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Electricity distribution incumbents' adaptation toward decarbonized and smarter grids: Evidence on the role market, regulatory, investment, and firm-level factors

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ABSTRACT

The transition to a cleaner and smarter electricity system is being spurred by new policy approaches aiming at delivering a decentralized, digital, and decarbonized energy future. This calls for the adaptation of incumbent technologies, policies, and actors, as well as for the introduction of new system components. The changing role of electricity distribution systems, and of distribution system operators, has been a focal aspect of recent market design efforts, given the critical role of network infrastructure and the importance to adjust its operations, and regulatory framework. We build on a novel dataset from 124 DSOs and apply a methodology combining Factor analysis and a Tobit model to evaluate the role of market, regulatory, investment, and firm-level factors on technological, business model, and market design adaptation. Our results indicate that hybrid regulatory models contribute to DSOs adaptation. Investing in smart grids is found to have a positive effect on adaptation. Regarding firm-level characteristics, the results indicate that unbundling does not affect adaptation, however larger DSOs are found to be better able to adapt. These findings provide timely empirical evidence for advancing regulatory and policy approaches toward the adaptation of incumbents in a rapidly changing electricity sector.

1. Introduction

Widespread electrification has been put forward as a building block on the transition to a low-carbon economy globally. In the European Union (EU) electricity consumption is projected to represent 30% of final energy use by 2030, and 40% by 2050 (Fulli et al., 2019). This growth on the use of electricity is set to unfold as the EU electricity sector transitions to a decentralized, digital and decarbonized future. These three drivers significantly challenge the existing power systems and require actions to bring a coordinated approach to the mix of legacy and innovative technologies, processes, market designs and energy resources (Di Silvestre, Favuzza, Riva Sanseverino and Zizzo, 2018).

Decentralization results from an increased participation and engagement of consumers in the electricity sector, with growing shares of generation connected to distribution grids, which could reach 30% of all generation capacity by 2030 (Fulli et al., 2019). Digitalization is increasingly taking place as communication and control technologies are coupled with electricity sector infrastructure, resulting in smarter grids, access to new streams of data, and the possibilities to develop new optimization and participation models. With a goal to achieve an 80% share of smart meters across Member States by 2020 (European Commission, 2012). Decarbonization is the policy driven effort to deliver sustainable electricity systems, supported by renewable energy technologies and energy efficiency. For this, by 2030, the EU aims to reduce greenhouse gas emission by 40% from 1990 levels (European Commission, 2014), and reach a share of 32% for renewable energy (European Commission, 2018), and 32.5% for energy efficiency (European Commission, 2018b).

These shifts challenge the critical energy infrastructure and operations of the electricity distribution networks, which has resulted in a growing need to understand the future role of electricity distribution system operators – the DSOs. This has focused on identifying the DSO's

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involvement with new technologies and services, and how these may interact with its core electricity distribution activities, as well as how these may interact with regulatory models, policies, and market design (Pereira et al., 2018a; Pereira et al., 2020).

Through this study we aim to provide empirical evidence on the role of market, regulatory, investments, and firm-level factors on the adaptation of the electricity distribution system. Using a novel database with data from of 124 DSOs we assess the effect of these factors on the transformation of the electricity distribution system operators. The novelty of this dataset is associated with the firm-level primary data on adaptation and transformation of the grid operators, which couldn't be found in the literature. This primary data was obtained through a questionnaire distributed to European Union DSOs, with the cooperation of national regulators, and industry associations. This research builds on and expands the study presented by Pereira et al. (2018b), which developed case studies to unravel novel insights on the challenges and opportunities of the transition to smart electricity distribution. The authors used an analytical framework encompassing business model and organizational aspects; operations, technology, and asset management; and market design and regulation. We build on this approach to evaluate how different factors impact the transformation of electricity distribution. Our approach expands recent contributions in the literature which have predominantly focused on understanding the effect of different factors on investment levels. For instance, Cambini et al. (2016) and Gwerder et al. (2019) studied the influence of different market and regulatory factors on smart grid investments in Europe. Similarly, Cullmann & Nieswand (2016) and Poudineh & Jamasb (2016) analyzed the factors affecting investment behavior in electricity distribution companies in Germany and Norway, respectively. However, focusing on investments provides only a partial understanding of the electricity sector transformation. Given the need to go beyond the financial allocation of resources and to understand how the electricity distribution companies are adapting, we draw on the existing practice of studying firm's behavior, but instead of using investments as our outcome variable, we build on a novel dataset of DSOs data to elaborate different measures of adaptation. Through this research we aim to provide evidence that contributes to advancing policy approaches and market designs that support a transition to a cleaner and smarter electricity sector.

The manuscript is structured as follows: Section 2 provides a review of new policy approaches for a cleaner and smarter grid, establishing the background for this study; Section 3 details data characteristics, the methodology and model specifications used; Section 4 presents the results and discussion; and Section 5 concludes and highlights policy implications.

2. New policy approaches for electricity distribution

The upward trend on the diffusion of distributed energy resources, such as wind and solar generation, as well as electricity storage, and electric mobility, in addition to more engaged electricity consumers has led to the need to understand the role of the electricity distribution networks in a cleaner and smart energy system. Against this backdrop, EU regulators through the Council of European Energy Regulators (CEER), have developed an updated regulatory perspective on the role of electricity distribution operations, taking into account the core electricity distribution activities of grid planning, deployment, operation, and maintenance, as well as activities associated with consumer engagement, and flexibility services. As a result CEER (2015) presented the principles to be used for regulating DSOs in a changing electricity sector, as follows:

- Principle 1: Distribution system operators must operate in order to meet reasonable service expectations, for network users and other system stakeholders, including: quality and security, non-discriminatory access to network infrastructure, and transparent data management, to name a few.
- Principle 2: Distribution system operators must operate as neutral market facilitators in terms of their core electricity distribution activities.
- Principle 3: Distribution system operators must operate in the public interest, with due care for the cost and benefits of any activity undertaken.
- Principle 4: Electricity consumers own their data, and this should be considered by DSOs when managing data.

These principles were developed as a framework that considers both the complexity of the transition to a smarter electricity sector in the EU, with the idiosyncrasies on market structures, activity profiles, and technical characteristics of DSOs across Member States. Accompanying the new regulatory principles, a framework to regulate the role of the DSO in the future has also been presented (Fig. 1). This logical framework aims to guide policy makers and regulators when analyzing activities to be performed by DSOs in the future.

The framework acknowledges the reality that European and Member States policies and regulatory models may have to change for DSOs to operate new technologies and to enable new markets. Activities that can benefit from competition are generally kept outside of the DSO operations, or considered under specific circumstances, such as when no other player is actively developing an activity with positive benefit to consumers. The framework follows the logic that competition is the most adequate means to deliver cost efficient services, and also that DSOs have typically a low risk profile due to its monopoly characteristics, and that its costs are recovered through regulated tariffs (CEER, 2015).

Updating the policies and regulations affecting electricity distribution can contribute to mitigate uncertainties regarding the role of DSOs and their involvement in activities related with electric mobility and charging infrastructure, electricity storage, energy efficiency services, data management, and flexibility services (CEER, 2015).

2.1. Clean energy for All Europeans

Market transformation efforts towards a liberalized electricity sector in the EU have shaped electricity distribution and DSOs to operate as neutral market facilitators, given their regional monopoly characteristics. However, reforming a liberalized electricity sector industry to serve the need for a low-carbon future requires a new market design, accompanied by an understanding of how DSOs should operate and interact with new system elements.

