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ORIGINAL ARTICLE

The effects of network regulation on electricity supply security: a European analysis

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Abstract This paper analyzes the interactions of the regulation of distribution networks and electricity supply security. In particular, the hypothesis is tested that *output*-based regulatory frameworks, which implicitly take into account quality-of-supply-criteria, improve the level of reliability vis à vis purely *incentive*-based schemes. To do so, novel empirical evidence is analyzed based on a cross-country panel data set covering 27 countries for the period from 1999 to 2013. Regional heterogeneity and potential endogeneity are controlled for. We find that the introduction of *output*-based regulation, *ceteris paribus*, leads to reductions of the annual outage duration by 16.05 % on average when compared to *incentive*-based systems. Given the substantial economic costs of power outages, marginal reliability improvements have considerable economic effects, which can now be quantfied. In the, admittedly hypothetical, case that EU member states, who have not yet done so, were to implement quality-controlling regulation, macroeconomic benefits amount to 930 m. € p.a. The findings support the argument that the value of electricity supply security should be explicitly accounted for when revising regulatory regimes in the future and that investment and maintenance possibilities for regulated firms need to adequately reflect the economic benefits of high levels of service reliability.

Keywords Electricity network regulation · Supply security · Reliability · Infrastructure enhancement · Econometric Analysis

JEL Classification G18 · L51 · Q41 · Q43

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1 Introduction

An uninterrupted and predictable supply of electricity is considered an essential attribute of industrialized countries. Ensuring high levels of supply security[1] has thus become an important objective of national and international energy policy.[2] Being a direct policy tool, the regulation of distribution networks affects the characteristics of power markets substantially. Historically however, regulation of networks primarily aimed at reducing electricity prices. Thus, independent regulatory authorities were established as a consequence of Directive 96/92/EC (European Commission 1996)[3] which initiated the liberalization of energy markets.[4]

In the light of increasingly interconnected European electricity markets however, the necessity has grown to harmonize national efforts to enhance supply security and apply best-practice regulatory schemes. The period investigated in this paper and the cross country structure of the European Union are well suited for efficacy assessments since cross-sectional data of regulation and supply security indices are available for a duration of 15 years. Furthermore, the time span was characterized by substantial organizational changes in the relevant electricity markets. These included the vertical disintegration of utilities, the privatization of state-owned firms in various countries, as well as the introduction of regulatory frameworks and independent authorities to monitor network tariffs (as evidenced in Karan and Kazdagli 2011 as well as European Commission 2006 and 2003).

Whereas the effects of regulation for transmission and distribution networks on electricity prices are well researched, evidence regarding the ramifications with regards to supply security remains scarce. This paper aims at closing this gap by analyzing the effects that different frameworks for regulating distribution systems have had on duration and frequency of power outages in the EU. Furthermore, the channels of interaction between regulatory authorities, politics and regulated firms are assessed. To do so, novel empirical evidence based on a cross-country data panel of 27 European countries for the period from 1999 until 2013 is assessed with special regard to distribution networks.[5] The remainder of this paper is structured as follows: Sect. 2 reviews the relevant literature and investigates the current status and differences of reg-

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[1] Which Eurelectric (2006) defines as: *"the ability of the electric power system to provide electricity to end-users with a specified level of continuity and quality in a sustainable manner, relating to the existing standards and contractual agreements at the points of delivery.* This is followed. However, while reliability optima are*a priori* unknown, a *1-day-in-10-years* outage frequency is commonly cited (see Telson 1975 and Brown 2002).

[2] The adverse consequences of failing infrastructure became obvious in a series of widespread power outages in 2003 and 2006, which were shown to have substantial social consequences (Bompard et al. 2011).

[3] This applies for those who have not done so prior to its introduction, such as the UK or Scandinavian countries.

[4] Recent policy developments in the EU extend trans-national frameworks to climate policy and for instance require the introduction of binding legislation promoting energy efficiency, 'green' energy production based on at least 20–27 % renewable energy sources until 2020 and 2030 respectively, the goal to reduce greenhouse gas emissions, and to enhance cross-border electricity transmission (European Parliament 2013).

[5] This is due to the fact that failures thereof account for more than 90 % of power interruptions in Europe (Council of European Energy Regulators 2012).

ulatory frameworks in the EU. Section 3 describes the utilized data and explains the methodology of the empirical models. Section 4 contains the results of the quantitative analyses, while Sect. 5 summarizes and concludes.

2 Regulatory theory and practice

Europe's move towards seamlessly interconnected electricity grids and markets is accompanied by the necessity to further harmonize the existing national regulatory approaches. Consequently, the need for a stronger link between quality of supply and regulation is widely recognized in the European Union (EU). This is also reflected by the activities to synchronize supply security indicators, by investment incentives for trans-national grid expansions[6] and by the legislative mandate to trans-nationally assess the economic costs of power outages.[7]

The interconnection between regulatory authorities and the behavior of distribution system operators (DSO) on the other hand has been investigated in a variety of studies. For instance, Cambini and Rondi (2010) assessed the interaction between regulation investments and operational costs.[8] Petrov et al. (2010) analyzed the general explicit and implicit drivers for grid investment with a focus on *incentive* and *rate-of-return* regulation while Poudineh and Jamasb (2013) do so for the special case of Norway.[9] Efficient regulatory frameworks are essential since market-driven forces, which exist to some extent in electricity generation, do not exist in regulated natural monopolies.[10] The debate on reliability-influencing factors accelerated further, as economic research has made substantial progress in quantifying the value of electricity supply security at the European level.[11] Still, empirical research primarily focused on evaluating the regulatory effects mostly in terms of consumer prices, productivity and macroeconomic benefits.

For instance, Haberfellner et al. (2002) presented evidence for lower electricity prices as a result of liberalization in Austria. Kratena (2004 and 2011) found substantial productivity increases of supply and distribution companies under regulation and

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[6] These are supported by the European "Projects of Common Interest (PCI)" scheme. Improved data collection is— among others—suggested by Council of European Energy Regulators (2012, p. 58) which announces the urgent necessity to, "*exchange information on continuity of supply and its regulation*", and to, "*investigate continuity of supply trends for a periodic review of regulation*".

[7] Directive 2003/54/EC (European Commission 2003) highlights the necessity that electricity supply security related aspects of electricity market regulation be considered in conjunction with price effects. For a thorough discussion of reliability valuation it is referred to Reichl et al. (2013), Bertazzi et al. (2005), de Nooij et al. (2007) or Lawton et al. (2003) for the United States.

[8] Eurelectric (2014) presented the industry's viewpoints, with adverse effects regulation has had on investments.

[9] Further analyses were carried out by Jongpepier and Hulshorst (2005).

[10] For an in-depth discussion on market structures, competition and regulatory characteristics it is referred to Depoorter (1999). In this paper regulation exclusively concerns stationary distribution network infrastructure for which the variable costs do not grow proportionally with its utilization.

[11] The macroeconomic importance of uninterrupted service is assessed among others in (Schmidthaler and Reichl 2014). This allows the monetization of net-benefits associated with improvements of electricity supply security due to successful regulatory amendments, which is carried out in Sect. 5.

identified a strong effect of regulation on the network prices. Accordingly, Austrian grid tariffs decreased by one cent per kWh[12] for industrial customers and 1.5 cent per kWh for households between 2001 and 2003. In total, these reductions represented a 12 % decrease of overall electricity prices.[13] While Doove et al. (2001), in contrast, found evidence for a positive correlation between electricity price and regulation—though the authors question the robustness of these findings—the majority of studies report a positive performance effect of regulated DSO (see for instance Steiner 2000).[14]

The interaction of electricity supply security and specific regulatory characteristics is less well researched. Jamasb and Pollitt (2007) as well as Giannakis et al. (2005) analyzed *incentive*-based regulatory schemes with a special focus on supply security for the British electricity market Haber (2005) evaluated different quality-standards for regulation and suggested a comprehensive solution for the medium voltage system in Austria to foster service reliability.

