0.815	0.066 [e]	0.111
	Bootstrapped samples	1590.84**(1107)	1.44	0.888	0.882	0.890	0.056	0.066

*** p < 0.001, ** p < 0.05 **, * p < 0.1

[a] Method: Bollen-Stein. Samples drawn per model *B* = 250, following Nevitt & Hancock (2001)

[b] 90% CI [0.062, 0.075], [c] 90% CI [0.062, 0.075], [d] 90% CI [0.063, 0.076], [e] 90% CI [0.060, 0.071]

The estimation of the structural models provided quantitative estimates for the causal relationships being analyzed, presented in Table 5.14, which includes the non-standardized effects (B), standardized effects (β), and standard errors of each model ($\sigma_{\bar{x}}$).

Exploring the common structural paths in the four models that hypothesized a positive relationship between dynamic and operational capabilities, the results obtained consistently confirm this effect. From the estimates obtained in Model 1, dynamic capabilities present a statistically significant positive effect on: smart gird deployment ($\beta\ H1a_{M1} = 0.38$), smart grid integration capabilities ($\beta\ H1b_{M1} = 0.61$), smart grid management ($\beta\ H1c_{M1} = 0.58$), and on core electricity distribution capabilities ($\beta\ H1d_{M1} = 0.67$), these effects are observed across the four models.

In terms of model specific structural paths, Model 1, focusing on operational electricity distribution performance, statistically significant positive effects were obtained for smart grid integration ($\beta\ H2b_{M1} = 0.17$), and for core electricity distribution capabilities ($\beta\ H2d_{M1} = 0.30$) on electricity distribution operational performance. However, no statistically significant positive effect was obtained for smart grid deployment capabilities, and smart grid management presented a non-significant negative effect. For Model 1 the control variable related to connected consumers presented also a significant positive effect ($\beta\ = 0.23$).

In model 2, focusing on innovation performance, a statistically significant positive effect was observed for core electricity distribution capabilities on both innovation exploration ($\beta\ H2d1_{M2} = 0.30$) and innovation exploitation ($\beta\ H2d2_{M2} = 0.38$). In terms of innovation exploration, no statistically significant positive effect was identified for smart grid deployment and smart grid management capabilities, and a non-significant negative effect between smart grid integration was observed. In terms of innovation exploitation, no statistically significant positive effect was identified for smart grid deployment and smart grid integration capabilities, and a non-significant negative effect between smart grid management was observed. For innovation exploration a positive effect is identified for both connected consumers ($\beta = 0.38$) and firms' age ($\beta = 0.18$) control variables, while for innovation exploitation only connected consumers presented a positive effect ($\beta = 0.22$).

For model 3, focusing on smart grid diffusion performance, statistically significant positive effects were identified for smart grid deployment ($\beta\ H2a_{M3} = 0.31$), and for core electricity distribution ($\beta\ H2d_{M3} = 0.28$). In this model no significant direct effects were found for smart grid integration, and a non-significant negative effect was observed for smart grid management capabilities. In this case, connected consumers have also a significant positive effect on smart grid diffusion ($\beta = 0.49$).

Model 4, focusing on overall business model innovation by combining measures of operational, innovation exploration, innovation exploitation, and smart grid diffusion performance, statistically significant positive results were obtained for core electricity distribution ($\beta\ H2d_{M4} = 0.42$). No statistically significant effects were observed for smart grid deployment, management, and integration. In terms of control variables, connected consumers were found to have a positive significant effect on business model innovation ($\beta = 0.40$).

For the four hypothesized models, the statistically significant results obtained are in line with the hypothesized positive relationships. The non-significant effects follow also the generally hypothesized positive relationship, except for smart grid management negative effect on operational performance, innovation exploitation, smart grid diffusion, and business model innovation, as well as the smart grid integration negative effect on innovation exploration.

Across the four models, 'connected consumers' was found to have a significant positive effect for the different outcome variables being considered. The effect of the firms' age was mostly insignificant, except for the effect on innovation exploration. Additionally, no significant relationship was observed for the control variable associated with the regulatory environment.

Table 5.14 Structural model estimation results

Effects	Model 1			Model 2						Model 3			Model 4		
	B	**$\sigma_{\bar{x}}$**	**β**	**B**	**$\sigma_{\bar{x}}$**	**β**	**B**	**$\sigma_{\bar{x}}$**	**β**	**B**	**$\sigma_{\bar{x}}$**	**β**	**B**	**$\sigma_{\bar{x}}$**	**β**
of ↓ on →	**Operational performance**			**Innovation exploration**			**Innovation exploitation**			**Smart grid diffusion**			**Business model innovation**		
Smart grid deployment	0.03	0.04	0.06	0.03	0.07	0.03	0.02	0.05	0.03	0.11	0.03	0.31***	0.03	0.03	0.10
Smart grid integration	0.12	0.06	0.17**	-0.13	0.09	-0.10	0.01	0.08	0.01	0.07	0.05	0.13	0.01	0.04	0.03
Smart grid management	-0.10	0.06	-0.18	0.03	0.10	0.03	-0.04	0.08	-0.05	-0.06	0.04	-0.14	-0.03	0.04	-0.08
Core electricity distribution	0.25	0.10	0.3**	0.42	0.16	0.30**	0.42	0.15	0.38**	0.17	0.06	0.28**	0.23	0.08	0.42**
Connected consumers	0.06	0.03	0.23**	0.18	0.05	0.38***	0.08	0.04	0.22**	0.10	0.02	0.49***	0.07	0.02	0.40***
Firm age	-0.01	0.09	-0.01	0.26	0.14	0.18*	0.19	0.13	0.17	0.03	0.07	0.06	0.09	0.06	0.16
Regulatory environment	0.02	0.06	0.03	0.17	0.11	0.17	0.08	0.08	0.10	0.03	0.04	0.08	0.06	0.04	0.15
Dynamic capabilities	**Smart grid deployment**			**Smart grid deployment**						**Smart grid deployment**			**Smart grid deployment**		
	0.61	0.12	0.38***	0.61	0.12	0.38***				0.61	0.12	0.38***	0.61	0.12	0.38***
	Smart grid integration			**Smart grid integration**						**Smart grid integration**			**Smart grid integration**		
	0.65	0.10	0.61***	0.64	0.10	0.59***				0.64	0.10	0.60***	0.64	0.10	0.59***
	Smart grid management			**Smart grid management**						**Smart grid management**			**Smart grid management**		
	0.84	0.15	0.58***	0.84	0.15	0.59***				0.84	0.15	0.60***	0.84	0.15	0.59***
	Core electricity distribution			**Core electricity distribution**						**Core electricity distribution**			**Core electricity distribution**		
	0.63	0.08	0.67***	0.63	0.08	0.67***				0.63	0.08	0.66***	0.63	0.08	0.67***

$p < 0.001$ ***, $p < 0.05$ **, $p < 0.1$ *

5.5 Discussion

A rapidly changing electricity sector has contributed to enhance the importance of business model innovation and adaptation from incumbent distribution firms. The assessment presented in this chapter provides insights on the role of capabilities in driving adaptation for EU DSOs.