The Clean Energy for All Europeans package represents the latest effort to develop a policy framework that accelerates the EU's clean energy transition, by focusing on renewable energy, energy efficiency, security of supply, governance, and the design of the electricity market (European Commission, 2016). As part of this policy package, a new electricity sector directive has been proposed and approved, with a revised role and scope for electricity distribution and DSOs (European Commission, 2017). The directive specifies the role of the DSO regarding the procurement of network services to ensure system flexibility, the integration of electric mobility and charging infrastructure, as well as electricity storage and data management.

Under this new policy approach, regulators are tasked with the implementation of the necessary mechanisms to incentivize the procurement of flexibility services that contribute to improved system efficiency and operations, such as local congestion management. Particularly, implemented regulations must enable the procurement of services from distributed energy resources (i.e.: distributed generation, demand response, electricity storage, and consider energy efficiency). Any flexibility systems procured must follow a market based, non-discriminatory, and transparent process. In terms of interaction with new technologies, DSOs are discouraged from owning, developing, managing or operating electric vehicle charging points and electricity storage units, unless no other parties have expressed interest (European Commission, 2017).

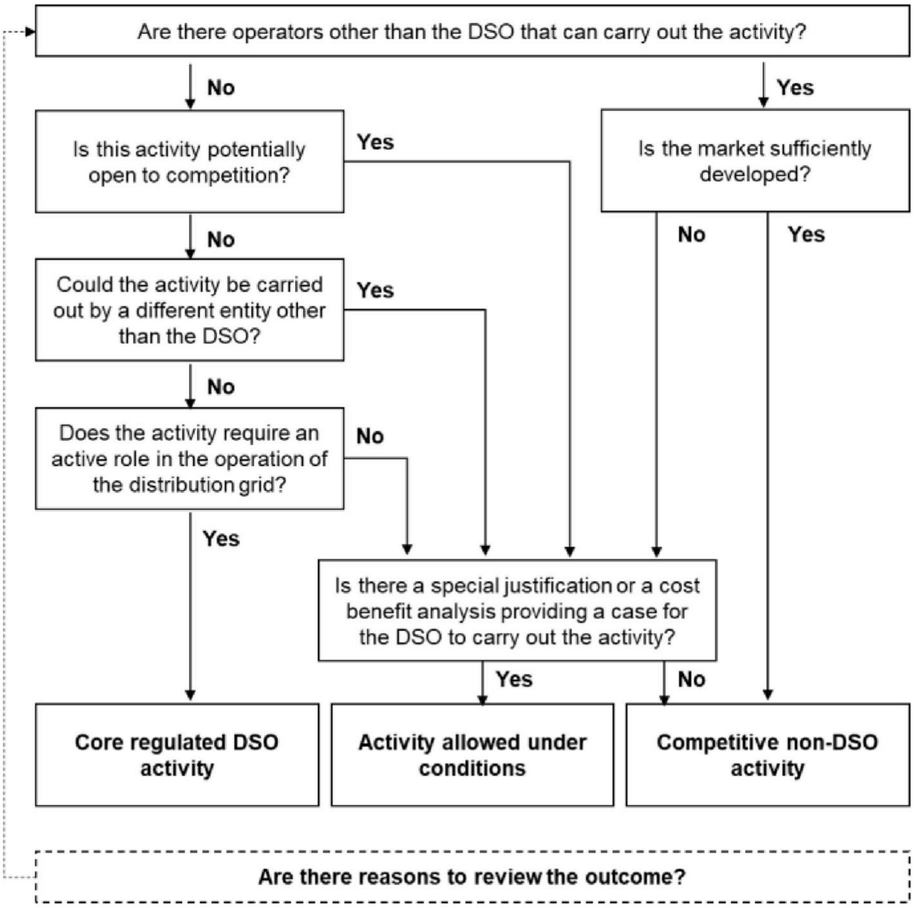

Fig. 1. Logical framework to evaluate electricity distribution activities. Source (CEER, 2015).

2.2. Evolution of regulatory models

The evolution of regulatory models to enable specific flexibility services and technologies will expand the scope of regulation as an important element to enable innovation and investments in smart grid technologies. Existing regulatory practices across the EU may expand to further specify how DSOs interact with new technologies and stakeholders, as these become more established parts of the electricity system. Upcoming regulatory approaches will build on previous efforts targeting quality of service and innovation and the need to encourage network operators to provide a reliable electricity distribution service while engaging in smart grid deployment (Eurelectric, 2014).

The regulatory models typically applied to DSOs can be characterized as cost-based regulatory approaches, and incentive-based regulatory approaches. Cost-based approaches can be applied through rate-of-return regulation, or cost-plus regulation. In a rate-of-return model the DSOs access a pre-defined return rate on their regulatory asset base. A cost-plus model gives the DSO a pre-defined profit margin to its cost structure. Cost-based regulatory models have been characterized by their low incentives for DSOs to minimize costs, as their profits benefit from a higher asset base or cost balance. Incentive-based approaches were implemented as an improvement compared to cost-based regulation. Incentive-based regulation is structured around rewards and penalties that aim to drive the DSO to achieve efficiency targets, normally aiming at cost control. This regulatory approach allows DSOs to capture part of the profits resulting from targets met or exceeded, while allowing network users to benefit from the efficiency gains through lower distribution network tariffs. Member States in the EU apply some form of incentive-based regulation, using a revenue cap, or a hybrid model, applying a mix of incentive-based cap regulation and a cost-based rate-of-return regulation (CEER, 2019), Table 1 shows the different regulatory models applied across EU countries.

Providing stimulus for innovation is also a strategic aspect that regulatory models must increasingly account for. The growth of available smart grid and automation technologies will require DSOs to engage in experimentation though R&D and demonstration pilots, which may not be cost efficient in the short-term, yet necessary to develop technical and operational capabilities to meet long-term digitalization and decarbonization goals (CEER, 2018). Despite the importance of supporting the implementation of smart grid and digital innovations, most Member States regulatory models still consider smart grid piloting and research activities as business as usual electricity distribution costs, despite the higher risk profile of testing new technologies and processes (Eurelectric, 2014), Fig. 2 shows the results of a survey on the type of regulatory mechanism available for innovation in EU countries conducted in 2014 and 2016. As a result, DSOs have considered regulation as a barrier when it comes to fostering innovation and R&D, Fig. 3 shows the results of a survey on the perception of the role of

Table 1
Regulatory models applied across EU 28 countries. Source: Gwerder et al. (2019).

Regulatory model	Countries
Cost	Belgium, Croatia, Cyprus, Greece, Malta
Hybrid	Czech Republic, Denmark, Estonia, Finland, Italy, Latvia, Poland, Portugal, Spain
Incentive	Austria, Bulgaria, France, Germany, Hungary, Ireland, Lithuania, Luxembourg, Netherlands, Romania, Slovakia, Slovenia, Sweden, United Kingdom

Fig. 2. Regulatory mechanisms to incentivize innovation and R&D. Source: Eurelectric (2014, 2016).

regulation for innovation conducted in 2014 and 2016. Despite the growth in the number of Member States, from 4 countries in 2014 to 9 in 2016, providing a specific regulatory mechanism to support innovation, only Finland, France, Ireland and the United Kingdom presented incentives for innovation that considered operational expenditures (i.e. OPEX) (Eurelectric, 2016).