Ter-Martirosyan and Kwoka (2010) conducted a thorough empirical analysis with respect to the interaction of regulation and quality of supply in electricity networks for various utilities and states in the United States. Their main finding is that *incentive*-based regulatory schemes, without quality controls, can lead to deteriorating levels of electricity supply security. Accordingly, quality standards are found to improve supply security when explicitly accounted for in regulatory regimes. This is supported by earlier work of Ter-Martirosyan (2003) who showed that combining *incentive* regulation with quality standards reduces the average power interruption duration by 11 % p.a.[15] Joskow (2011) as well as Groenli and Haberfellner (2002) analyzed different schemes for electricity market regulation and provide insights into different experiences following the implementation. While improvements in terms of supply security are evident, it is found to being "*difficult to disentangle the effects of privatization, restructuring and incentive regulation from one another*" (Joskow 2011). In other sectors, the effects of the introduction of market regulation have been analyzed more thoroughly. Uri (2003) and Sappington (2003) for instance discussed the experiences in the telecommunication industry, which—while different—has a similar regulatory history thereby providing evidence on the best practices for incorporating quality standards into network regulation.

Furthermore, auxiliary effects from regulation such as its influence on the profitability of power companies and distribution system operators have been assessed in great detail. Cambini and Rondi (2010) analyzed the effects of regulation on investment behavior. Interestingly, they find that in the first decade after market reforms in the EU, utilities invest relatively more if *incentive* regulation regimes are in place than

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[12] Throughout the paper, the European currency, Euro (€) as well as cents (ct) are utilized; the exchange rate of for one € was set at 1.24 U.S. $ in November 2014.

[13] As a result, GDP in Austria is found to having increased by one percent for the period from 2001 and 2011.

[14] However, contradictory evidence exists; Zhang et al. (2005) for example, pointed out for developing countries that the mere introduction of competition does not lead to higher productivity of the regulated companies.

[15] However, apart from regulation various factors , such as public resistance, social factors and market uncertainties, are found to hinder investments into the grid infrastructure (see Cohen et al. 2014).

is the case with *rate-of-return* regulation.[16] Assessing the political goals of regulation, Jamasb and Pollitt (2007) asserted that quality regulation generally aims at achieving an equilibrium between benefits and macroeconomic costs. Regulation thus serves as an instrument to find an optimal level of reliability.

2.1 Liberalization, unbundling and privatization in the EU

In most member states of the European Union, liberalization took place in the period from 1998 to 2008 in which state-owned utilities responsible for generation, transmission and distribution were dismantled and in some countries (partly) privatized. Parallel to this unbundling, independent regulatory authorities had been established with the clear objective to govern certain infrastructure elements of the energy system (see Nixon 2009 for a discussion of natural monopolies) while generation, trading and services started to face competition. Thus, in addition to regulatory influences, electricity markets also faced substantial paradigm shifts due to policy interventions and market developments, which assessments of regulatory efficacy in terms of reliability thus needs to explicitly control for.[17]

2.2 Classification of regulatory regimes

In this paper, the differentiation between regulation frameworks was conducted on the basis of data provided by Conway and Nicoletti (2007), applying definitions[18] by Vogelsang (2010), Braeutigam (1989), Cambini and Rondi (2010) and Haber (2005). This classification includes four distinct frameworks: (a) no regulation (*no reg*), (b) rate-of-return regulation (*ROR*), (c) incentive regulation (*incentive*), and (d) output-based regulation (*output*).

Most of these regulatory frameworks have been applied throughout Europe in different intensities and for periods from 2 to 15 years. In recent years, a trend towards more homogeneous and *output*-orientated regulatory frameworks is observable in the EU. This development is illustrated in Fig. 1, which depicts the classification of regulatory schemes for 2004 and 2009, respectively.[19]

Rate-of-return (*ROR*) regulation,[20] used to be the dominating regulatory scheme. *ROR* requires that the revenue from grid operation cannot exceed the costs of operation plus some set return on investment and profits. Thus, after subtraction of operating

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[16] This is subject to endogeneity (ownership), which once controlled for, changes the situation drastically.

[17] This includes the increasing trans-European power exchanges, such as the introduction of smart technologies in various countries, which DSO are in many countries responsible for, thereby making them relevant for regulatory considerations, and the increasing use of renewable energy sources (European Commission 2010).

[18] The rationale and choice for this classification and the possible channels of interaction with the level of electricity supply security can be found in the Appendix.

[19] Details on regulatory development are provided in the Appendix. White indicates data unavailability in Fig. 1.

[20] *Rate-of-return (ROR)* is also referred to as “cost-based” or “cost-plus” regulation, see Mueller et al. (2010).

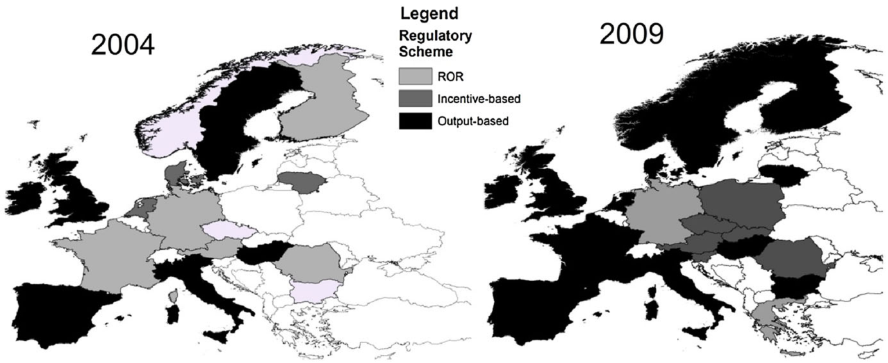

Fig. 1 Changes of distribution network regulation in Europe between 2004 and 2009

costs (OPEX) from revenues, the resulting earnings should be equal to the costs on capital (CAPEX) with a certain premium (see Hoffrichter 2011 or Mueller et al. 2010). Being an efficiently implementable scheme, it was used extensively in Europe.

In contrast, regulatory frameworks, which incentivize efficiency on the basis of peer-benchmarking are collectively referred to as *incentive* regulation. This includes for instance "yardstick regulation", "price-caps", "revenue caps" and—in general—schemes, which provide incentives for above-average performing DSO. They often entail maximum allowances with regards to utilities' revenues or network tariffs charged, benchmark and other averaging devices, "adder", which is applied in the USA, as well as risk and profit sharing frameworks.

Regulatory schemes which take into account the quality of supply—i.e. how reliably DSO deliver their output—have been implemented in some countries as a consequence of suboptimal outcomes from certain incentive regulation schemes. In this paper, these schemes are denoted as *output* regulation. In addition to the primary goal of ensuring competitive network tariffs, *output*-based frameworks thus incorporate additional service quality criteria.[21] They involve the use of monetary incentives levied on grid operators for quality improvements, or penalties for above average outage statistics. Most importantly, in order to fall into the *output* regulation category, a direct monetary incentive must be involved in the legal framework, which can include monetary compensation to customers as well as penalties to DSO regarding granted earnings from tariffs.

2.3 Regulatory practice and evolution

Historically, *ROR* was used on a wide range. As it avoids certain problems of information asymmetry, it was in many countries the first regulatory system implemented. In

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[21] In the EU, the majority of *output* schemes represent incentive-based frameworks with explicit incentives for DSO to increase quality of supply (Cambini et al. 2012b). This encapsulates the quantity of physical power demand which is primarily determined by market forces—i.e. demand and supply. Accordingly, no single incident of a lack of quantity—i.e. generation capacity—has been found to be responsible for a single power outage in the EU during the period under consideration (Council of European Energy Regulators 2014).

addition it is not counter intuitive to assume it to be a successful strategy to improve quality of supply as already Spence (1975) suggests*" that rate-of-return regulation may have attractive features when quality is a variable"*. However, finding a socially optimal level of supply security is paramount in order to prevent inefficiencies which may arise if the approved expenditures or return on investments is set too high. This was challenging *ROR* and became known to lead to over-capitalization (Averch-Johnson effect, see Averch and Johnson 1962).