Dynamic capabilities represent the ability of firms to adapt to rapidly changing markets, which can be also considered as the ability of a firm to adapt its strategy by adjusting its activities and resources to create and capture value. For DSOs this was explored by focusing on their ability to foresee change, learn, and transform their business model, considering technological, business model, and policy aspects. Dynamic capabilities were found to contribute to shape the DSOs operations considering both core electricity distribution capabilities, and smart grid distribution capabilities. These results position adaptation capabilities as relevant contributors to adjust the role of the DSO in both traditional (i.e.: core electricity distribution capabilities) and new activities (i.e.: smart grid related capabilities). These results are in line with previous findings in the literature estimating the relationship of adaptation capabilities on operational capabilities.

Exploring the individual effects of dynamic capabilities across the different types of operational capabilities considered in this study provides additional information beyond their general importance for adaptation. Dynamic capabilities indicate a greater effect size (β), on core electricity distribution capabilities ($\beta = 0.67$), followed by smart grid integration ($\beta = 0.61$), and smart grid management ($\beta = 0.58$), and a relatively smaller effect on smart grid deployment ($\beta = 0.38$). These insights indicate a greater ability of utilities to adapt their operational capabilities associated with their traditional activities (i.e.: core electricity distribution capabilities), comparable in effect size to their impact on smart grid integration and management capabilities. However, the effect size on smart grid deployment is relatively lower.

Observing these effect sizes amidst the electricity distribution industry transition provides further insight, given that, as incumbents, DSOs have traditionally been responsible for operating, maintaining, and expanding network infrastructure (i.e.: core electricity distribution capabilities). The empirical findings indicate that dynamic capabilities contribute to a greater extent to adapting this type of operational capabilities. The similar effect sizes observed for smart grid integration and smart grid management capabilities can be argued as being associated to the operational nature of these smart grid capabilities, for which DSOs may be able to transfer knowledge from integrating and managing traditional electricity distribution technologies and processes. The smaller effect size of dynamic capabilities on smart grid deployment capabilities can be argued as being associated with the differences in deploying smart grid technology, to traditional network technologies. These findings indicate also that DSOs ability to adapt is mostly related to their traditional operations, further contributing to the need to develop supportive framework conditions that enable DSOs to also adapt new smart grid related capabilities.

In addition to evaluating the role of dynamic capabilities and their effect on operational capabilities as a source of insight on DSOs business model innovation and adaptation, this study considered also the role of operational capabilities on DSOs performance. Regarding operational performance, core electricity distribution capabilities present an effect size of ($\beta = 0.3$), followed by smart grid integration ($\beta = 0.17$). These outcomes are in line with the ongoing smart and sustainable transition of DSOs, which while focusing on their core electricity distribution activities are increasingly integrating smart grid technologies. Furthermore, these findings support the added value of integrating smart grids to increase distribution performance.

In terms of innovation performance this study encompassed both innovation exploration and innovation exploitation. Exploratory innovation representing innovative efforts new to the electricity distribution industry, and exploitative innovation representing innovative efforts that are new to the DSOs but already applied by other firms. In this case, only core electricity distribution capabilities present a significant effect size ($\beta = 0.30$) for innovation exploration and ($\beta = 0.38$) for innovation exploitation. These findings indicate that innovation activities at the DSO level remain mainly driven by core electricity distribution activities.

Exploring the findings for smart grid diffusion the results indicate a moderate effect of smart grid deployment ($\beta = 0.31$), followed by core electricity distribution ($\beta = 0.28$), further emphasizing the importance of both core and smart grid activities for smart grids diffusion.

Lastly, when assessing the impact of operational capabilities on overall business model innovation, encompassing operational, innovation, and smart grid performance dimensions, only core electricity distribution capabilities were found to have a moderate effect ($\beta = 0.42$), as the main driver for business model innovation and adaptation.

Across models, connected consumers, as a proxy for DSO scale, were found to have a significant positive effect indicating that larger DSOs benefit in terms of operational performance ($\beta = 0.23$), innovation exploration ($\beta = 0.38$), innovation exploitation ($\beta = 0.22$), smart grid diffusion ($\beta = 0.49$), and overall business model innovation ($\beta = 0.40$). Considering the effect sizes across the different performance measures, the impact of this control variable on smart grid diffusion is noteworthy. This observed effect of connected consumers on smart grid diffusion performance gains further relevance considering that of the 2 400 DSOs operating in the EU electricity distribution industry, only 190 have above 100 000 connected consumers.

5.6 Conclusions

This chapter presented a capabilities approach to analyze business model innovation and adaptation in DSOs. The relationship between dynamic capabilities, as key adaptation enablers, and operational capabilities, was explored, as well as the relationship between operational capabilities and DSOs performance. A SEM approach was used supported by novel primary data collected from 129 EU DSOs from 27 countries. Dynamic capabilities were found to directly contribute to reshaping DSOs operations, thus validating their role in supporting business model innovation.

Yet, the results obtained indicate a greater ability of DSOs to adapt their traditional electricity distribution capabilities, in comparison to smart grid deployment capabilities. While this validates the value of dynamic capabilities in incumbent regulated firms, it also suggests the need for continued efforts in supporting DSOs adaptation. These empirical results contribute to a better understanding of the role of capabilities for DSOs adaptation and can be valuable for understanding sociotechnical transitions impacting other network and capital-intensive industries.

Policy makers and regulators working on the electricity sector market design are believed to be adequate recipients of these findings. These indicate a greater ability of DSOs to adapt their core capabilities, in comparison to their smart grid related capabilities, and how these might affect the deployment of smart grids and the electricity sector transition. Likewise, the results obtained indicate the importance of business model adaptation in the electricity sector, for which operational capabilities presented a consistent contribution across different performance measures. This contributes to the need to devote efforts to understand how capability development can be supported, for which regulatory developments can play a critical role by acknowledging the relevance of adaptation in regulated monopolies and including incentives that support capability development.

The findings in this chapter provided empirical evidence on the impact of DSOs size across several measures of performance. The evidence suggests that larger DSOs benefit when it comes to distribution performance, innovation exploration, innovation exploitation, smart grid diffusion, and overall business model innovation and adaptation. Policy makers should consider these results and how this might impact the delivery of benefits associated with the electricity sector transition. Particularly, considering the growing trends towards the support of local energy markets, energy communities, and the remunicipalization of electricity distribution networks, all of which may suggest more disaggregated and smaller scale DSO configurations.