Regulatory adaptation will require an assessment of the role of different regulatory tools and how these are applied to support and drive DSOs operations and innovation. A key aspect of new regulatory approaches is how electricity distribution costs are considered for calculating allowed revenues. The choice between a different approach to capital expenditures (CAPEX) and operational expenditures (OPEX), or a similar approach to both CAPEX and OPEX, or alternatively a total expenditures (TOTEX) approach. TOTEX approaches are considered as beneficial given that DSOs are generally not biased to overdo their OPEX or CAPEX costs to capture specific financial gains. This is particularly relevant considering the transition to a smarter and decarbonized electricity sector, through a TOTEX approach DSOs have the ability to define the necessary resources to meet regulatory goals, which can result in a higher proportion of OPEX in the short-term, while possibly reducing and deferring network investments (CEER, 2018). Therefore, TOTEX has been presented as a regulatory approach that supports electricity distribution operational efficiency, while allowing for innovation and R&D expenditures to take place.

2.3. *Electricity distribution system operators in the EU*

The EU electricity distribution system consists of approximately 2.400 DSOs, distributing 2.700 TWh a year to 260 million connected consumers (Eurelectric, 2013; Prettico et al., 2019). The liberalization of the electricity sector established that DSOs that are part of a vertically integrated company and serve over 100.000 connected consumers must meet legal, functional, and accounting unbundling requirements. In the EU this applies to 190 DSOs, while DSOs serving less than 100.000 connected consumers can be exempted from unbundling in order to achieve economies of scale by integrating other activities horizontally (Eurelectric, 2013; Pereira et al., 2020). In terms of electricity distribution system structure and characteristics, Member Sates present very differentiated ownership models, market concentration, and operational characteristics, associated with historical policy and infrastructure developments (Eurelectric, 2013).

The engagement of the DSOs in smart grid activities and investments is also an important characteristic to consider. The following indicators for engagement in smart grid activities are part of the European Commission Joint Research Centre (EC JRC) DSO observatory (Prettico et al., 2019; Prettico et al., 2016). In terms of use of non-ancillary services by DSOs, particularly demand flexibility programs, such as Demand Side Management (DSM) and Demand Response (DR), 57% of the surveyed DSOs have no engagement with flexibility programs, and 32% indicated that they engage in this type of non-ancillary service by implementing ripple control, alleviating constrained networks, and mass remote control, Fig. 4. Consumer engagement and managing active consumers is a relevant aspect of deploying smarter electricity distribution grids, as connected consumers with distributed generation or storage units, as well as those willing to participate in demand flexibility programs require a new customer centric approach. In this regard, the EC JRC survey found that only 28% of DSOs engage with active consumers/prosumers, which suggests that prosumers are largely managed as traditional passive consumers, Fig. 5. These indicators provide a broad perspective on the engagement of DSOs in non-ancillary services. This engagement can be direct, when linked to the grid management operations, in which DSOs take a leading role in developing, managing and providing flexibility services and managing consumers and consumer-producers loads, which in the current policy framework is discouraged (Section 2.1), with flexibility procurement being the suggested adequate pathway for grid operators. However, DSOs can also engage indirectly in the provision of flexibility services and active demand management, by participating in research and development and pilot programs to test new services and uses of smart grid infrastructure, as well as when cooperating with other service providers that require consumption and infrastructure data to provide flexibility services. This indirect engagement positions DSOs as important facilitators of flexibility services to be provided following a market-based, non-discriminatory, and transparent process by other market players.

In addition to smart grid operations, the extent to which DSOs are investing in smart grid projects and technologies provides an additional measure of industry characterization. Data released by the EC JRC smart grids observatory shows that by 2015 DSOs had invested a total of 814 Million Euros (M€) in smart grid projects, of which 142 M€ where directed to R&D, and 672.3 M€ for demonstration projects (Gangale et al., 2017), Fig. 6. DSOs have been identified as one of the most engaged stakeholders in terms of smart grid investments, having a key role in supporting the implementation of new infrastructure and processes (Pereira et al., 2019; Prettico et al., 2019).

Fig. 7 presents DSOs investments per smart grid domain, and specifies the source of funding, being either private funds, or public funds originating from European Commission or National budgets. Smart Network Management contributes to increased grid flexibility through the deployment of network monitoring and control equipment, as well as communication technologies. In this domain DSOs invested 377 M€, of which 300 M€ originated from private funds. Demand Side Management initiatives include those focused on shifting consumption temporally through DR programs, as well as energy efficiency improvement programs. These can include the implementation of consumer centric models, where smart meters, in-home displays and real time monitoring technologies are installed to increase awareness and shape behaviors. DSOs invested 206 M€ in this type of projects, of which 140 M€ came from the private sector. In terms of smart grid investments focused on the integration of new technologies DSOs invested 180 M€ for distributed generation and storage, 53 M€ for electric mobility, and 5 M€ for large scale renewable energy systems (Gangale et al., 2017; Prettico et al., 2019).

3. Methodology

To provide empirical evidence on the role of market, regulatory, investment, and firm factors on the transformation of electricity distribution systems we draw on a combination of primary and secondary data. Primary data was collected through a novel questionnaire applied directly to DSOs operating in the EU, as a means to obtain proxies on electricity distribution system transformation. Secondary data was collected for the factors utilized in the analysis.

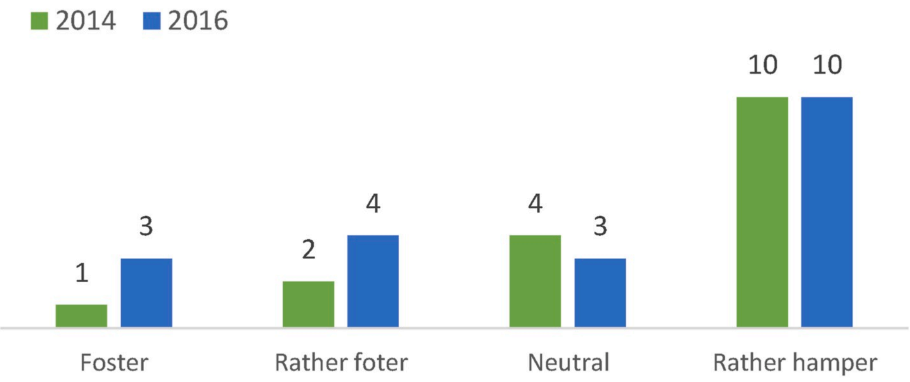

Fig. 3. Role of regulation in fostering DSOs engagement on innovation and R&D. Source: Eurelectric (2014, 2016).

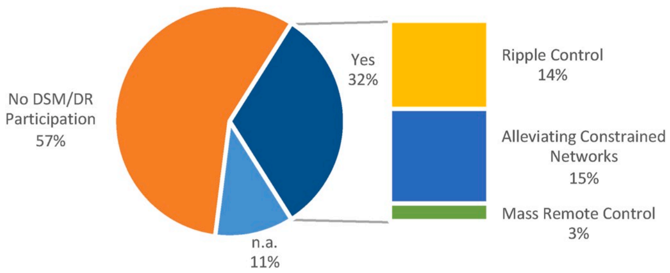

Fig. 4. DSOs engagement in flexibility programs. Source: Prettico et al. (2019).

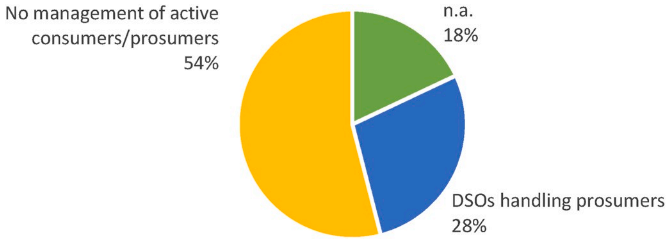

Fig. 5. DSOs engagement in active consumer management. Source: Prettico et al. (2019).