Thus, in the European Union, *incentive*-based schemes were introduced to provide economic benefits by lowering the network tariffs consumers pay. As shown in Fig. 1, today, the pertinent policy choice is likely to be between *incentive*-based and *output*-based regimes. This has substantial consequences in terms of reliability due to the fact that, grid tariffs – being subject to regulation[22]—represent the main source of income for DSO. Given utility maximizing firms, downward pressure on electricity prices leads, *ceteris paribus,* to changes in the propensity to invest and maintain the grid infrastructure.[23]

Mainly for this reasons, various countries have opted to explicitly account for *output*-based performance, such as the duration of outages in a certain area or voltage level. Others, however, maintain reliability-independent schemes, while the number of countries implementing *rate-of-return* regulation has decreased throughout.[24]

3 Empirical analysis

This section presents the applied methodology, discusses the data used in this analysis and briefly explains the econometric approach used to ensure consistent estimates of the causal effects regulation has with regards to electricity supply security. The final data set contains 261 observations of 27 countries for the period from 1999 to 2013.

3.1 Data

This analysis incorporates reliability indices of 27 European member states provided by Council of European Energy Regulators (2012; 2014 and 2015, respectively), economic data from OECD (2012) and Heritage Foundation (2014) as well as regulatory data from Conway and Nicoletti (2007) and WIOD (2012).[25] In addition, a set of covariates such as climate-related, geographic, structural and energy-specific variables ensures high validity of model estimates. A summary is located in the Appendix.

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[22] This paper accounts for medium and short-term changes in DSO behaviour in response to regulatory changes. Different regulatory approaches to *OPEX* and *CAPEX* exist. The emphasis is put on regulatory effects on *OPEX*.

[23] This—in combination with substantial information asymmetry—led various national regulatory authorities to implement measures which specifically account for effects on electricity supply security (i.e.*output* regulation).

[24] Further discussion of different schemes can be found in Bremer Energie Institut (2010), Virendra and Scarsi (2004) or Haber (2005). The details of this classification procedure are also available in the Appendix.

[25] Evidence on classification is also provided by Cambini et al. (2012a), who study the different types and efficiencies of regulation schemes among distribution system operators.

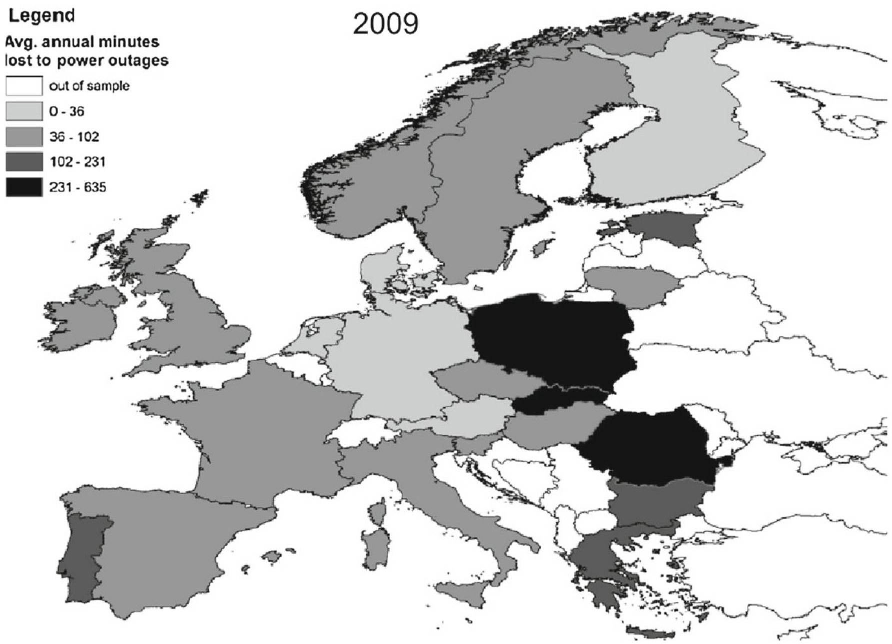

Fig. 2 Level of electricity supply security (SAIDI) in Europe, 2009

The dependent variables—i.e. the indicators for electricity supply security—are measured quantitatively by means of the *System Average Interruption Duration Index* (SAIDI) as well as the *System Average Interruption Frequency Index* (SAIFI).[26] Figure 2 depicts the regional distribution of the level of electricity supply security as represented by the annual power interruption duration index.

The reliability of power supply varies significantly across Europe. A cluster of in central European countries for instance exhibit superior levels of supply security. New EU member states might benefit most from reliability-improving regulatory frameworks as outage levels are above-average. In 2009,[27] for instance, the average German citizen experienced 14.63 min without power supply, whereas Romanian consumers were on average disconnected for 638 min. The EU-wide mean was 117 min in 2009. For the period under consideration most EU member states experienced steady – but decelerating—increases of service reliability.[28] Council of European Energy Regulators (2012) 5th Benchmark Report on the continuity of supply and its update (Council of European Energy Regulators 2014, 2015) provided the data for outage duration and

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[26] SAIDI is available for all but four of the nations in the sample; these nations use comparable metrics that measure minutes of power loss due to unplanned outages. Definitions of indices are presented in the Appendix.

[27] 2009 is a year for which most countries reported outage duration and frequency indicators making it suitable for comparisons.

[28] The definition of SAIDI is given in the Appendix along with a representation of the differences in the sample.

Table 1 Power outage duration for EU 27 from 1999–2012 by regulation scheme

Regulatory framework	Obs. (N)	Mean (Ø)	SD (σ)	Lower bound (Min.)	Upper bound (Max.)
Rate-of-return	69	223.6	206.5	10.0	1073.0
Incentive	62	194.1	168.8	15.3	638.0
Output	130	100.1	91.3	11.3	912.6

Power outage duration in min. p.a. based on Council of European Energy Regulators (2014)

frequency caused by unplanned power interruptions. A summary of outage duration in minutes p.a. for each regulatory regime is presented in Table 1.

This simple correlation table indicates that service reliability is higher in the presence of *output*-based regimes. However, it is neither known if this is due to structural differences of the observed sample or characteristics of regulatory regimes nor if *reverse causation* might have led to just these regulatory regimes. As regulation represents but one influential factor that affects the level of service reliability in a country, a comprehensive set of control variables is needed in addition to appropriate model choice to better explain the influential factors of regulatory frameworks.

Table 2 gives a summary of the variables to be used in the applied econometric model.[29]

Descriptive statistics are located in the Appendix. In addition to these covariates, a dummy variable accounts for the fact whether or not exceptional incidents, such as extreme weather-related events occurred.[30]

3.2 Estimation methodology

This paper posits that the level of electricity supply security in each country is a function of the observable independent variables. These are presented in Table 2 and include indicators of regulation types, as well as variables describing the economic, geographic and demographic conditions of the included countries. They are used to estimate the SAIDI and SAIFI index in distinct regressions. Both indicators enter the regression following a log base 10 conversion to give the dependent variable a more normally distributed shape.

$$\log(y_{ct}) = \alpha_t + \tau_c + z_{ct}\gamma + x_{ct}\beta + \varepsilon, \tag{1}$$

where y_{ct} denotes the dependent variable, SAIDI or SAIFI, for country c in year t. α_t refers to the time fixed effect, whereas τ_c stands for the group fixed effect in which country c falls. z_{ct} is the row vector holding the two policy-relevant regulation indicators while γ refers to the column vector containing the corresponding coefficients. x_{ct}

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[29] This division, which is explained subsequently, is crucial in understanding the bi-directional causality chains found to be associated with regulation.

[30] This is done by the dummy variable *incl_execptional_events*. Data comparability and homogeneity is ensured for the dependent variables by the exclusive use of data from Council of European Energy Regulators (2014), which also contains a discussion of the differences in countries' measurement methods.