The assessment presented in this chapter provides a framework through which business model innovation and adaptation can be further studied to understand the electricity sector transformation. Utilities and policy makers can use and further develop the measurements presented in this chapter as a validated tool for business model innovation and adaptation diagnosis. This study builds on cross-sectional data on a sample of 129 DSOs from 27 EU countries. Future work could aim to obtain a larger sample to enable further analyses and ensure the validity of the hypothesized causal relationships. In addition, a larger sample, and a longitudinal approach, may contribute to understand how the conceptual model changes under different regulatory frameworks.

Chapter 6
Conclusions

6.1 Contributions to advance sustainable energy systems

The growing impact of climate change on society has increased the importance of shifting towards sustainable energy systems to strengthen resiliency and support a better use of the earth's resources. This work contributed to the advance of knowledge on sustainable energy systems by studying the changing role of utilities managing critical electricity distribution network infrastructure. Particularly, this work delved on policy, technology, and business model adaptation for smart and sustainable electricity distribution, with EU DSOs as a focus of the analysis. This research contributions', structured around policy-oriented empirical assessments, are supported by novel primary data providing timely insights for a better understanding of the sociotechnical transition of electricity distribution natural monopolies, as well as structured methodologies that facilitated the assessment of these issues. The initiative-based learning methodologies implemented throughout this thesis contribute with knowledge to the growing field of enquiry around the utilities of the future. These contributions result from the development of three topical assessments presented in Chapter 3, as a foresight study on policy alternatives for the future; Chapter 4, as a case study approach on adaptation challenges and opportunities; and Chapter 5, as a capabilities approach on business model innovation and adaptation. These empirical assessments depart from the evolving sociotechnical transition of the electricity industry in the EU (cf. Chapter 2) and aim to provide a more detailed understanding on DSOs adaptation.

Chapter 3 presented a foresight study analyzing adaptation alternatives towards smart and sustainable electricity distribution. The results highlight adaptation challenges for implementing new technologies and business practices. Experts support innovation and transition to new roles, and innovative services, while warranting that core electricity distribution activities are secured. The findings support the importance of electricity distribution for neutral market facilitation, contributing to market development and enabling new market players. This shift in roles is expected to be achieved through R&D support policies, innovation friendly regulatory frameworks, and concerted actions at the EU and Member States level. The results provide policy-adaptation guidelines for electricity distribution industry stakeholders and are expected to support policy makers working on electricity sector adaptation and can contribute to the ongoing market redesign efforts under the Energy Union.

Chapter 4 presented a case study approach, through which challenges and opportunities were identified considering the ongoing changes in business models, technologies, and policies. These areas of analysis, which overlap with those analyzed on Chapter 3, contribute to establishing a bridge between what are the future alternatives for DSOs and the present situation on how DSOs are facing the ongoing transition. The results indicate considerable uncertainty for DSOs regarding the value of large-scale smart meter rollouts. Also, a corporate culture with resistance to change is observed, challenging the integration of novel technologies and processes. Traditional regulation is seen as a barrier to smart grid investments and is associated with job losses and knowledge destruction. Policy-makers can benefit from these insights on the dynamics of DSOs, which can contribute to public policy design and market reform that traditionally has often been mainly concerned about operational efficiency in a steady-state, stable economy.

Chapter 5 presented a capabilities approach to explore business model innovation and adaptation for network utilities. This assessment considered the insights obtained through Chapter 3 and 4 and unveiled an overarching analysis of DSOs adaptability, drawing on primary data from DSOs operating across the EU. The findings obtained from this assessment provide insight on the role of strategic capabilities (i.e.: dynamic capabilities) in adjusting electricity distribution operations, as well as the role of operational capabilities on performance. The findings indicate a greater ability of DSOs to adapt their traditional operational capabilities, and a relatively lower ability to adapt their smart grid deployment capabilities. Smart grid integration is found to contribute to operational performance, validating the added value of deploying smart grids. Furthermore, DSO scale is found to have a significant impact on operational, innovation, smart grid diffusion and adaptation performance. The results contribute to the ongoing policy and market design adaptation process and unveil a detailed assessment of the value of capabilities as a building block for business model adaptation and innovation for electricity distribution utilities.

The results of these assessments provide a more detailed understanding into the changing role of the DSOs. By developing and analyzing future alternatives, evidence was obtained on what are the possible development pathways for the electricity distribution of the future. This forward-looking analysis of possibilities was complemented with an analysis of challenges and opportunities at present. Lastly, the assessment of adaptation at present and in the future was accompanied by an analysis of the DSOs ability to adapt to a rapidly changing electricity sector.

6.2 Revisiting the research questions

This research, focusing on the adaptation of DSOs in an electricity distribution industry in transition, was guided by three research questions framing this study's scope. These research questions were approached throughout this thesis and are now revisited providing a synthesis of the conclusions obtained.

What are the future alternatives for DSOs in a smarter and more sustainable electricity sector?

Possibilities to expand the DSO's traditional operational activities into new business areas were identified. The results enhance the need for adapting business strategies, pursuing new sources of revenue, and providing innovative services. The findings indicate also the need for a more proactive attitude to electricity distribution industry transformation from the DSOs, which should experiment and implement new business models and initiatives regardless of the traditional regulatory framework and existing market designs in place.

The results obtained highlight the relevance of the DSOs in the future as the electricity sector becomes smarter and more sustainable. Future development of the DSOs role includes the integration of DER technologies and the facilitation of flexibility services, all of which are expected to be provided with DSOs acting as neural market facilitators.

These findings indicate the possibilities for redesigning DSOs as platforms to support both the provision of critical electricity distribution services, ensuring quality of service, as well as to enable the implementation of new added value services by integrating and managing new technologies. Delivering these future roles will be influenced by market design options taken by policy makers and regulators. The need for innovation supportive policies was identified, as well as the relevance of implementing flexibility services governance models across the EU.

The transition towards smart and sustainable electricity distribution indicates opportunities for transforming the role of incumbent DSOs. These findings are relevant as new technologies and market players appear in a changing electricity sector. The evolution of the role of DSOs to operate as neutral platforms for electricity distribution and flexibility services can be seen as an indicator of the need to ensure these innovations are developed and implemented under a policy-driven and regulated environment, focused on delivering benefits of all the stakeholders involved, with emphasis to connected consumers.

How do the shifts in business model, technology, and market design characteristics impact DSOs?