3.1. Data

3.1.1. Electricity distribution transformation

Data on electricity distribution system transformation was obtained through a questionnaire developed to measure DSOs capacity to change their role in the electricity sector as a result of ongoing technological and policy shifts. To formulate the items included in the questionnaire, we drew on Teece's business model innovation capabilities theoretical development, which provides a framework to obtain a granular understanding of firm's ability to adjust in rapidly changing markets, which we refine to study DSOs ability to adapt in a changing energy landscape (Teece, 2007, 2018). We applied an iterative process to develop the questionnaire, which included a calibration step with industry experts to further validate the relevance of the items included and the structure.

Questionnaire distribution targeted the population of approximately 2.400 DSOs present in the EU. This was achieved with the support of National Regulatory Agencies, which provided lists of electricity distribution companies operating in their jurisdictions, and was complemented with desk-based research by the authors. As a result of this effort we obtained a sample with data from 129 DSOs, of which 124 are used in this study, as submissions with incomplete data were removed from the sample. The data was collected in 2017.

Electricity distribution system transformation was measured using 18 survey items, which DSO representatives responding to the questionnaire rated using a 6-point Likert scale, with 1 for "Not capable at all" and 6 for "Extremely capable". Throughout the questionnaire development process the authors, in collaboration with industry experts designed the questionnaire items aiming at capturing two main themes. The first theme was related to (1) the ability of a DSO to foresee change, (2) the ability of a DSO to learn and capture the necessary competencies to adapt, and (3) the ability of DSOs to implement transformative actions as a result of the changing energy landscape. These dimensions can be regarded as broader, more general, firm-focused adaptation aspects (see Teece (2007) for a detailed theoretical development. The second theme was related to (1) the ability of DSOs to adapt to changes on policies and regulations applicable to electricity distribution and the electricity sector, (2) the ability of DSOs to adapt to changes in technologies, such as the integration of distributed generation and smart grid elements, and (3) the ability of DSOs to adapt their internal processes and firm characteristics as a response to the transformative changes taking place in the electricity sector. These dimensions can be regarded as electricity

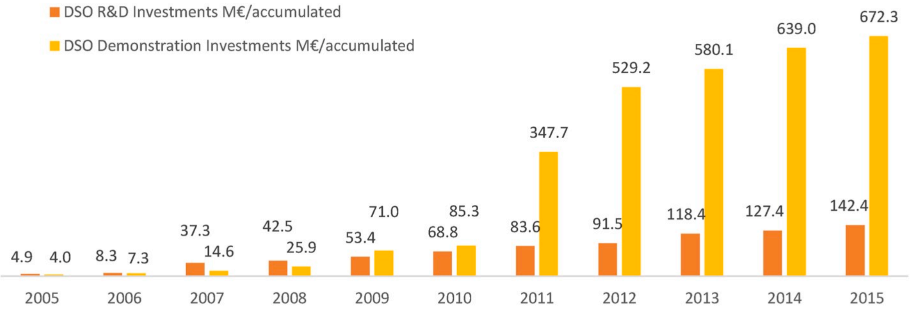

Fig. 6. DSOs smart grid investments, accumulated yearly investments, M€. Source: Gangale et al. (2017).

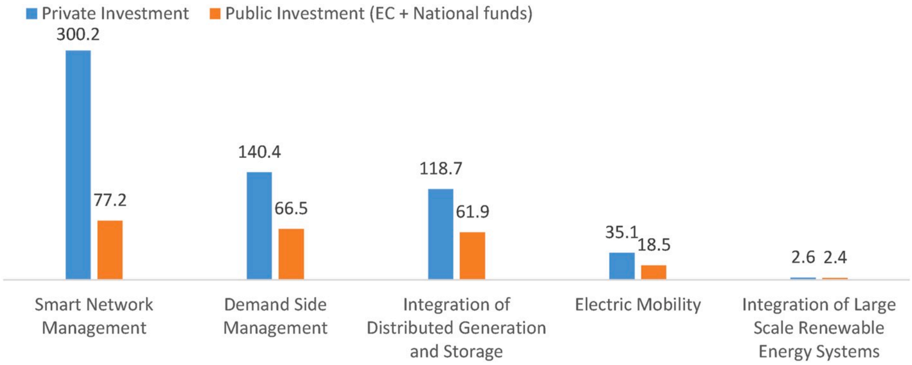

Fig. 7. DSOs smart grid investments, accumulated investments, 2002–2015, M€. Source: Gangale et al. (2017).

distribution system specific as they focus on the changes impacting electricity distribution infrastructure and DSOs, further discussed in Pereira et al. (2018b). The distribution of the questionnaire items across these two themes is presented in the Annexes, Table 9.

3.1.2. *Market, regulatory, investment and firm-level factors*

In this study we considered market, regulatory, investment, and firm factors and analyzed their role on electricity distribution system transformation. The different dimensions included in this empirical analysis provide a broader lens to study the adaptation of incumbent actors in the electricity sector, as is the case of DSOs. The selection of factors builds on previous contributions from Cambini et al. (2016) and Gwerder et al. (2019), which analyzed the impact of different market and regulatory factors on smart grid investments.

To capture market characteristics, our analysis includes a measure of DSOs market concentration, following Eurelectric (2013) classification, as being “Low concentration”, “Medium concentration”, and “High concentration”. Low concentration corresponds to the cases where the electricity distribution system is structured around small and local DSOs, in which the three largest DSOs distribute less than 50% of the electricity. Medium concentration corresponds to when the three largest DSOs distribute more than 60% of the electricity, or when one dominant DSO distributes 80% of the electricity. High concentration exists when one DSO distributes more than 99% of the electricity.[1]

The regulatory characteristics considered include the case when the DSO is subject to incentive regulation, or hybrid regulation.[2] Additionally, we also consider the cases in which innovation incentives schemes exist for DSOs, such as when the regulator defines a higher rate of return on smart grid related investments, or other mechanism that considers smart grid investments, or the costs associated with rolling out innovative technologies. The data for this factor was obtained from Gwerder et al. (2019).

Smart grid investments were considered in Cambini et al. (2016) and Gwerder et al. (2019), which studied the impact of market and regulatory factors on smart grid investments. In our approach we analyze the role of aggregate DSOs smart grid investments at the country level on DSOs transformation. Taking this into account we calculate the median of smart grid investments in $€/M€_{GDP}$ presented in Gwerder et al. (2019) and classify Member States as having “Low” or “High” smart grid investments, with “Low” for country level DSO investments smaller or equal to 9.22 $€/M€_{GDP}$ (i.e.: the median), or “High” for values greater than 9.22 $€/M€_{GDP}$. The data used for this measure is presented in the Annexes, Table 10.

Our assessment incorporates firm-level factors in order to understand if specific DSO-level characteristics influence their transformation, alongside other market, regulatory, and investment factors. For this we consider connected consumers as an important DSO attribute, particularly as the number of connected consumers has been used as a criterion in European Union legislation to decide on the degree of unbundling to which a DSO has to comply with. We classify the DSOs in two categories, as having up to 150.000 connected consumers, or over 150.000 connected consumers. We consider a 150.000 connected consumers threshold to be able to capture the subgroup of DSOs that while being subject to unbundling rules, due to their connected consumer base being above the existing 100.000 consumer threshold for unbundling, can still be considered as relatively small. Unbundling rules for electricity distribution networks have been implemented to provide a framework for a competitive internal energy market to be established, one in which network access, development, and operation is conducted in a non-discriminatory way. For this factor we consider if the DSO has been subject to any form of unbundling. Data for these firm-level factors was collected from DSOs through the questionnaire described in Section 3.1.1. Table 2 provides details on the factors considered in this study, as

Table 2
Factor frequencies.