Table 2 Variables used in econometric models

Variable	Description
Dependent variables	
log_saidi	Log of annual power outage duration (minutes)
log_saifi	Log of annual power outage frequency (events p.a.)
Policy variables	
output_dso	Indicator for the existence of *output* regulation
ror_dso	Indicator for the existence of *rate-of-return* regulation
incentive_dso	Indicator for the existence of *incentive* regulation–baseline
Regressors	
gdp_capita	Annual GDP per capita in 1000 €
cables_undergr.	Share of low voltage network which lies underground (%)
cons_dry_days	Number of consecutive dry days in the year*
networkcost_ind.	Network costs of power bill for industrial customers (%)
energy_int	Energy consumption per 1000 € GDP in kg oil equiv.
renewable_share	Renewable production, % of electricity produced by wind, hydro, biomass, PV and other renewable sources
entry_regulated	Indicator variable for the presence of entry regulation
pub_ownership	Share of electricity industry which is publicly owned** (%)
price_residential	Residential electricity price in €/kWh
latitude_capital	Latitude of capital of respective country
hhi_concentration	Herfindahl-Hirschman index electricity retail div. by 1000
Instruments	
num_dso_capita	Number of DSO per million inhabitants
pct_verticalint	Electricity industry that is vertically integrated (%)
investmentfreedom	Measure of restrictions imposed on investments
price_industry	Industrial electricity price in €/kWh
pop_density	Population density in people/sq km
el_cons_capita	Residential electricity demand per capita in MWh p.a.
wtp_weighted	Level of weighted utility deterioration due to actual power interruptions and WTP to avoid them

* Imputations were carried out for ≈5 % of Obs. ** Figures were converted from ordinal ranking to percentages

is the row vector with covariates and their coefficients are stored in β. As usual, ε is the error term. z_{ct} is implemented by means of a binary dummy variable where "1" signifies that the observation was subject to the corresponding regulatory scheme. A value of "0" thus indicates the absence of the regulatory scheme in question for the particular year and country, respectively. To avoid collinearity the dummy for *incentive*-based regulation was omitted from z_{ct}.

Country group as well as year specific fixed effects were included to account for the systematic cross-country heterogeneity and to control for the general decreasing trend

Table 3 Applied country groups

Group name	Obs.	Included countries
Central Europe	47	Austria, Germany, Slovenia, Belgium, The Netherlands, Luxembourg
Iberian Peninsula and France	41	Spain, Portugal, France
United Kingdom and Ireland	24	United Kingdom, Ireland
Southern Europe	35	Italy, Greece, Malta, Cyprus
Scandinavia	60	Estonia, Lithuania, Latvia, Sweden, Denmark, Finland
Central Eastern Europe	45	Hungary, Bulgaria, Slovak Republic, Poland, Romania, Czech Republic

Groups are based on transmission line and power market interconnections

in outage duration over the time period.[31] The applied group classification is based on physical power line interconnections between certain countries.[32] Thus, Table 3 displays the applied group specification based on market similarities and physical ties between interconnected countries.

Another important issue originates from the potential endogeneity of the treatment variables, i.e. the indicators for regulatory scheme. The possibility of endogenous causality links between the introduction of certain regulatory schemes and the supply security indices has been debated in various empirical studies of regulatory change for the case of energy and other regulated markets. Cambini and Rondi 2010 for instance elaborate on the issue[33] as do Ter-Martirosyan and Kwoka (2010) who report that the probability of enforcing quality control regulation by means of *output*-based regimes is potentially influenced by the level of supply security.[34]

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[31] Unobservable characteristics affect supply security and vary at the national level. This includes, for instance, the response time of crews and grid managers in the case of unplanned power outages, or the peculiarities of a particular grid and network protocols which are too nuanced to include in a quantitative model.

[32] Power lines connect countries' power lines and thus affect the levels of supply security. This is evidenced by the trans-national power interruptions such as the incident in Italy on September 28th 2003, which originated in Switzerland is one example thereof. For a thorough analysis of major power outages it is referred to Bompard et al. (2011). The increasing importance and challenges of trans-national interconnections in terms of supply security are found to be especially relevant for supply security in the future (see de Jong and Hakvoort 2006 as well as Pidlisna 2014). For instance, trans-border electricity exchange in Europe is anticipated to increase to up to 15 % of the overall power demand by 2030 from 8.5 % in 2012.

[33] Duso (2001) for instance investigated the cellular industries in the USA, whereas Duso and Roeller (2003) provided insights into the driving forces behind endogenous deregulation decisions in the OECD and associated effects on productivity. They find substantial evidence for endogeneity and that competition has positive effects on deregulation, implying that very competitive countries tend to open up markets earlier.

[34] This analysis focused on electricity market regulation in the United States. The presented evidence on reverse causation potentially stems from utilities lobbying against *output*-based schemes in regions or countries with poor electricity supply security. Conversely, public pressure from consumers may enhance the likelihood of adopting user friendly, *output*-based regulatory frameworks, especially in areas where electricity supply security is poor. Summarizing, the authors conclude that, "*there is some indication of endogeneity, although, importantly, not to the extent of fundamentally altering our basic results*" (Ter-Martirosyan and Kwoka 2010, p. 272).

Thus, in order to test the empirical evidence for endogenous causality chains an augmented Durbin-Wu-Hausman test was conducted as suggested by Davidson and MacKinnon (1993). Following the outlined approach, evidence for endogeneity is indeed confirmed for *output*-based regulatory frameworks. This is not the case for *rate-of-return* regulation. The exogenous nature of *rate-of-return* regulation is supported by theoretical considerations and corresponds with the history of regulatory evolution.[35]

The initial need to introduce regulatory mandates was in many countries seen as an exogenous shock—i.e. EU Directive 96/92/EC to liberalize electricity markets. This potentially explains the exogenous nature of *ROR*. On the contrary, this does not hold for *output*, whose implementation in many cases took place at a later stage in which more mature markets potentially exhibited stronger influence of certain interest groups.

Thus, to correct for endogeneity of *output* regulation and much in accordance to Zellner and Theil (1962), a three stage least square model was applied. This model instruments for *output* to correct for endogeneity and enhances estimator efficiency by simultaneously estimating slope coefficients for a two equation system where y_{ct} (in Eq. 1) is SAIDI in one equation and SAIFI in the other. We follow the strategy for derivation of the instruments outlined by Ter-Martirosyan and Kwoka (2010) as well as Donald and Sappington (1997). Thus, the following instruments were used: the number of DSO per m. inhabitants (*num_dso_capita)*, the degree of utilities' vertical integration (*pct_vertical integration*), the freedom of investment (*investment_freedom*), a latent proxy for utility loss due to power outages (*latent_suffering_WTP_Saidi*, *wtp_weighted*) which approximates peoples' utility loss from supply interruptions indicated by their Willingness-to-Pay to avoid power cuts (as reported in Gutierrez et al. 2013) weighted by the actual unavailability of electricity service in the respective year and country, the electricity price paid by industrial customers (*price_ind*), the number of people living within one km^2 as a measure of country differences (*pop_density*) as well as households' power demand divided by population (*el_cons_capita_kwh*). A discussion of first stage results is provided in the Appendix.

Most importantly, isolating the effects due to regulatory frameworks and decisions with regard to electricity supply security is ensured by utilization of appropriate covariates as outlined before. Thus, the set of control variables includes for instance *pct_pub_ownership,* which controls for the remaining local or federal government's stake as a shareholder in the electricity market. *Entry_regulated* accounts for market characteristics which changed substantially during the period under consideration. It controls for the fact whether entry into electricity market is open and incumbents can be challenged by innovative firms.[36] The inclusion of *investment freedom* allows a better judgment of a country's degree to which it is based on market economy decisions, whereas the employed fixed effects account for the unobserved heterogeneity which

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[35] The internal market legislation (European Commission 1996) implemented throughout the EU starting in 1999 required from member states the introduction of regulation where most countries did not have such a system before. Based on the longstanding experience with *rate-of-return* in other industries many countries adopted a *rate-of-return* regulation system at first (See for instance Biglaiser and Riordan 2000).

[36] However, this applies to the non-regulated part such as generation, trading and energy balancing, not the natural monopoly part of transmission and distribution networks. Nevertheless, market openness being a structural variable can thus be controlled for.

encompasses structural differences among national energy markets. Market concentration is accounted for by *num_dso_capita* (in the first stage) and *hhi_concentration* which controls for the number of DSO per capita as well as the Herfindahl-Hirschman index for electricity retailing.[37] Interestingly, the number of DSO per capita is statistically significant—and negative in sign—in the first stage indicating a lower propensity of countries to implement *output*-based frameworks.[38]

3.3 Short- versus long-run effects of regulation

Reliability of electricity supply is affected by the operational expenditures DSO carry out, such as maintenance, as well as by structural investments in the infrastructure. This is relevant for the choice of modelling approach as well and corresponds to the differentiation of OPEX and CAPEX, respectively. OPEX include, amongst others, the costs for maintenance, blackout response capabilities, restoration capacities etc., while CAPEX are associated with structural investments such as the capacity and modernity of the network infrastructure. Regulatory practice affects OPEX differently from CAPEX. The reimbursement mechanisms of OPEX significantly differ between regulatory regimes (see Greene 2008), meaning these are subject to the outcome of benchmarking in *incentive* and also for some *output*-based regimes with quality standards, while *ROR* regimes typically assess the resulting profitability and is less concerned with the cost structure.