Distributed energy resources influence the DSO's ability to adapt, given that the surge of distributed generation impacts strategic decisions and investment plans leading to a more reactive role of the DSO when adjusting operations, technologies and asset management practices. Evolving to a framework with higher shares of distributed renewables is expected to benefit from the widespread availability of flexibility services, which DSOs see as a valuable opportunity. The deployment of smart grids is perceived as critical to enable flexibility services, for which DSOs see value in the possibilities resulting from electric mobility, electricity storage, smart metering, and distribution automation, and increasingly data-driven services. However, uncertainty was found regarding the value for DSOs resulting from deploying smart grid technologies, in specific the value of full scale rollouts of smart meters. DSOs indicated that while having more data from the grid is an important step, having data from all the connected consumers was not seen as relevant at this stage. These findings are relevant in an electricity distribution industry in transition, particularly considering the important role of smart meters, as the first step towards deploying smart grids.

The insights obtained provide evidence of a DSO corporate culture with inertia to adopting new processes and technologies associated with a smarter grid environment, which was found to be associated with the regulatory frameworks mainly focused on achieving improvements in operational efficiency. Furthermore, the results obtained indicate that smaller DSOs face greater challenges in the ongoing energy transition, in specific when rolling out smart grid and smart meter technologies, operating small isolated areas, achieving economies of scale, and acquiring new technologies for grid modernization.

DSOs amidst the ongoing changes in the electricity sector are reconsidering their capabilities and how to leverage on their technologies and operations to continue as a relevant player in a smarter and sustainable electricity sector. The assessment unveils a perspective in which DSOs continue as relevant players. The relationship between DSOs and smart grid technologies deployment however requires further clarification, as well as the role of regulations in supporting the transition to new technologies, business processes, and consequently business models and the value capture and creation approach in the electricity distribution industry.

How capable are DSOs to implement business model innovation and adaptation in a rapidly changing electricity sector?

The findings obtained demonstrate the DSO's ability to adjust their operational capabilities. For which a greater ability to adapt core electricity distribution operation capabilities is observed (i.e.: those related with traditional electricity distribution, and network operation and maintenance activities), paralleled by a lower ability to adapt smart grid deployment capabilities. These results enhance the value of capabilities in supporting DSOs adaptation, while indicating the need to further develop smart grid deployment capabilities.

The role of capabilities on DSOs performance was also explored, considering operational, innovation, smart grid diffusion, and overall business model innovation performance. Core electricity distribution capabilities were found to consistently contribute to performance. Smart grid related capabilities were found to contribute to operational performance, validating the added value of deploying smart grids towards a smart and sustainable energy future. Considering the empirical findings regarding the impact of DSOs size on adaptation previously discussed, this assessment explored the impact of DSO size, measured through connected consumes, to understand its role in performance. The results obtained indicate a significant impact of size on operational performance, innovation performance, smart grid diffusion performance, and business model innovation. These findings show benefits for larger DSOs across performance indicators. These results gain further relevance considering the ongoing energy transition trends in which local energy markets, community energy projects, distributed generation, and smaller scale DSO operations are gaining momentum.

DSOs amidst a rapidly changing electricity sector demonstrate strategic and operational capabilities that facilitate both adaptation and performance, supporting business model innovation. For smart grid deployment to continue, the backing from favorable policy and technological developments is expected. In this framework, DSOs show evidence of being able to increasingly strengthen their smart grid related capabilities to support the deployment, integration, and management of new technologies and processes that support the transition towards a decentralized and decarbonized electricity sector. Evidence of DSOs benefiting from scale can be observed as an indicator of the possibilities for DSOs to evolve into a role that combines the provision of critical electricity distribution services, the facilitation of flexibility services, and the support to smaller scale local energy initiatives, for instance by providing technology and operational support services to local energy communities, for which DSOs have accumulated experience.

6.3 Limitations overcome

This research explored policy, technology, and business model adaptation for smart and sustainable electricity distribution following a sociotechnical transitions approach. Studying these aspects in an integrated manner required a multidisciplinary effort. This was achieved for each of the research designs presented in this study by drawing on both the existing literature and expert's knowledge. Engaging with academics, DSOs, NRAs, and other electricity sector representatives contributed to ensure that the foresight analysis, the case studies, and the capabilities approach developed followed appropriate methodologies and resulted in actionable findings.

Approaching electricity sector challenges through a social sciences and humanities lens has been gaining attention, however these approaches remain incipient within the wider range of studies tackling the challenges of the power sector, mainly dominated by siloed engineering and economic approaches. This research contributed to enhance the relevance and added value of developing a social sciences and humanities knowledge base as a critical building block to support the transition towards smart and sustainable energy systems.

This research is characterized by its novel results, obtained through the collection of primary data across countries and stakeholders in the EU. To the best of our knowledge, this data set is the first one to be assembled. Data collection barriers were overcome by designing a strategy that engaged research participants by providing feedback, and sharing preliminary findings and published outcomes throughout the development of the study. Data collection from DSOs across the EU was particularly challenging, for which support from NRAs was important in the identification of electricity distribution firms in each country.

6.4 Pathways for future work

This study's research design is based on cross-sectional data to understand the electricity distribution industry transition. Future work could tap into the added value of a longitudinal research design using time series data. This can contribute to understand how the transition towards smart and sustainable electricity distribution unfolds, and to explore how different policies affect adaptation.

The EU regional focus of this study was valuable given the shared framework of policies and climate and energy ambitions. However, the findings resulting from this approach may not be representative of the electricity distribution transition dynamics worldwide. Future work could expand the regional scope of the assessments presented. For instance, additional evaluations can target the transition occurring in industrialized countries that have followed the market liberalization strategy prior to the smart and sustainable development strategy. Also, the transition in developing countries may benefit from transferable knowledge from other countries experiences.

This research focused on the changes impacting critical electricity sector infrastructure, by studying DSOs. Nonetheless, the changes impacting DSOs bring also new challenges and opportunities for firms upstream and downstream. Future work can draw on the methodologies presented in this study to explore the changing roles of other critical electricity sector infrastructures and stakeholders, such as incumbent electricity generation firms, TSOs, electricity retailers, as well as new entrants and their role in the electricity sector in the future.

The analysis of electricity distribution utilities adaptation presented in this study yielded insights on the ability of incumbent network firms providing services of general economic interest for society to adapt. Future work can draw on the insights and methods described throughout this work to tackle challenges in other network industries providing essential and capital-intensive services to society, such as the transportation industry, waste industry, water industry, and gas industry.