Category	Factors		Frequency	%
Market	**DSO market concentration**	Low	62	50
		Medium	53	42.7
		High	9	7.3
Regulatory	**Regulatory mechanism**	Cost	5	4
		Hybrid	53	42.7
		Incentive	66	53.2
	Innovation support scheme	No	72	58.1
		Yes	52	41.9
Investment	**DSO investment in smart grids (Normalized by GDP)**	Low	36	29
		High	88	71
Firm-level	**DSO connected consumers**	Up to 150 000	37	29.8
		Over 150 000	87	70.2
	DSO unbundling	No	10	8.1
		Yes	114	91.9

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[1] The variable “DSO market concentration” considers three levels of concentration Low, Medium, and High. In our model we built it as three dummy variables, one for each category: DSO Market concentration (Medium), when yes Medium = 1, when no Medium = 0; DSO Market concentration (High), when yes High = 1, when no High = 0; and DSO Market concentration (Low), when yes Low = 1, when no Low = 0. However, we only introduce in the model N-1 dummy variables, therefore we use DSO Market concentration (Medium) and (High), the level (Low) is the base case.

[2] The same approach was followed for the “Regulatory mechanism” variables. The coefficient of Incentive regulation measures the difference between Incentive and Cost regulatory mechanism. The coefficient of Hybrid regulation measures the difference between Hybrid and Cost regulatory mechanism. As the introduced variables are: Regulatory mechanism (Incentive), when yes Incentive = 1, when no Incentive = 0; and Regulatory mechanism (Hybrid), when yes Hybrid = 1, when no Hybrid = 0. And Regulatory mechanism (Cost), when yes Cost = 1, when no Cost = 0, is left out, as Cost is the base case.

well as factor frequencies.

3.2. Methods and model specification

Our method of analysis is structured in two steps. In the first step we applied a factor model to reduce the dimensionality of the answers' obtained from the DSOs questionnaire, described in Section 3.1.1, down to fewer unobserved variables that may summarize the agent's behavior. We applied a factor model using an orthogonal Varimax rotation in order to identify the factors that maximize the variance of the square loading to each non-correlated factor. The determination on the number of factors to retain was guided by two criteria, the commonly used Kaiser criteria, as well as the Variance Extracted Criteria, with an aim to achieve a 75% Variance Extracted, as the variance accounted for in the retained factors (Kaiser, 1960; Watson, 2017). By applying a factor model we are able to investigate if any of the observed variables Y_1, Y_2, Y_3, …, Y_n are linearly related to a small number of unobserved (latent) factors F_1, F_2, …, F_k with $k < n$:

$$\begin{aligned}\boldsymbol{Y}_1 &= \lambda_{10} + \lambda_{11}\boldsymbol{F}_1 + \lambda_{12}\boldsymbol{F}_2 + \ldots + \lambda_{1k}\boldsymbol{F}_k + \boldsymbol{\varepsilon}_1\\ \boldsymbol{Y}_2 &= \lambda_{20} + \lambda_{21}\boldsymbol{F}_1 + \lambda_{22}\boldsymbol{F}_2 + \ldots + \lambda_{2k}\boldsymbol{F}_k + \boldsymbol{\varepsilon}_2\\ &\vdots\\ \boldsymbol{Y}_n &= \lambda_{n0} + \lambda_{n1}\boldsymbol{F}_1 + \lambda_{n2}\boldsymbol{F}_2 + \ldots + \lambda_{nk}\boldsymbol{F}_k + \boldsymbol{\varepsilon}_n\end{aligned}$$

Where the error terms are independent of each other and $\boldsymbol{E}(\boldsymbol{\varepsilon}_i) = 0$ ***and*** $\boldsymbol{Var}(\boldsymbol{\varepsilon}_i) = \boldsymbol{\sigma}_i^2$, and the factors are independent of each other with variance equal to one.

In the second step, we estimated a Tobit Type I model, to evaluate which variables explain the factors extracted (Tobin, 1958). A Tobit model is adequate in this case because our dependent variables are censored at one and six (the maximum and minimum of the Likert scale used in the questionnaire applied to DSOs, Section 3.1.1). Given the specification of our data using an OLS model would produce inconsistent estimators, namely biased estimates of the slope's coefficients and of the intercept, and therefore conceal the real association between the variables. The Tobit model expresses the observed response, $\boldsymbol{F}_i$, in terms of an underlying latent variable, $\boldsymbol{F}_i^*$:

$$\boldsymbol{F}_i^* = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1\boldsymbol{X}_1 + \boldsymbol{\beta}_2\boldsymbol{X}_2 + \boldsymbol{\mu}$$

Such that the latent variable $\boldsymbol{F}_i^*$ satisfies the classical linear model assumptions; in particular, it has a normal, homoscedastic distribution with a linear conditional mean. However, we just observe $\boldsymbol{F}_i$such that:

$$\boldsymbol{F}_i = \begin{cases} \boldsymbol{F}_i^* & \boldsymbol{if} \quad \boldsymbol{F}_L < \boldsymbol{F}_i^* < \boldsymbol{F}_U \\ \boldsymbol{F}_L & \boldsymbol{if} \quad \boldsymbol{F}_i^* \leq \boldsymbol{F}_L \\ \boldsymbol{F}_U & \boldsymbol{if} \quad \boldsymbol{F}_i^* \geq \boldsymbol{F}_U \end{cases}$$

The coefficients of the model are estimated by maximum-likelihood.

Notwithstanding the themes used for questionnaire design described in Section 3.1.1, given that the questionnaire used was developed specifically for this study, we conducted an Exploratory Factor Analysis to identify the structure of underlying themes present in the collected data, which we then used to reduce the initial set of questionnaire items. Regarding sample size adequacy, as a relevant factor in terms of reliability the Kaiser–Meyer–Olkin measure of sampling adequacy for our dataset is 0.946, a value close to 1 indicates that the sample is adequate to identify distinct and reliable factors (Field, 2009). In addition, as we aim to identify the underlying themes in a set of related questionnaire items, for this we use Bartlett's Test of Sphericity, with a χ^2 (153) = 2113.93, $p < 0.001$, indicating that the observed correlations are sufficiently large for the analysis. From the application of the Kaiser criteria and a Variance Extracted guideline of explaining at least 75% of the variance we retain 3 factors, explaining 75.91% of the variance [3] [4], Table 3. For robustness, we considered the impact of applying also Jolliffe (1972) criteria for retaining factors with eigenvalues above 0.7, based on which we would continue to retain 3 factors [5].

We considered the general structure the questionnaire items loading into each factor to identify the main theme they represent on the scope of the electricity distribution system transformation. Factor 1 aggregates items generally associated with transformation as a result of policy and regulatory shits, we labeled this factor as "Policy, regulatory and market design adaptation". Factor 2 combines questionnaire items generally associated with transformation resulting from the need to redefine internal processes, operations, and organizational structures, we labeled this factor as "Business model and organizational adaptation". Factor 3 combines items generally regarding transformation as a result of technological, system, and infrastructure changes, we labeled this factor as "Technological adaptation". Descriptive statistics for the factors are presented in Table 4.

As described above, we use Tobit regressions to estimate the effects of the previously defined market, regulatory, investment, and firm-level factors on the electricity distribution system transformation. Based on the three factors retained from the questionnaire on DSOs we specify three models, as described in Table 5, through which we study the effect of the independent variables described on the three factors identified related to DSO adaptation.

Through the underlying structure of the data identified from the factor analysis, the models specified (Table 5) allow us to conduct an exploratory empirical analysis of the role of market, regulatory, investment and firm-level characteristics on the transformation of electricity distribution systems, through a DSOs perspective as the operators of the electricity grid infrastructure. The models presented differ in the dependent variable being considered. Model 1 is specified with Factor 1 as dependent variable focusing on policy, regulatory, and market design adaptation. Model 2 is specified with Factor 2 as dependent variable focusing on business model and organizational adaptation. Lastly Model 3 is specified with Factor 3 as dependent variable focusing on technological adaptation.