On the other hand investments in supply security-relevant network infrastructure are typically proposed by DSO and subsequently assessed on the basis of their importance by the regulator. This is usually achieved with expert testimonials and the specific configuration of the measure is then subject to negotiations between the DSO and the regulator. Most importantly, this paper focuses on OPEX as it was outlined by the similar approach of Ter-Martirosyan and Kwoka (2010).[39] Operational expenses respond to changes in regulation rather quickly, especially as changes in regulatory regimes are well known in advance of their implementation by the DSO. Thus, the regulatory effects on operating expenditures are paramount in this analysis as they are found to influence reliability most directly. In addition, DSO are assumed to have sufficient time to adapt their cost structure to the new regulatory frameworks imposed such that its ramifications for supply reliability become effective almost immediately.[40]

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[37] The latter has been divided by 1000 in order to ensure homogeneous variable levels.

[38] No inferences about the reasons thereof can be made at this stage of research.

[39] The authors summarize the dichotomy between OPEX and CAPEX: "*Operations and maintenance expenditures are examined separately to allow for the possibility that incentive regulation affects them differently, and in turn that they affect quality differently[...]Capital expenditures undoubtedly matter as well, but are highly variable, and have effects subject to long lags. Accordingly, we focus on variable costs, to which most examples of quality problems are traced.*" This definition is followed throughout.

[40] While testing for different lag assumptions this analysis refrains from a somewhat arbitrary definition of homogeneous lags for all observations. Thus, the coefficients of interest, i.e. those for the policy indicator variables, estimate the average change in reliability elicited by a regulatory regime irrespective of how long ago the regulation was implemented.

4 Estimation results

The results are presented in Table 4. Negative slope coefficients are associated with lower outage duration and frequency, i.e. higher levels of supply security. Most importantly, the coefficients of regulatory regimes are consistently negative—and for the case of *output*—significant at least at the 0.05 level. This lends support to the existence of regulatory influence on supply security.

In particular, the introduction of *output-based* regulation enhanced the level of supply security in a country when compared to *incentive* regulation. Improvements are found to have been greater with regards to the frequency of interruptions, but are

Table 4 Estimation of slope coefficients

	(1) log_saidi	(1) log_saifi
output_dso	−0.267**	−0.497***
	(−2.72)	(−5.18)
ror_dso	−0.156*	−0.259**
	(−2.21)	(−3.75)
incl_exceptional_events	0.253***	0.206***
	(5.21)	(4.33)
gdp_capita_t	−0.016***	−0.007**
	(−5.99)	(−2.66)
cables_undergr.	−0.001	−0.004***
	(−1.8)	(−5.91)
cons_dry_days	0.001	0.000
	(0.7)	(0.13)
network_cost_industry	−0.006*	−0.008**
	(−2.37)	(−3.21)
energy_intensity_to	0.000	0.000
	(0.68)	(1.61)
renewable_share	0.004*	0.002
	(2.52)	(1.42)
entry_regulated	0.100	0.053
	(2.39)	(1.3)
pct_pub_ownership	0.003**	0.001
	(3.27)	(1.13)
price_residential	−0.016*	0.000
	(−2.23)	(0.07)
latitude_capital	−0.009	−0.010
	(−1.12)	(−1.36)
hhi_concentration_t	−0.007	−0.020
	(−0.52)	(−1.44)

t statistics in parentheses, N = 230
* p < .05; ** p < .01; *** p < .001

consistent with reduction in both SAIDI and SAIFI. In contrast to the basic correlation assessment presented in Table 1—not only *output* is associated with higher supply security vis-à-vis *incentive* regulation, but so is *rate-of-return.*[41]

Apart from the discussed regulatory variables, the share of network tariff of industrial customers' electricity expenditures (*network_cost_industry*), the country-specific indicator of *gdp_capita_t*, are shown to have a statistically significant negative effect on both the overall duration and frequency of power outages.[42]

On the contrary, the share of renewable energy sources (*renewable_share*) in the electricity generation mix[43] and the indicator if power companies are (partly) state-owned (*pub_ownership,* for SAIDI) are associated with a less reliable electricity supply, while the share of low and medium voltage cables located underground (*cables_undergr.* for SAIFI) is—as expected—associated with less frequent outages.[44] Country-group fixed effects are significant for all groups at the 0.05 level. This supports the notion of systematic differences between certain European regional groups. Interpretation of country-specific regulatory effects thus needs to carefully take into account regional idiosyncrasies.[45]

4.1 Welfare relevance of electricity supply security

Knowing the magnitude of reliability influencing factors allows for the quantification of improvements to supply security in absolute and economic terms.[46] In order to do so the log-linear model in Table 5 needs to be corrected to account for the log-normal distribution. Following Moeltner and Layton (2002) as well as Woo and Train (1988), the transformation of log values is done by means of Eq. (2)

$$E(Y_c|x_c\hat{\beta}) = t \cdot \exp(\hat{y}_c), \tag{2}$$

for which Y_c denotes the prediction of the actual country-specific value of power outages in minutes per year. The commonly-used correction factor t is defined as a fraction of the mean of observed values divided by the mean of all predictions, such as

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[41] The coefficient for *ror_dso,* though being smaller in magnitude—and slightly less robust –is preferable in terms of supply security when comparted to purely tariff-focused *incentive* regulation. One explanation lies in the fact that the downward trend of network tariffs—and consequently of operating expenditures—accelerated in many cases with the introduction of *incentive* regulation, lending support to the hypothesis that lower network tariffs—which are found to have resulted from *incentive* regulation (Kratena 2011) came at the cost of less reliable levels of supply security. It is important to dwell on the fact that this might be justifiable and – based on Spence (1975)—even macro-economically efficient.

[42] For SAIDI, this is the case also for the electricity price residential customers pay (*price_residential*).

[43] Renewable energy is heavily debated in the European climate and energy policy while the necessity of public ownership of utilities is discussed intensively in industrial policy. This explains their inclusion into the model.

[44] The dummy *incl_exceptional_events* is significant and positive as expected, lending to the fact that outage durations and frequencies are higher if exceptional events occur.

[45] In addition, the applied year fixed effects are significant at the 5 % level for both, SAIDI and SAIFI models.

[46] Coefficient's log values need to be converted because their exponentiation would result in biased predictions for duration and frequencies.

$$t_s = \frac{\bar{Y}_s}{exp(\hat{y}_s)}. \tag{3}$$

Making use of Eqs. (2) and (3), the expected reduction of annual power outage duration in case the remaining EU member states implement *output* based regulation, is *ceteris paribus* assessed at 16.05 %. Furthermore, this model allows the quantification of the associated macroeconomic benefits due to enhanced supply security. If—hypothetically[47]—*output* regulation is implemented across the board in all European countries which have not yet done so,[48] GDP-relevant outage costs of 930 m. € p.a. are avoided in the EU.[49]

Thus, possible reliability enhancements are macro-economically relevant, particularly for new EU member states which exhibit above-average outage durations and frequencies. Improvements are thus particularly feasible for countries in group *Central & Eastern Europe.*[50]

5 Summary and discussion

This paper analyzes the connection between regulation and electricity supply security based on cross-country data for the period from 1999 to 2013 in the European Union. As evidenced by a vast literature, the provision of lower electricity prices to consumers, which was the primary goal of liberalization, unbundling, and the introduction of network regulation, has largely been achieved. Still, scientific evidence on regulation's efficacy with special regard to service reliability in Europe had been scarce.

The presented approach evaluates the effects of the regulation of distribution networks, which account for more than 90 % of power interruptions. A distinction was made between three policy-relevant regulatory frameworks, *rate-of-return*, *incentive* and *output* regulation. The applied econometric approach considered the heterogeneity across EU member states. The potential for reverse causation was considered by testing the hypothesis of endogeneity for *rate-of-return* and *output* regulation, which, for the latter was confirmed. The consequential utilization of an instrumental variable approach ensures consistent estimates.