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Appendixes

Appendix A. Policy Delphi expert participation individual report

DSOs in a smarter EU electricity market
Expert Participation Individual Report
Periera, Silva, and Soule, 2017

April, 2017

DSOs in a smarter EU electricity market

EXPERT PARTICIPATION INDIVIDUAL REPORT

Guillermo Ivan Pereira, Patrícia Pereira da Silva, and Deborah Soule

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MIT Portugal Program in Sustainable Energy Systems

This report provides a summary of the results obtained from the data collected through the first and second round questionnaires. In addition, your individual assessments of each policy alternative for both rounds are presented with the label "Your choice".

Please note: *Your privacy is important to us. Participation in this study is voluntary. Your identity will be kept confidential. Information we collect will be seen only by the small research team. All data will be kept secure, and will be reported only in aggregated form. No organization or individual will be identified as having taken part in this research, except where explicitly authorized in writing.*

EXPERT PARTICIPATION INDIVIDUAL REPORT

Expert details	**Name**	*[Expert name]*
	Email	*[Expert email]*
	Country	*[Expert country]*
	Expert Identification	*[Expert identification code]*

1. How should DSOs position themselves regarding business model and organizational innovation?

		Strongly disagree (1)	Disagree (2)	Somewhat disagree (3)	Neither agree or disagree (4)	Somewhat agree (5)	Agree (6)	Strongly agree (7)
DSOs should limit their business strategy to the possibilities allowed by existing regulations.	1st Round	17%	31%	19%	4%	12%	11%	6%
						Your choice		
	2nd Round	18%	49%	15%	1%	7%	8%	3%
							Your choice	

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Appendix figure A.1 Policy Delphi expert participation individual report

DSOs in a smarter EU electricity market
Expert Participation Individual Report
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April, 2017

2. How do you perceive the difficulty of DSOs adaptation to a changing electricity sector?

		Very difficult (1)	*Difficult (2)*	*Somewhat difficult (3)*	*Neither difficult or easy (4)*	*Somewhat easy (5)*	*Easy (6)*	*Very easy (7)*
DSOs will be able to adapt their role in a timely manner.	1st Round	3%	23%	40%	17%	12%	5%	0%
						Your choice		
	2nd Round	1%	33%	50%	12%	3%	1%	0%
							Your choice	
DSOs will be able to integrate new technologies to support the transition to smarter distribution grids.	1st Round	0%	14%	37%	16%	23%	9%	0%
				Your choice				
	2nd Round	0%	11%	51%	18%	17%	3%	0%
			Your choice					
DSOs will be able to integrate new business processes and management practices.	1st Round	3%	16%	32%	19%	23%	7%	0%
						Your choice		
	2nd Round	1%	14%	48%	20%	17%	1%	0%
							Your choice	
DSOs will be able to adapt to a changing electricity sector only with adapted regulation.	1st Round	3%	16%	15%	28%	21%	14%	2%
						Your choice		
	2nd Round	0%	9%	16%	44%	24%	8%	0%
						Your choice		

3. In the future DSOs should be involved in the following activities?

		Strongly disagree (1)	*Disagree (2)*	*Somewhat disagree (3)*	*Neither agree or disagree (4)*	*Somewhat agree (5)*	*Agree (6)*	*Strongly agree (7)*
Smart meter ownership.	1st Round	1%	7%	5%	21%	8%	27%	32%
						Your choice		
	2nd Round	2%	5%	4%	18%	5%	23%	43%
							Your choice	
Managing a data marketplace (i.e. to enable the development of added value services by other market players).	1st Round	2%	9%	8%	17%	13%	33%	19%
			Your choice					
	2nd Round	0%	5%	8%	12%	13%	43%	20%
							Your choice	
Provide energy efficiency and energy savings advise to end-users.	1st Round	4%	7%	6%	15%	18%	27%	23%
							Your choice	
	2nd Round	5%	8%	6%	15%	11%	32%	24%
								Your choice
Electric vehicle infrastructure ownership.	1st Round	4%	17%	8%	27%	16%	16%	12%
			Your choice					
	2nd Round	5%	25%	4%	20%	12%	19%	15%
								Your choice
Management of distributed generation technologies.	1st Round	6%	11%	8%	11%	15%	29%	21%
			Your choice					
	2nd Round	4%	9%	4%	9%	13%	45%	17%
			Your choice					
Electricity retail.	1st Round	28%	23%	9%	13%	11%	11%	6%
		Your choice						
	2nd Round	50%	27%	4%	11%	3%	4%	1%
		Your choice						

4. How should DSOs position themselves for technological innovation and research and development (R&D) activities?

		1st priority (1)	*2nd priority (2)*	*3rd priority (3)*
DSOs should conduct exploratory R&D activities for new technologies and innovative applications.	1st Round	26%	25%	49%
				Your choice
	2nd Round	22%	31%	47%
				Your choice
DSOs should pilot and demonstrate the potential and impact of emerging technologies.	1st Round	38%	46%	16%
			Your choice	
	2nd Round	41%	53%	6%
			Your choice	
DSOs should exploit tested and proven technologies, deploying external R&D results from universities, ICT firms, and other DSOs.	1st Round	37%	28%	35%
		Your choice		
	2nd Round	37%	16%	48%
		Your choice		

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Appendix figure A.1 (continued) Policy Delphi expert participation individual report

5. How important are the following policy-oriented actions in the ongoing DSOs transition?

		Not at all important (1)	*Low importance (2)*	*Slightly important (3)*	*Neutral (4)*	*Moderately important (5)*	*Very important (6)*	*Extremely important (7)*
The role of the DSOs should only be specified at the Member State level, allowing each country to establish its role to fit the specific context.	1st Round	7%	21%	14%	16%	15%	17%	10%
							Your choice	
	2nd Round	2%	27%	8%	20%	17%	20%	5%
							Your choice	
The unbundling threshold, currently set to DSOs with 100 000 connected consumers should be re-considered as it can challenge the adaptation and innovation potential of DSOs.	1st Round	6%	6%	5%	32%	22%	19%	11%
							Your choice	
	2nd Round	3%	7%	3%	50%	22%	11%	4%
						Your choice		
A new regulatory body should be established focusing on the transition to a smarter grid framework, with a strategy and incentives for DSOs to innovate.	1st Round	13%	9%	6%	12%	19%	26%	16%
		Your choice						
	2nd Round	20%	8%	0%	10%	14%	38%	11%
		Your choice						
The DSOs and TSOs congestion management and balancing responsibilities should be defined at the EU-level.	1st Round	2%	7%	5%	20%	25%	25%	17%
						Your choice		
	2nd Round	2%	5%	4%	18%	28%	33%	10%
			Your choice					