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[3] In some cases, the Kaiser criteria has been identified to result in overestimation of the number of factors, however simulation studies have shown accuracy when using it to analyze less than 30 variables, and when the communalities of the observed variables are above 0.7 (Field, 2009). In addition to the possibility for overestimation, the Kaiser criteria has also been suggested as too strict given its guidance to only retain factors with eigenvalues above 1. In line with this a recommendation to retain factors with eigenvalues above 0.7 is suggested by Jolliffe (1972).In this analysis we apply the Kaiser criteria to 18 variables, below the suggested threshold under which Kaiser's criterion performs well, and communalities after extraction over 0.7 (communalities average of 0.712), above the suggested threshold. In addition, we also consider the Extracted Variance as part of the factor retention decision.

[4] In terms of model fit, we observe that retaining 3 factors results in 15 (9%) non-redundant residuals with values greater than 0.05, under the 50% recommended value (Field, 2009).

[5] Underlying data structures with 2 and 4 factors were also analyzed without an impact on the decision to retain 3 factors. A model with 4 factors would explain 79.6% of the variance, and result in 8 (5%) non-redundant residuals with values greater than 0.05, however the fourth factor would have an eigenvalue below 0.7 and 2 factors would having less than 3 meaningful loading items, thus a 4 factor underlying structure for the dataset under analysis would not result in a set of meaningfully different dimensions to retain as distinct factors (Zwick and Velicer, 1986). Conversely, a model with 2 factors would explain 70% of the variance, and result in 40 (25%) of non-significant residuals. Therefore, based on the initial questionnaire design themes, and the Kaiser criteria and Variance Extracted guideline, we retain a structure of 3 factors. Results are available from the authors upon request.

Table 3
Electricity industry transformation factor analysis.

Measured item	Factor loadings		
	1	2	3
Identify the resources needed to adapt our business strategy	0.63		
Identify the business areas that require adaptation	0.59		
Identify changes in policies and regulation to ensure the adequacy of our business strategy	0.61		
Influence policies and regulation to be aligned with our business strategy	0.70		
Understand the impact of policy and regulatory changes on our business	0.74		
Identify ways to adapt our business strategy to fit policy and regulatory requirements	0.72		
Adapt our activities and responsibilities given policy and regulatory changes	0.62		
Understand the implications of smart grid technologies		0.46	
Learn to integrate new technologies		0.59	
Adapt our organization to use new technologies (e.g. teams, responsibilities, departments, strategy, resource allocation, etc.)		0.71	
Change our business to use new technologies		0.75	
Systematically analyze future strategies as we move toward a smarter grid environment		0.55	
Develop flexible organizational practices that adapt to our business model and strategy		0.76	
Implement business changes to explore opportunities from policy and regulatory changes		0.66	
Identify system changes (e.g. understanding the impact of distributed generation, the impact of the current DSO-TSO relationship, etc.)			0.5
Identify the changing needs of grid users (e.g. accommodating the increasing number of smart homes, residential storage units, electric vehicles, etc.)			0.56
Identify technologies to improve the quality and efficiency of our operations			0.75
Identify new technologies (e.g. smart metering, electric vehicle charging infrastructure, flexibility management, etc.)			0.84

Extraction Method: Maximum Likelihood.
Rotation Method: Varimax with Kaiser Normalization.
Cumulative % of variance accounted by the 3 factors: 75.91%

Factor	Theme
1	Policy, regulatory and market design adaptation
2	Business model and organizational adaptation
3	Technological adaptation

4. Results and discussion

In the following tables (Table 6, Table 7, and Table 8) we present the estimations for the three models under analysis described above (Table 5). For each model we present the original specification on column (a). A specification including the base case of the dummy variables for "DSO market concentration: Low" and for "Regulatory mechanism: Cost regulation" on column (b). On the remaining columns (c), (d), and (e) we present the model estimation under alternative specifications when sequentially removing non-significant variables, with one variable removed per iteration. This approach allowed us to test the robustness of the results obtained in the original specification presented in (a). By testing for alternative model equation specifications in each model we observe that generally the variables that are significant over the complete specification, specification (a) for each model, are not only significant over alternative specifications but present similar estimated coefficients. Regarding the specification test, only model 2 has a low p-value for the normality of the residuals, even though we cannot reject the null hypothesis at 1%.

Table 4
Factor descriptive statistics.

Factor	N	Minimum	Maximum	Mean		Std. Deviation
				Statistic	Std. Error	
1	124	2	6	4.190	0.077	0.855
2	124	2	6	4.080	0.081	0.905
3	124	2	6	4.391	0.077	0.855

The results obtained contribute to a more detailed understanding of the role of market, regulatory, investment, and firm-level aspects in supporting a transition toward smart and decarbonized electricity distribution systems. Market concentration, included in our study to analyze the role of market characteristics, showed no significant effects across models. These results are in line with those presented in Gwerder et al. (2019), which found no association between electricity distribution sector concentration and investment in smart grids. Noteworthily, both our findings and those presented by Gwerder et al. (2019), differ from the results presented on an earlier study from Cambini et al. (2016), which found a significant impact of market concentration on smart grid investments, with lower concentration associated with higher levels of investment in smart grids. Our empirical evidence expands on the findings on the changing dynamics of market structures presented in Pereira et al. (2018b), which indicated that "*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.*" (Pereira et al., 2018b: p.436). Therefore, our findings suggest that despite the diversity of market concentrations observed across Member States these are not a significant determinant of DSO's ability to transition and adapt to a changing electricity sector landscape.

In terms of regulatory dimensions, our results indicate that hybrid regulatory models contribute to business model and organizational adaptation (Table 7, Model 2, $\beta = 1.241$), and to technological adaptation (Table 8, Model 3, $\beta = 0.891$), while no significant effects were observed in terms of policy, regulatory, and market design adaptation (Table 6, Model 1). Incentive based regulatory models showed no significant effects across models. Our findings are partly in line with those presented in Cambini et al. (2016) and Gwerder et al. (2019), which found that both hybrid and incentive based regulatory approaches perform better at promoting smart grid investments than cost based regulatory approaches. Our findings further substantiate that hybrid models are more effective regulatory approaches to support the need for new investments in infrastructure and services as part of the transition to smart distribution grids. The evidence obtained of no significant effect of incentive regulation on DSOs adaptation benefits from the insights provided in Pereira et al. (2018b), which discussed DSOs perspectives, and indicated that when incentive regulation is focused mostly on achieving greater operational efficiency it can represent *"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"* (Pereira et al., 2018b: p.436). Notwithstanding, Cossent et al. (2009) argued the importance of incentive regulation, applied to OPEX and CAPEX for a transition to a distribution system with high shares of distributed generation, one of the key components of a smarter and decarbonized electricity sector. These perspectives combined suggest the need to reconsider the incentive mechanisms available in existing regulatory models to meet the needs of a changing electricity distribution system, particularly how these could be used regarding different expenditures types at the DSO level.

Additionally, we found no significant effect for regulatory models comprising a dedicated innovation support scheme, such as the existence of increased rate of return for investing in smart grids. This finding

Table 5
Tobit model specification.