The estimation results lend support to the hypothesis that the choice of regulation scheme affects the level of electricity supply security. The model structure allows for a comparison of *ROR* and *output* vis-à-vis *incentive* regulation, which remains a widely used regulatory scheme. In particular, the coefficients for *output* and *rate-of-return* regulation are negative and statistically significant with regard to both the SAIDI and SAIFI indices indicating *ceteris paribus* higher levels of supply security when present

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[47] The assessment is based on the online assessment tool http://www.blackout-simulator.com.

[48] The hypothetical assumption here is that countries are able to change to an *output*-based scheme.

[49] This calculation uses a model presented in Schmidthaler and Reichl (2014) and assumes a linear relationship of damages and outage duration during the first 60 min. The duration of power outages is compared to the last available observation in each country; with the exception of Greece, Spain, Italy, Latvia, Malta, Poland, Portugal, who report outage duration indices until 2011, this is 2012. Bulgaria reports up until 2010.

[50] This group included Hungary, Bulgaria, Poland, Slovak Republic, Romania and the Czech Republic with outage durations ranging from 77 to 630 min.

in regulation. In particular, the slope coefficients for *ROR* regulation are smaller in absolute terms than those for *output*, indicating that the former has a lesser effect on supply security. In addition, while highlighting the necessity of appropriate investment allowances to DSO, a move from *incentive* back to *rate-of-return* is highly unlikely in practice.

When computing the hypothetical case of a Europe-wide introduction of *output* regulation, it is shown that annual outage durations can be reduced by 16 % on average if such quality standards are introduced. If, for example, the 11 EU member states who have as yet not introduced quality control mechanisms in their regulatory frameworks were to do so, the annual outage durations are expected to decrease by 10–227 min based on the nation considered. Since the socially optimal level of supply security is *a priori* unknown, assessing opportunity costs is done to quantify the value of reliability improvements. The economic ramifications of the anticipated reductions in annual outage duration based on the possible enhancements due to regulation are assessed at 930 m. € *per annum*. A better understanding of the potential improvements of best-practice regulation thus for the first time allows an objective consideration of benefits and costs while providing evidence for policymakers and industry.

The results presented in this paper make a strong case that regulatory regimes should consider controls for quality of supply in addition to providing financial instruments for DSO to carry out adequate investments and maintenance operations. While the presented net benefits from the introduction of *output*-based regulation can be used in cost-benefit analyses, further research is needed to formulate appropriate quality control mechanisms to improve energy supply security and to provide country-specific recommendations to policy makers and industry.

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Appendix

Definition of dependent variables SAIDI and SAIFI

Following Reichl et al. (2008), the applied indicators, SAIDI and SAIFI, respectively, are described in Eqs. (4) and (5). The system average interruption duration index (SAIDI) is defined by

$$\mathrm{SAIDI} = \frac{\sum_{j=1}^{J} n_j \times t_j}{N} \tag{4}$$

where n_j is the number of customers affected by outage j, t_j is the number of minutes outage j lasted, and N is the total number of electricity customers, and a particular outage is $j \in \{1 \ldots J\}$ where J is the total number of outagesexperienced during that year. This figure is calculated independently for each nation and year in the sample.

The system average interruption frequency index (SAIFI) on the other hand quantifies the average number of outages p.a. which a customer experiences. SAIFI is defined

Table 5 Durbin–Wu–Hausman fest of endogeneity

Model	Treatment	*Output*		*Rate-of-return (ROR)*	
		Durbin	Wu–Hausman	Durbin	Wu–Hausman
SAIDI	$\chi^2/\boldsymbol{F}$	11.9354	10.7389	0.939792	0.807005
	Prob $> \chi^2/\boldsymbol{F}$	0.0006	0.0012	0.3323	0.3701
SAIFI	$\chi^2/\boldsymbol{F}$	19.5923	18.1576	0.624973	0.531312
	Prob $> \chi^2/\boldsymbol{F}$	0.0000	0.0000	0.4292	0.4669

as a measure for every installed kVA (installed capacity as kilovolt-ampere) per year. A value of 1 implies that every kVA installed per customer, experiences one power outage in the year at question. Equation (5) provides a definition of SAIFI.

$$\text{SAIFI} = \frac{\sum_j I_j}{L_s} \tag{5}$$

I_j ... interrupted capacity in kVA for interruption j

L_s ... total system capacity in kVA in system s

Model specification and endogeneity: Durbin–Wu–Hausman Test

Endogeneity of the treatment variables was tested to identify the need for instrumental variable inclusion. Based on theoretical considerations, potential endogeneity primarily concerns the two variables *ROR* and *output*.[51]

The applied Hausman tests subtracts the independently estimated standard coefficients ($\hat{\beta}_{SC}$) from the estimates of the IV approach ($\hat{\beta}_{IV}$). The squared sum is then divided by subtracted variances of $\hat{\beta}_{IV}$ minus $\hat{\beta}_{SC}$. The test statistics is χ^2-distributed. Based on the test outcome H_0 is declined for *output* but not for *rate-of-return*. This supports the inclusion of an instrumental variable approach. The test setting was done for each linear combination of model and treatment variable, respectively. Table 5 depicts the test statistics from model highlighting that endogeneity for *output* regulation is supported at the 0.05 level. This is not the case for *ROR*.[52]

The respective test statistic is testimony of the ambiguous causality chain. As a result of confirmed endogeneity, a three stage least square—3SLS—model was applied (see Zellner and Theil 1962) instrumenting for *output* making use of a number of instruments. In doing so, most of the statistically significant instrument variables in

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[51] This is relevant as these treatments are within direct political influence and discretion. The Hausman test was done independently for SAIDI and SAIFI, thus representing a two-stage-least-square setup. For estimation of the slope coefficients, the three-stage model has been applied due to higher estimation efficiency and—thus smaller standard errors.

[52] In addition, for the initial model, the Bruesch-Pagan-Godfrey test revealed severe heteroskedasticity which led us to employ White's robust estimator for the variance-covariance matrix to ensure trustworthy standard errors and t-values (Breusch and Pagan 1979 as well as White 1980).

the first stage model show the expected sign.[53] This is the case for the number of DSO per million inhabitants (*num_dso_capita),* the electricity price paid by industrial customers (*price_ind*) and households' power demand divided by population (*el_cons_capita_kwh*) whose slope coefficients are statistically significant and negative in sign.

Interestingly, the number of people living within one km^2 a (*pop_density*) is positive indicating the possibility of an increased democratic pressure to introduce *output* regulation in rather urban settings. The degree of utilities' vertical integration (*pct_vertical integration*), the freedom of investment (*investment_freedom*) and the latent proxy for utility loss due to power outages (*latent_suffering_WTP_Saidi*, *wtp_weighted*) are negative but lack statistical significance.

Regulatory classification

Following Haber (2005), Vogelsang (2010), Braeutigam (1989) and Cambini and Rondi (2010), regulatory regimes were classified into three categories which are defined subsequently.[54]

Rate-of-return or cost-based regulation (ROR)

ROR is based on a premium on top of costs[55] determined by the regulatory authority. In many cases, DSO are granted tariffs which cover their costs, plus an allowed return on investment. *ROR* also applies to frameworks, within which a revenue cap is set. Most importantly, *ROR* is strictly **quality independent**.

Incentive or benchmark based regulation (incentive)

incentive is the envelope terminology for regulatory regimes which set tariffs based on benchmark systems.[56] Regimes which are also known by the following *termini* are included in the categorization: price cap, revenue cap, rate moratoria, profit sharing, banded rate-of-return, menus and yardstick regulation. Most importantly distribution tariffs depend on those of peer companies. Furthermore, **tariffs are independent quality of supply** and determined by the regulator based on productivity comparison with other regulated firms.

Output or quality based regulation (output)

Output, characterizes a family of regulatory schemes which explicitly **include quality measures into a country's regulatory framework**. This type of regulation is based

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[53] The choice for including these instruments was driven by economic theory as presented in Sect. 3.

[54] A set of strictly technocratic criteria was applied which are presented in Figure classification procedure.

[55] This holds for revenues and/or prices as well.

[56] This is opposed to *ROR*, which does not incorporate peer DSO's performance.