6. What's the future of DSOs in the electricity sector?

		Strongly disagree (1)	*Disagree (2)*	*Somewhat disagree (3)*	*Neither agree or disagree (4)*	*Somewhat agree (5)*	*Agree (6)*	*Strongly agree (7)*
DSOs will continue with their traditional activities, solving most of the grid related issues at the planning stage, operating as passive network managers.	1st Round	21%	24%	12%	7%	13%	15%	8%
							Your choice	
	2nd Round	26%	40%	12%	3%	6%	10%	4%
							Your choice	

7. When will DSOs fully evolve toward active network managers, procuring flexibility services?

		DSOs become active network managers between 2017-2020 (1)	*DSOs become active network managers between 2021-2030 (2)*	*DSOs become active network managers between 2031-2040 (3)*	*DSOs become active network managers between 2041-2050 (4)*	*DSOs will not become active network managers (5)*
Small DSOs (Less than 100 000 connected consumers)	1st Round	10%	53%	23%	3%	12%
			Your choice			
	2nd Round	4%	78%	16%	0%	3%
		Your choice				
Large DSOs (Unbundled, with 100 000 or more connected consumers)	1st Round	14%	62%	17%	3%	4%
		Your choice				
	2nd Round	11%	77%	11%	2%	0%
		Your choice				

Appendix figure A.1 (continued) Policy Delphi expert participation individual report

Appendix B. DSOs adaptation questionnaire

The questionnaire development included an initial review of studies measuring capabilities. The resulting questionnaire was validated by a group of representatives from DSOs and academia to strengthen the relevance of the developed measures. From the literature review resulted an inventory of different measures used to assess capabilities, innovation, business performance, market characteristics, and general aspects used as control variables. Appendix table B.1 presents the sections and content included in the questionnaire.

Appendix table B.1 Questionnaire structure

Section	Content
Electricity distribution capabilities	Section for evaluating electricity distribution firm-level capabilities. The topics include: • Dynamic capabilities • Operational capabilities
Electricity distribution performance	Section for evaluating electricity distribution performance. The topics include: • Operational performance • Innovation performance • Smart grids diffusion performance
Electricity distribution operations	Section to characterize the electricity distribution operations

The following sections detail the scope of each section included in the questionnaire, in relation to both the literature on capabilities, and specific electricity sector characteristics.

Electricity distribution capabilities

The electricity distribution capabilities measures included in this section focus on core electricity distribution capabilities, smarter distribution grid capabilities, and dynamic capabilities.

Operational capabilities: core and smart electricity distribution capabilities

The measurements for core electricity distribution capabilities and smarter grid capabilities aim to evaluate operational capabilities. The operational capabilities are segmented in two groups, which is deemed adequate considering that core electricity distribution capabilities are related to essential activities developed by DSOs, regardless of their level of engagement in the smart grid environment, whilst it is also important to measure smart grid capabilities for DSOs that have smart grid operations.

Core electricity distribution capabilities measures aim to evaluate the ability of DSOs to perform essential electricity distribution activities, including: network operation and maintenance, network monitoring and fault detection, technical support services to grid users, and network planning. Smarter distribution grid capabilities aim to evaluate the extent to which an electricity distribution firm is engaged in smart grid operations.

The measures included in this section reflect the specificities of the electricity distribution network industry and were validated through previous studies that measured operational capabilities. For instance, Lall (1992) studied the impact of core operational capabilities through the assessment of technological capabilities at the firm level, focusing on the capabilities associated with the various stages of technological development, such as: pre-investment capabilities, project execution capabilities, process engineering capabilities, product engineering capabilities, and industrial engineering capabilities. Panda & Ramanathan (1996, 1997) developed an electricity sector dedicated framework for analyzing the influence of technological capabilities in strategic planning. In this framework, core capabilities measures focused on: design and engineering capability, construction capability, production capability, marketing and selling capability, servicing capability. Wang et al. (2006) analyzed the role of operational capabilities in firms' performance, the study considered technological capabilities, and costumer value related capabilities. Rothaermel & Hess (2007) analyzed the drivers for firm level innovation by considering individual, firm, and network level effects. In this study, operational capabilities were measured considering: intellectual human capital development capability, and research and development capability. Similarly, Ortega (2010) studied the moderating role of core operational capabilities by measuring managerial capabilities, marketing capabilities and technological capabilities. Su et al. (2010) analyzed the impact of uncertainty and capabilities in firms' innovation, for which operational capabilities were measured through indicators focusing on marketing capabilities, technological capabilities, and product and service provision capabilities. Protogerou et al. (2012) analyzed the impact of capabilities on firms' performance, for which operational capabilities were measured by focusing on marketing capabilities, and technological capabilities. Hao & Yu (2012) explored the relationship between core capabilities and innovation performance by focusing on: technological capabilities, management capabilities, and network development capabilities. Clausen (2013) studied the impact of capabilities in the type of innovation activities undertaken at the firm-level, for which operational capabilities were measured by focusing on: technological capabilities, and market capabilities. Reichert & Zawislak (2014) researched on the relationship between core operational capabilities and firm performance, for which core capabilities were measured by focusing on technological capabilities, including: research and development capability, and patenting capabilities.

From the review of existing measures in the literature it is possible to observe that these are often general in terms of industry characteristics and specificities, apart from the specific electricity sector application presented by Panda & Ramanathan (1996, 1997). The measures developed for this section considered the general characteristics presented in the literature and were further customized to reflect the sector specific characteristics of the electricity distribution industry. The core electricity distribution capabilities measures encompass aspects related to network operation, network monitoring, grid users support, network maintenance, and network planning. The smart distribution grid capabilities measures encompass aspects related to distributed generation technology integration, electricity storage technology integration, electric vehicle charging infrastructure integration, smart metering deployment and integration, and planning and asset management activities. The specification of these measures is based in ongoing debates on the role of DSOs in a smarter grid environment, such as that of Oosterkamp et al. (2014), which analyzed different scenarios for the evolution of electricity distribution operations considering the diffusion of smart grid technologies and the uptake of associated services. Also, the European Electricity Grid Initiative research and innovation roadmap 2013 – 2022 was considered for developing the smarter distribution grid capabilities measures (European Electricity Grid Initiative, 2013). Core electricity distribution capabilities and the smarter distribution grid capabilities are measured through Likert scales from 1 to 6 to reflect the level of capability of the DSOs.

Dynamic capabilities

The dynamic capabilities measures included in this section focus on change foresight capability, learning capability, and transformation capability. These items aim to evaluate how DSOs adapt to a changing electricity distribution industry amidst the energy transition underway, by adapting a dynamic capabilities perspectives of DSOs (Teece & Pisano, 1994; Teece, 1996; Teece et al., 1997).