		Model 1	Model 2	Model 3
Dependent variable		Factor 1 *"Policy, regulatory and market design adaptation"*	Factor 2 *"Business model and organizational adaptation"*	Factor 3 *"Technological adaptation"*
Independent variables	**Market**	DSO market concentration	DSO market concentration	DSO market concentration
	Regulatory	Incentive regulation Hybrid regulation Innovation support scheme	Incentive regulation Hybrid regulation Innovation support scheme	Incentive regulation Hybrid regulation Innovation support scheme
	Investment	DSO investment in smart grids	DSO investment in smart grids	DSO investment in smart grids
	Firm	DSO connected consumers DSO unbundling	DSO connected consumers DSO unbundling	DSO connected consumers DSO unbundling

Table 6
Model 1 (Factor 1 "Policy, regulatory and market design adaptation" determinants).

		Specification				
		Original	**With base case dummies**	**Alternative**		
		(a)	**(b)**	**(c)**	**(d)**	**(e)**
Constant		3.072*** (0.535)	3.6591*** (0.521)	3.058*** (0.534)	3.133*** (0.492)	3.432 *** (0.306)
Market	***DSO market concentration (Low) (Base case)***		*−0.131 (0.347)*			
	DSO market concentration (Medium)	0.062 (0.180)	−0.069 (0.385)			
	DSO market concentration (High)	0.131 (0.347)		0.126 (0.347)		
Regulatory	***Cost regulation (Base case)***		*−0.456 (0.498)*			
	Incentive regulation	0.338 (0.451)	−0.118 (0.180)	0.375 (0.438)	0.305 (0.393)	
	Hybrid regulation	0.456 (0.498)		0.503 (0.480)	0.412 (0.410)	0.122 (0.168)
	Innovation support scheme	−0.179 (0.211)	−0.179 (0.211)	−0.201 (0.201)	−0.181 (0.192)	−0.167 (0.192)
Investment	**DSO investment in smart grids**	0.284 (0.192)	0.284 (0.192)	0.286 (0.192)	0.278 (0.191)	0.276 (0.191)
Firm	**DSO connected consumers**	0.390** (0.186)	0.390** (0.186)	0.413** (0.173)	0.402** (0.171)	0.390** (0.170)
	DSO unbundling	0.345 (0.287)	0.345 (0.287)	0.338 (0.286)	0.354 (0.283)	0.343 (0.283)
Sigma		0.836 (0.054)	0.836 (0.054)	0.836 (0.054)	0.836 (0.055)	0.838 (0.055)
N		124	124	124	124	124
Likelihood Ratio test		12.480 [0.131]	12.480 [0.131]	12.480 [0.131]	12.214 [0.057]	11.562 [0.041]
Normality test		1.512 [0.469]	1.512 [0.469]	1.512 [0.469]	1.711 [0.424]	2.219 [0.330]

Notes: numbers in parentheses are z-statistics and numbers in square brackets are p-values P>|z||.
***, **, * indicate that coefficients are statistically significant at the 1%, 5% and 10% significance level, respectively.

Table 7
Model 2 (Factor 2 "Business model and organizational adaptation" determinants).

		Specification				
		Original	**With base case dummies**	**Alternative**		
		(a)	**(b)**	**(c)**	**(d)**	**(e)**
Constant		2.798*** (0.554)	4.387*** (0.540)	2.675*** (0.507)	2.631*** (0.505)	2.849*** (0.437)
Market	***DSO market concentration (Low) (Base case)***		*−0.349 (0.359)*			
	DSO market concentration (Medium)	0.130 (0.186)	−0.219 (0.398)	0.137 (0.186)		
	DSO market concentration (High)	0.349 (0.359)		0.319 (0.355)	0.306 (0.356)	
Regulatory	***Cost regulation (Base case)***		*−1.241** (0.516)*			
	Incentive regulation	0.731 (0.467)	−0.509** (0.817)	0.720 (0.467)	0.801* (0.455)	0.628 (0.409)
	Hybrid regulation	1.241** (0.516)		1.209** (0.514)	1.310*** (0.496)	1.090** (0.426)
	Innovation support scheme	−0.294 (0.219)	−0.294 (0.219)	−0.271 (0.215)	−0.319 (0.206)	−0.273 (0.199)
Investment	**DSO investment in smart grids**	0.341* (0.199)	0.341* (0.199)	0.333* (0.199)	0.337* (0.199)	0.319* (0.199)
Firm	**DSO connected consumers**	0.464** (0.192)	0.464** (0.192)	0.447** (0.190)	0.498*** (0.178)	0.473*** (0.176)
	DSO unbundling	−0.161 (0.297)	−0.161 (0.297)			
Sigma		0.865 (0.057)	0.865 (0.057)	0.866 (0.057)	0.868 (0.057)	0.870 (0.057)
N		124	124	124	124	124
Likelihood Ratio test		20.559 [0.008]	20.559 [0.008]	20.215 [0.005]	19.611 [0.003]	18.771 [0.002]
Normality test		5.486 [0.064]	5.486 [0.064]	6.562 [0.038]	7.821 [0.020]	7.847 [0.020]

Notes: numbers in parentheses are z-statistics and numbers in square brackets are p-values P>|z||.
***, **, * indicate that coefficients are statistically significant at the 1%, 5% and 10% significance level, respectively.

differs from the results presented in Cambini et al. (2016) and Gwerder et al. (2019), which found that innovation mechanisms contributed to higher levels of investment in smart grids. This may be an indicator of the existence of a lag on the effect of dedicated innovation incentives between smart grid investments and DSO adaptation, which is sensible as investments are typically the initial step on a process of adaptation, followed by a reform of assets, activities, and responsibilities, all of which combined contribute to redefining the position of the DSOs in the electricity system.

Regarding the investment dimension, in this study represented by

Table 8
Model 3 (Factor 3 “Technological adaptation” determinants).

		Specification				
		Original	With base case dummies	Alternative		
		(a)	(b)	(c)	(d)	(e)
Constant		3.240*** (0.550)	4.513*** (0.537)	3.088*** (0.504)	3.165*** (0.493)	3.356 (0.437)
Market	***DSO market concentration (Low) (Base case)***		*−0.383 (0.356)*			
	DSO market concentration (Medium)	0.140 (0.185)	−0.242 (0.396)	0.150 (0.185)	0.190 (0.177)	0.171 (0.176)
	DSO market concentration (High)	0.383 (0.356)		0.345 (0.353)	0.286 (0.344)	
Regulatory	***Cost regulation (Base case)***		*−0.891* (0.513)*			
	Incentive regulation	0.718 (0.463)	−0.173 (0.187)	0.703 (0.464)	0.618 (449)	0.476 (0.416)
	Hybrid regulation	0.891* (0.513)		0.851* (0.511)	0.711 (0.471)	0.540 (0.425)
	Innovation support scheme	−0.180 (0.219)	−0.180 (0.219)	−0.151 (0.215)		
Investment	**DSO investment in smart grids**	0.380* (0.198)	0.380* (0.198)	0.370* (0.198)	0.305* (0.175)	0.307* (0.176)
Firm	**DSO connected consumers**	0.453** (0.191)	0.453** (0.191)	0.433** (0.189)	0.430** (0.189)	0.410** (0.188)
	DSO unbundling	−0.200 (0.295)	−0.200 (0.295)			
Sigma		0.858 (0.058)	0.858 (0.058)	0.860 (0.058)	0.862 (0.058)	0.865 (0.058)
N		124	124	124	124	124
Likelihood Ratio test		15.392 [0.052]	15.392 [0.052]	14.863 [0.038]	14.315 [0.026]	13.550 [0.019]
Normality test		3.494 [0.174]	3.494 [0.174]	2.844 [0.241]	2.412 [0.299]	3.014 [0.222]

Notes: numbers in parentheses are z-statistics and numbers in square brackets are p-values P>|z||.
***, **, * indicate that coefficients are statistically significant at the 1%, 5% and 10% significance level, respectively.

the level of DSOs investment in smart grids, the results indicate that a greater level of investment contributes to both business model and organizational adaptation (Table 7, Model 2, $\beta = 0.341$), and to technological adaptation (Table 8, Model 3, $\beta = 0.380$), while no significant effects were observed in terms of policy, regulatory, and market design adaptation (Table 6, Model 1). This evidence reinforces the relevance of directing funding to develop and implement smart grid technologies. In addition, these results contribute to establish the link between the ongoing financial efforts as part of the energy transition and their contribution to the transformation of the electricity distribution system.