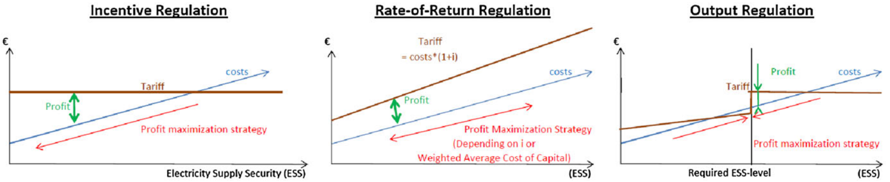

Fig. 3 Electricity market regulation and electricity supply security

on mandatory rewards and punishments if standards are not met. A stringent legal framework for all affected entities is mandatory.

Figure 3 depicts the respective relationships between costs and electricity supply security. Regardless of the type of regulation, a grid operator is assumed to exhibit profit maximizing behavior. However, this does not paint a full picture. In terms of social welfare, DSO profits ought to be considered in conjunction with consumer rents.[57]

Thus, incorporating quality of supply standards into the tariff negotiations between regulatory authority and DSO puts a value on the good of electricity supply security. As depicted in Figure 3 on the very right, only *output* regulation requires a binding monetary reward or punishment (depending on deteriorations or improvements of service reliability) which apply whether certain standards are met.[58]

The process of regulatory classification in this paper was strictly conducted along the following procedure:

Classification process

1. Missing information on regulation schemes leads to classification as *no reg*—and thus—omission from the sample.
2. In regulatory practice, *incentive* and *output* regulation schemes share many common properties. A scheme is classified as *output* **if and only if** the source used[59] yields precise information that mandatory monetary penalties or rewards are involved in regulation.
3. Whenever **monetary remunerations to customers** (e.g. payments, or rate reductions) exist in the case that utilities fail to provide sufficient levels of electricity supply security to consumers,[60] the respective regulation regime is **categorized** as *output*.
4. The same applies to *ROR* regulation. Although the overlap is less pronounced compared to *incentive* and *output*, the most distinctive criteria differentiating *ROR*

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[57] This is summarized by Spence (1975) who concluded that: *"profitability is not a sufficient criterion for deciding on the social value of quality"*.

[58] This can either be a penalty if certain criteria are not met or a bonus for keeping reliability above certain levels.

[59] Sources are in most cases the national reports submitted to the Council of European Energy Regulators.

[60] This is the case in the UK, Norway and the Netherlands (Council of European Energy Regulators 2012, p. 51)

Table 6 Classification of regulation schemes in the European Union

Criterion	Characteristics of criterion	Indicator for
1	Mandatory penalties if pre-defined standards are not metExplicit incorporation of outage frequency in regulation	*output*
2	Mandatory re-compensatory payments to customers in the event of outages (defined durations or frequencies)	*output*
3	Benchmark/yardstick system with regards to tariffs	*incentive*
4	Peer comparison/set paths for cost development	*incentive*
5	Existence of a set premium on the costs of capital (after deduction of OPEX from costs/gross revenue)	*ROR*
6	Revenues cap via a markup on costs of production	*ROR*
7	Existence of price caps	*ROR*
8	Existence of revenue caps	*ROR*

from *output* is the lack of quality controls. The differentiation between *incentive* and *ROR* is straightforward as various studies (Vogelsang 2010 or Braeutigam 1989) elaborate on this issue.

5. If the regulatory regime recognizes positive and/or negative **trends of electricity supply security**[61], or if *boni* are awarded due to reliability improvements, *output* is assigned.

Summarizing the classification procedure, Table 6 includes the technocratic methodology used for the categorization of the regulation schemes of the European countries subject of this paper. Necessary and sufficient conditions are based on these characteristics.

The classification strictly followed the conditions of Table 6 for every country and year in the panel. National reports—such as CRE (2006) and CRE (2010) for the case of France—on regulatory practices were scanned with regards to each criterion. Those regulatory schemes that satisfied all of the necessary, or at least one of the sufficient were classified according to this scheme. While *incentive* and *output* regimes may contain many of the same elements they are distinguished first and foremost by criteria 1 and 2, which provides a clear delineation between the two regulation types.[62]

In addition to significant progress with regards to regulatory designs, evidence for enhanced consumer rights exists. Council of European Energy Regulators (2012) finds in this regard, that: "*In 16 countries, the network user has the right to be reimbursed*

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[61] This is contrary to the utilization of absolute levels of electricity supply security.

[62] As implied by criterion 3, some incentive regimes may contain explicit mention of the ESS, but these regimes do not contain direct monetary incentives for operators to improve quality.

(or to receive reduction of network tariffs) after a very long interruption. In 4 countries, compensation relates to a maximum number of interruptions in one year. In 5 countries, compensation applies for planned interruptions, with different implementation solutions (related to the duration or to the notice)." In case a member state implemented frameworks for customer compensations, its regulatory scheme for the year in question is classified as *output.* However, a necessary condition for the categorization as *output* requires strict legal frameworks. A vague threat to change regulation or reward the DSO in the future is not sufficient for a regulatory scheme to be classified as *output* regulation.

Classification case study: regulation in France

The applied classification procedure for France provides a vivid example. Data for France's regulation approach are available for the entire study period (1999–2013) and stem from the publications of the French national energy regulator (CRE 2006 and 2010). Up until 2009, the French regulatory criteria were neither combined with monetary incentives related to reliability of any kind, nor were tariffs for networks set based on a benchmark system without security of supply indicators. Thus, France exhibited a rather puristic *ROR* system. Starting in 2003, an—at first—voluntary measurement of electricity supply security was started.[63] However mandatory penalties for not being able to provide certain reliability levels were introduced as of 2009. Starting in 2009 and stretching until the end of the period under consideration, a new tariff system for the use of the public French transmission and distribution networks (TURPE 3) was introduced: "*... includes incentive mechanisms aimed at controlling manageable operation costs, at improving quality of supply and service, as well as minimising the cost of purchasing losses on the networks.*" (CRE 2010).

For the case of France, the applied classification is based on a stringent legistic framework which defines the monetary (dis-)incentive for deteriorating or improving levels of electricity supply security. These considerations of reliability are the necessary and sufficient conditions to fall into the category *output* regulation as of 2009. Thus, France provides a vivid example of a significant change in the regulatory framework from *ROR* to *output*.

Country-specific data on regulatory classification

Using the outlined classification procedure as well as the available reliability indices led to the following assessment of EU member states.

> *Austria* Reliability indices for Austria are available since 2002. Austria introduced *rate-of-return* regulation in 2001 and switched to *incentive* regulation in 2006 which is still in use (Frontier Economics 2011).

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[63] This is reflected in a report by the French National Regulator (CRE 2006) which states that: "*Since December 2003 CRE has drawn up an activity report containing a set of indicators containing a set of indicators to be periodically filled in by grid operators*".

Belgium Reliability indices are available since 2011. *ROR* regulation was applied from 2009 to 2013 (Perrin 2013).

Bulgaria Reliability indices for Bulgaria are available since 2008. Bulgaria implemented *incentive* regulation in 2005. In 2010, Bulgaria introduced quality criteria to the DSO regulation, which is still in place, rendering it *output* (Council of European Energy Regulators 2012).

Cyprus Reliability indices are available since 2012. *ROR* regulation is prevalent for 2012 which supply security indicators are available (Council of European Energy Regulators 2012).

Czech Republic Reliability indices are available since 2004. The Czech Republic introduced regulation, which was a revenue cap method, in 2005. Even though strong support for including quality measures were considered in 2009, no such parameters were included in the new *incentive*-based revenue cap regulatory regime which shall be applied from 2010 to 2014 (Council of European Energy Regulators 2012).

Denmark Reliability indices are available since 2007. Denmark implemented a *rate-of-return* regulation scheme in 2000. It switched to price cap regulation in 2004 which did not include quality parameters. This changed in 2008, for both TSO and DSO, when Denmark included quality measures thereby assigning it *output* (Council of European Energy Regulators 2012; Nordic Energy Regulators 2011).

Estonia Reliability indices are available for 2005 until 2011. In this period *ROR* was the prevailing regulatory scheme.

Finland Reliability indices are available since 1999. In 2005 Finland switched from a *rate-of-return* regime to *incentive* regulation, with quality controls added in 2008 (Nordic Energy Regulators 2011).