The change foresight capability measures aim to explore the ability of DSOs to perceive upcoming changes in the electricity sector. The measures included have been validated by similar approaches in the literature that focused in evaluating the ability of firms to foresee change in their market. Primarily, the importance of sensing capabilities was acknowledged in Teece & Pisano (1994), as an important capability to support business transformation. Moreover, Teece (2007) further enhanced the importance of foresight capabilities as necessary to identify opportunities. In terms of practical applications of measures to assess the level of change foresight capabilities: Panda & Ramanathan (1996) measured steering capabilities of electricity sector firms by focusing on path finding capabilities, which can be observed as a proxy for foresight. Rush et al. (2007) developed a measurement tool for a policy-oriented capability assessment of firms'. In this study change foresight was evaluated by focusing on: awareness, and search capabilities. Janssen et al. (2016) measured change foresight capabilities of firms by focusing on: technological options sensing capabilities, and consumer needs sensing capabilities.

Learning capability measures aim to explore the ability of DSOs to integrate the necessary knowledge to adapt to a changing electricity sector. The measures included have been validated by similar approaches in the literature. Learning as a relevant capability for firm adaptation to rapidly changing markets was emphasized in Teece & Pisano (1994) conceptualization of dynamic capabilities. Learning capabilities encompass the ability of a firm to integrate a new process, technology, practice, or activity to perform better or provide innovative products/services. Empirical applications of the learning capability concept have been developed in the literature. Panda & Ramanathan (1996) measured learning as the capability of the firm to provide training. Wang et al. (2006) assessed learning capabilities by focusing on learning orientation. Rush et al. (2007) measured learning capability of firms by focusing on core competence development capabilities, and technological learning capabilities. Alegre & Chiva (2008) analyzed learning capabilities by focusing on: experimentation, risk-taking, interactions with the external environment, dialogue, and participative decision making capabilities. Protogerou et al. (2012) measured learning capabilities of industrial firms by focusing processes for in-house learning and knowledge development, on the job skills development, and team efficiency.

Transformation capability measures aim to explore the ability of DSOs to implement actions that facilitate their adaptation to a changing electricity sector. The importance of transformation as a dynamic capability is discussed in Teece & Pisano (1994) and is related to the ability to reconfigure the firms' asset structure to accomplish the necessary transition. In addition, Teece (2007) further emphasized the importance of transformation capabilities. The measures developed in specific for this section are based on validated studies. For instance, Panda & Ramanathan (1996) measured creation capabilities, focusing on the ability to implement product/service improvements, the ability to implement a new organizational structure, and the ability to plan and execute projects, which can be observed as transformation capabilities. Rush et al. (2007) measured technology strategy, selection and implementation, which can be observed as transformation capabilities. Protogerou et al. (2012) measured coordination capabilities of the firm by focusing on: the integration of business processes, adoption of the latest management tools and techniques, and business plan development. Clausen (2013) measured transformation by focusing on resource reconfiguration capabilities. Janssen et al.

(2016) measured the ability of firms to conceptualize and scale, which can be recognized as the capability to transform their business. The dynamic capability measures included in this section were developed considering the changes taking place in the electricity distribution sector, by including specific regulatory, technological, and business model innovation and strategy aspects within each of the dynamic capabilities dimensions being evaluated.

Electricity distribution performance

Business performance

The business performance measures included in this item aim to evaluate the electricity distribution industry performance. The items included in this section were developed considering validated models available in the literature. For instance, Ortega (2010) collected indicators on return on investment, profit margins, market share, growth of sales, and general performance to measure business performance. Similarly, Reichert & Zawislak (2014) measured business performance through quantitative indicators on sales, profits, and market related indicators. Wang et al. (2006) evaluated business performance by measuring firms' perception in terms of profitability, growth of market share, cost effectiveness, and overall firm performance. Protogerou et al. (2012) measured business performance through profitability and market performance, both relative to competition. Janssen et al. (2016) studied business performance by focusing on the origin of revenues, and in growth and profitability. The items specified in this section are based on perception scales.

Innovation performance

The measures included in this section aim to evaluate the innovation performance of electricity distribution companies. Innovation in electricity distribution has gained importance due to the possibility for innovative technologies integration, as well as new service provision possibilities. This importance is visible in the European Electricity Grid Initiative roadmap for research and innovation 2013 – 2022 that indicates the focus areas for innovation for electricity grids, with specific provisions for DSOs. This section aims to obtain a general perspective on the engagement in innovation activities.

The measures included to evaluate innovation performance are based on qualitative perception scales specifically developed for the electricity distribution industry. These measures have been developed by considering validated items in the literature. Existing contributions can be aggregated in two groups, one based on quantitative indicators, and the other on qualitative/perception-based indicators. Those measuring innovation performance through quantitative indicators, for instance Love & Roper (1999) measured innovation performance by focusing on research and development investments, technology transfer, and networking. Rothaermel & Hess (2007) measured innovation performance by collecting data on the number of patents granted to the firm. Similarly, Su et al. (2010) measured innovation performance through research and development investments relative to sales.

Contributions using qualitative/perception based measures have also been applied in prior work. Alegre & Chiva (2008) measured innovation performance through product innovation items focusing on the efficacy of product innovations, which encompassed for instance product replacement, market share evolution, and opening of new markets. Additionally, the efficiency of product innovations was measured, which included items related to resource allocation such as product development time, human resources allocated, product development cost, to name a few. Clausen (2013) measured innovation performance through product innovation, focusing on the evaluation of exploitative innovation (i.e. new to the firm products), and on the evaluation of explorative innovation (i.e. new to the market products). An hybrid approach, blending quantitative and qualitative items is visible in Fosfuri & Tribo (2008), which measured innovation performance through a mix of quantitative and perception based indicators. Quantitative indicators measured the sales resulting from previously implemented innovations. Qualitative indicators focused on evaluating the firms' engagement in: contracted research and development, engagement in research and development collaboration, innovation related strategic changes, to name a few.

The measures included to evaluate innovation performance, encompass explorative and exploitative innovation to assess the ways in which DSOs engage on innovation activities. By developing new technologies, practices, or processes, which are new to the industry, observed as exploratory innovation. And by exploiting the benefits of readily available technologies, observed as exploitative innovation. The items included in this section were designed considering previous empirical applications. For instance, He & Wong (2004) studied the impact of innovation exploration and exploitation on firm performance, measured through a questionnaire tool. Similarly, Clausen (2013) measured engagement on innovation activities by focusing on new to the firm innovation (i.e. exploitation) and new to the market innovation (i.e. exploration).