The results obtained in terms of firm characteristics indicate that a higher level of connected consumers, here used as a proxy for DSO size, contributes to adaptation across models (Model 1, $\beta = 0.39$, Model 2, $\beta = 0.464$, Model 3, $\beta = 0.453$). These results further expand the insights presented in Pereira et al. (2018b), which indicated that larger DSOs had greater adaptation challenges due to their more traditional business structure, while smaller DSOs faced adaptation challenges related to rolling out smart grid and smart metering technology, operating the electricity distribution grid in small isolated areas, achieving economies of scale, and acquiring new technologies. The findings obtained in this study provide further insight and indicate that larger DSOs are better positioned to adapt. Our results further complement the analysis presented in Poudineh and Jamasb (2016), which using a sample of Norwegian firms, found that electricity distribution companies investments were not responsive to the number of connected consumers.

Regarding unbundling, no significant effects were observed, indicating that across our sample of 124 DSOs unbundling does not interfere with electricity sector adaptation. This result can be considered as further supporting the unbundling rules in place in European legislation, which have been implemented to contribute to market integration in an increasingly complex electricity system (Cossent et al., 2009; Ruester et al., 2014).

5. Conclusions and policy implications

The ongoing energy transition is reshaping the electricity sector and how it interfaces with disruptive technologies, ambitious energy policies, and new demand and supply dynamics. At the interface of these rapid changes, electricity distribution networks, and DSOs responsible for their adequate functioning, are tasked with the need to adapt to a smarter and decarbonized future, while ensuring ongoing quality of service. This context imposes a challenging need to balance the need for distribution service reliability, while supporting innovation and the experimentation with new technologies and approaches at the grid edge.

Through this study we aimed to expand the extant literature on DSOs adaptation. We focused on providing empirical evidence on the role of market, regulatory, investment, and firm-level factors on DSOs adaptation, by drawing on a novel dataset with data from 124 EU DSOs.

Our findings contribute guidance to ongoing policy design efforts following the recent Clean Energy for All Europeans approved electricity directives and regulation. Hybrid regulatory models were found to be beneficial to DSOs adaptation. Regulators may consider this as a positive sign for further developing and implementing hybrid models that balance both the need of regulatory measures that support the efficiency of grid planning, deployment, management and operation, as well as adequate levers to build capacity for a smarter and decarbonized grid.

Investing in smart grids R&D and demonstration was found to contribute to DSOs adaptation. This finding supports the effectiveness of devoting funds to experimenting and developing smart grid technologies. Regulators and policy makers can consider this finding as a positive reinforcement of the capacity building benefits of allowing DSOs to allocate financial resources for smart grids projects and initiatives. Moreover, this empirical evidence can be considered by policy makers and program managers responsible for designing the investment roadmap to be implemented in the next Framework Program after Horizon 2020.

Regarding DSO firm-level characteristics, we find that unbundling does not affect adaptation. This finding further contributes to the established practice in the European Union of mandating unbundling as a necessary step for non-discriminatory functioning of the distribution networks, and as a key pillar for achieving an internal energy market. Notwithstanding, we observe that larger DSOs are better able to adapt to a changing electricity sector. This finding must be considered by policy makers working on market design issues, and calls for a better understanding of how DSO size affects the delivery of smarter and decarbonized grids in the regions they operate. This may create the need for more granular policy approaches to manage the challenges faced by smaller DSOs when deploying smart grids and integrating distributed energy resources.

The findings presented in this study are limited by the DSO sample obtained and the proxies used to represent market, regulatory, investment, and firm-level characteristics. This study represents an initial effort in understanding electricity sector incumbents’ behavior, beyond the established practice of understanding factors affecting investments. These results can be further expanded by including new proxies across dimensions. Future studies can further elaborate on the approach presented and test different outcome variables associated with different measures of electricity sector adaptation and transformation, such as smart grid delivery, and digitalization.

Declaration of competing interest

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

CRediT authorship contribution statement

Guillermo Ivan Pereira: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Patrícia Pereira da Silva:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Pedro André Cerqueira:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

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Annexes.

Table 9
Questionnaire development themes

Theme 1	Theme 2	Questionnaire item
Change foresight	***Technology***	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.)
	Firm	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.)
	Policy and regulatory	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
Learning	***Technology***	Understand the implications of smart grid technologies
		Learn to integrate new technologies
	Firm	Identify the resources needed to adapt our business strategy
		Identify the business areas that require adaptation
	Policy and regulatory	Understand the impact of policy and regulatory changes on our business
		Identify ways to adapt our business strategy to fit policy and regulatory requirements
Transformation	***Technology***	Adapt our organization to use new technologies (e.g. teams, responsibilities, departments, strategy, resource allocation, etc.)
		Change our business to use new technologies
	Firm	Systematically analyze future strategies as we move toward a smarter grid environment
		Develop flexible organizational practices that adapt to our business model and strategy
	Policy and regulatory	Adapt our activities and responsibilities given policy and regulatory changes
		Implement business changes to explore opportunities from policy and regulatory changes

Table 10
DSO smart grid investment, adapted from Gwerder et al. (2019).

Country	Country Code	Average GDP M€ 2008–2015	DSO Investment R&D + Demo M€ 2008–2015	DSO Normalized investment €/M€ of GDP
Austria	AT	313493.775	7.01038	22.3621
Belgium	BE	379702.125	11.1054	29.2476
Bulgaria	BG	79710.525	0.51182	6.42096
Switzerland	CH	623471.95	0	0
Cyprus	CY	18711.0375	0	0
Czech Republic	CZ	4127294.625	32.0556	7.76672
Germany	DE	2733227.5	68.7751	25.1626
Denmark	DK	1876312.25	2.77847	1.48081
Estonia	EE	17378.5625	0	0
Greece	EL	204926.45	2.03827	9.94637
Spain	ES	1066248.375	91.2384	85.5695
Finland	FI	197111.875	9.26433	47.0003
France	FR	2067083.625	106.415	51.4809
Croatia	HR	334182.55	0	0
Hungary	HU	29386466.88	4.8	0.16334
Ireland	IE	188726.1875	4.96234	26.2939
Italy	IT	1617356.288	58.3435	36.0734
Lithuania	LT	32654.6375	0	0
Luxembourg	LU	43894.2625	7.5	170.865
Latvia	LV	21771.275	0	0
Malta	MT	7279.8875	0	0

(*continued on next page*)

Table 10 (*continued*)

Country	Country Code	Average GDP M€ 2008–2015	DSO Investment R&D + Demo M€ 2008–2015	DSO Normalized investment €/M€ of GDP
Netherlands	NL	646940.125	19.1073	29.5349
Norway	NO	2842264.125	8.23871	2.89864
Poland	PL	1559485	7.94298	5.09334
Portugal	PT	175246.5875	11.0771	63.2088
Romania	RO	593439.4	5.04304	8.49798
Sweden	SE	3680511	23.1226	6.28243
Slovenia	SI	37004.1125	4.71381	127.386
Slovakia	SK	71572.1	0.72183	10.0853
United Kingdom	UK	1685065	284.35	168.747

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