Smart grid diffusion performance

The measures included in this section aim to evaluate engagement of DSOs in smart grids diffusion. Understanding the role of the DSOs in a smarter grid environment has gained relevance, due to the uprising possibilities for technology integration and innovative service provision that arise from the diffusion of smart grid technologies. The roles of DSOs are often specified as being passive, reactive, and active, which would entail a lower, moderate, and high level of engagement in the smart grid environment, respectively (Oosterkamp et al., 2014). DSOs acting as passive network managers, solve most of their electricity grid challenges at the planning stage, by dimensioning a grid that has enough capacity for the expected system demands. These DSOs have mostly limited smart grid capabilities. DSOs acting as reactive network managers, solve most of their electricity grid challenges at the operational stage, often restricting the injection of distributed generation to avoid grid congestion. These DSOs have a limited set of smart grid capabilities that allow them to manage their network in a more efficient way. DSOs acting as active network managers, can solve their grid challenges across various timeframes, throughout planning and operation.

Electricity distribution operations

The measures included in this section aim to gather quantitative indicators of electricity distribution operations. These items are placed in the ending part of the questionnaire as optional questions to avoid respondent drop-out from the questionnaire. The final version was tested and validated by a group of experts, Appendix table B.2.

Appendix table B.2 DSO adaptation questionnaire reviewers

Stakeholder group	Region	Country	Reviews
Universities	Southern Europe	Portugal	3
DSOs	Eastern Europe	Croatia	1
	Northern Europe	Finland	1
	Southern Europe	Greece	1
		Portugal	2
Electricity sector associations	European Union	Belgium	1
Consulting firms	Eastern Europe	Croatia	1
	Total reviewers		**10**

Appendix table B.3 presents the final version of the questionnaire sent to DSOs.

Appendix table B.3 DSO adaptation questionnaire

Section	Items	Measurement
Identification	Country of operation [a]	
Electricity distribution capabilities		
Core electricity distribution capabilities [a]	Operate our grid to provide an efficient and reliable service	Not capable at all, Slightly capable, Moderately capable, Capable, Very capable, Extremely capable
	Monitor our grid and detect faults	
	Conduct grid maintenance to avoid or solve faults	
	Provide high quality service to all grid users	
	Reinforce and expand our grid infrastructure in a timely manner	
Smarter distribution grid capabilities [a]	Integrate distributed generation technologies (e.g. solar PV and wind)	Not capable at all, Slightly capable, Moderately capable, Capable, Very capable, Extremely capable
	Integrate DSO-owned electricity storage technologies for grid management	
	Integrate grid user-owned electricity storage technology for grid management	
	Integrate electric vehicles charging infrastructure	
	Own electric vehicles charging infrastructure	
	Manage or facilitate system flexibility by coordinating distributed generation	
	Manage or facilitate system flexibility by triggering demand response actions	
	Manage or facilitate system flexibility by coordinating distributed electricity storage	
	Deploy smart meters for all connected consumers	
	Own smart meter infrastructure	
	Conduct planning and asset management adequate for a smarter grid future	
Dynamic capabilities		
Change foresight capability [a]	Identify technologies to improve the quality and efficiency of our operations	Not capable at all, Slightly capable, Moderately capable, Capable, Very capable, Extremely capable
	Identify new technologies (e.g. smart metering, electric vehicle charging infrastructure, flexibility management, etc.)	
	Identify changes in policies and regulation to ensure the adequacy of our business strategy	
	Influence policies and regulation to be aligned with our business strategy	
	Identify system changes (e.g. understanding the impact of distributed generation, the impact of the current DSO-TSO relationship, etc.)	
	Identify the changing needs of grid users (e.g. accommodating the increasing number of smart homes, residential storage units, electric vehicles, etc.)	
Learning capability [a]	Understand the implications of smart grid technologies	Not capable at all, Slightly capable, Moderately capable, Capable, Very capable, Extremely capable
	Learn to integrate new technologies	
	Understand the impact of policy and regulatory changes on our business	
	Identify ways to adapt our business strategy to fit policy and regulatory requirements	

Appendix table B.3 DSO adaptation questionnaire

Section	Items	Measurement
	Identify the resources needed to adapt our business strategy	
	Identify the business areas that require adaptation	
Transformation capability [a]	Adapt our organisation to use new technologies (e.g. teams, responsibilities, departments, strategy, resource allocation, etc.)	Not capable at all, Slightly capable, Moderately capable, Capable, Very capable, Extremely capable
	Change our business to use new technologies	
	Adapt our activities and responsibilities given policy and regulatory changes	
	Implement business changes to explore opportunities from policy and regulatory changes	
	Systematically analyse future strategies as we move toward a smarter grid environment	
	Develop flexible organisational practices that adapt to our business model and strategy	
Electricity distribution performance		
Electricity distribution operational performance [a]	Improved cost efficiency	Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree
	Improved service quality and reliability indicators (e.g. SAIFI, SAIDI)	
	Improved general performance across departments	
Innovation performance		
Explorative innovation	Introduced technologies, processes or practices that are new to the electricity distribution sector	Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree
	Started experimenting with innovative technologies in our operations	
Exploitative innovation	Improved our ability to increase quality of service	
	Improved our ability to increase cost efficiency of our operations	
Smart grids diffusion		
Smart grids diffusion performance [a]	We solve most of the grid challenges	at the planning stage, at the operational stage, and across planning and operational stages
	Our main grid management practice is to	plan sufficient grid capacity to deal with changing system demands, restrict distributed generation injections to manage grid congestion, manage distribution system flexibilities
	Considering smarter distribution operations	we are aware of the opportunities; we are experimenting with new processes, technologies, and practices; we have integrated smart grid technologies (e.g. smart meters, electric vehicle charging infrastructure, distributed generation, automation devices)
	In terms of engagement in smart grids diffusion	we consider the possibilities for becoming more engaged in the deployment of smart grids, we observed operational improvements from deploying a smarter

Appendix table B.3 DSO adaptation questionnaire

Section	Items	Measurement
		distribution grid, our processes, technologies, and practices reflect an extensive engagement in the deployment and facilitation of smart grids
	Our investments in a smarter distribution grid are	residual, moderate, and substantial
DSO Operations		
Electricity distribution business environment [a]	Connected consumers in 2016	1 to 50 000 50 000 to 150 000 150 000 to 350 000 350 000 to 1 000 000 1 000 000 to 2 000 000 2 000 000 to 5 000 000 Over 5 000 000
Regulatory framework characteristics [a]	Allows us to perform new roles	Strongly disagree, Disagree, Somewhat disagree, Somewhat agree, Agree, Strongly agree
	Allows for new investments to be conducted to explore new roles	
	Encourages innovation	
	We find it easy to adapt to the demands of the regulatory framework	
Electricity distribution operations [a]	Years' operating in the electricity distribution sector	Up to 5, 5 to 20, 20 to 50, Over 50

[a] Presented as a mandatory questionnaire item