France Reliability indices are available since 1999. *ROR* was in place until 2008. In 2009, France switched to an *incentive*-based regulation including quality requirements (Council of European Energy Regulators 2012).

Germany Reliability indices are available since 2006. Germany had *ROR* in place until 2008, succeeded by *incentive* regulation which included quality of supply standards as of 2012 (Cambini and Rondi 2010).

Greece Reliability indices are available since 2008. In 2008 on Greece started to collect quality of service indicators. In the time period from 2008 to 2013 a *rate-of-return* regulatory scheme was in place.

Hungary Reliability indices are available since 1999. Hungary used *incentive* regulation since the mid 1990s. Quality incentives were added in 2003, for DSO (Council of European Energy Regulators 2005).

Ireland Reliability indices are available since 1999, as "*customer minutes lost*" the same as Britain. In 2001 Ireland introduced *output*. These quality controls are considered an incentive to improve quality of supply (Council of European Energy Regulators 2005).

Italy Reliability indices are available since 1999. Through 1999, Italy used *rate-of-return* regulation. As of 2000, Italy introduced *incentive* regulation with quality incentives for the DSO. This system of regulation is still in place today. Nevertheless, this regulatory framework deviates from other *incentive*-based regulation schemes.[64] The type of regulation thus includes quality measures rendering it *output* regulation.

Latvia Reliability indices are available since 2007. From 2007 to 2013, *ROR* was the prevailing regulatory scheme.

Lithuania Reliability indices are available since 2005. Lithuania introduced a price cap system in 2002 (50/50 price/revenue cap combination for DSO). This system evolved in 2008 to include compensation payments to the customer, who lay claims in the event of failure to provide a high quality energy supply making it *output* in this analysis (Council of European Energy Regulators 2005 and 2012).

Luxembourg Reliability indices are available since 2011. *ROR* regulation was the prevailing regulatory regime.

Malta Reliability indices are available since 2001 with *ROR* being the regulatory framework of choice.

The Netherlands Reliability indices are available since 1999. Until 2003 regulation included a set of set minimum quality standards. For violations of these standards the grid operator had to pay compensation for outages longer than 1 h. During the second regulation period the Dutch regulators use a yardstick competition mechanism with integrated price and reliability regulation, which was put in place in 2005 rendering it *output* (Netherlands Bureau for Economic Policy Analysis 2004).

Norway was included for comparison. Reliability indices are available since 2005. Regulation included a revenue cap with quality controls rendering it an *output*-based scheme (Nordic Energy Regulators 2011).

Poland Reliability indices since 2008. Starting in 2009 an *incentive* regulation without any quality measures has been in place, while prior to that Polish DSO were still *rate-of-return* regulated (Council of European Energy Regulators 2012).

Portugal Reliability indices are available since 2001. Portugal uses *incentive* regulation for DSO which with added quality incentives as of 2003. ERSE (the national regulator) introduced an *“automatic payment of compensation for non-compliance with the individual standards of commercial quality of service”* (Council of European Energy Regulators 2005).

Romania Reliability indices since 2008. After one year of *rate-of-return* regulation Romania introduced *incentive* in the first regulatory period which was characterized by a revenue cap with profit sharing. In the future (second period) Romania will implement *output* regulation (Perrin 2013). These classifications were approved by Transelectrica Romania, the national TSO.

Slovak Republic Reliability indices are available since 2009. Though being slightly different, the index is recorded in a manner very similar to the SAIDI index. In this period, the Slovak Republic had *incentive* regulation scheme without any specific quality measures.

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[64] An example for such an exception is provided by Council of European Energy Regulators (2008, pp. 14–15): *“...the Authority also reviewed the tariff components covering the allowed costs arising from service quality improvements and from the adoption of initiatives designed to control and manage demand through the efficient use of resources.”*

Slovenia Reliability indices are available from 2008 onwards. In this time frame Slovenia had *incentive* regulation scheme without any specific quality measures; quality standards were added in 2011 (Council of European Energy Regulators 2012) characterizing it as *output*-based regulation.

Spain Reliability indices are available since 1999. The index includes average minutes of power outage experienced per customer excluding exceptional event as the TIEPI and NIEPI indices. In 1999 and 2000 an *incentive* regulation without quality measures was in place. After 2000 quality criteria were introduced (Cambini and Rondi 2010; Council of European Energy Regulators 2005) rendering it *output*.

Sweden Reliability indices are available since 2004. During this period the regulatory scheme consisted of efficiency targets with quality controls designating it *output* regulation (Nordic Energy Regulators 2011).

United Kingdom Data on average minutes of power outage experienced per customer excluding exceptional events for Great Britain are available since 2002, called "*customer minutes lost*", this is a similar measure to SAIDI. Great Britain introduced "*Standards of Performance*" relatively early, in 1991. It has since been using quality standards in further developed regulations (Council of European Energy Regulators 2005) and thus falls into the *output* category.

Table 7 depicts this classification indicating a persistent move away from ROR in most European countries while incentive and output-based regimes have increased substantially.

Summary of variables

Table 8 presents a summary and descriptive statistics of the control variables used in this paper.

Table 7 Classification of distribution network regulation in Europe

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Austria	–	–	–	*ROR*	*ROR*	*ROR*	*ROR*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*
Belgium	–	–	–	–	–	–	–	–	–	–	–	–	*ROR*	*ROR*	*ROR*
Bulgaria	–	–	–	–	–	–	–	–	–	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*
Cyprus	–	–	–	–	–	–	–	–	–	–	–	–	–	*ROR*	*ROR*
Czech Republik	–	–	–	–	–	–	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*	*i*
Denmark	–	*ROR*	*ROR*	*ROR*	*ROR*	*i*	*i*	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Estonia	–	–	–	–	–	–	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	–	–
Finland	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*i*	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
France	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Germany	–	–	–	–	–	–	–	*ROR*	*ROR*	*ROR*	*i*	*i*	*i*	*o-b*	*o-b*
Greece	–	–	–	–	–	–	–	–	–	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*
Hungary	*i*	*i*	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Ireland	–	–	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Italy	*ROR*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Latvia	–	–	–	–	–	–	–	–	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*
Lithuania	–	–	–	–	–	–	*i*	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Luxembourg	–	–	–	–	–	–	–	–	–	–	–	–	*ROR*	*ROR*	*ROR*
Malta	–	–	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*	*ROR*
Netherlands	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Norway	–	–	–	–	–	–	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Poland	–	–	–	–	–	–	–	–	*ROR*	*ROR*	*i*	*i*	*i*	*i*	*i*

Table 7 continued

Year	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Portugal	–	–	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Romania	–	–	–	–	–	–	–	–	–	*i*	*i*	*i*	*i*	*i*	*i*
Slovak Republic	–	–	–	–	–	–	–	–	–	*i*	*i*	*i*	*i*	*i*	*i*
Slovenia	–	–	–	–	–	–	–	–	–	*i*	*i*	*i*	*i*	*i*	*i*
Spain	*i*	*i*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*	*o-b*
Sweden	i	i	i	i	o—b	o—b	o—b	o—b	o—b	o—b	o—b	o—b	o—b	o—b	o—b

ROR denotes *rate-of-return* regulation; *i* denotes *incentive* regulation; *o-b* denotes *output*-based regulation as applied throughout the paper

Table 8 Variables sources and descriptive statistics

Variable	Source	Mean	Std. dev
Dependent variables			
log_minlost_all	Council of European Energy Regulators (2014)	2.02	0.40
log_saifi	Council of European Energy Regulators (2014)	0.18	0.33
Policy variables			
incentive_dso	Various sources (National regulators, Perrin 2013, Council of European Energy Regulators 2005 and 2012, Nordic Energy Regulators 2011)	0.28	0.45
ror_dso		0.25	0.44
output_dso		0.46	0.50
Regressors			
incl_exceptional_events	Council of European Energy Regulators (2014)	0.50	0.50
gdp_capita	Eurostat (2014d)	20.62	14.41
cables_undergr.	Eurelectric (2003) Commission of the European Communities (2003)	47.39	27.41
cons_dry_days	European Climate Assessment & Dataset (2014)	33.14	32.27
networkcost_ind	European Commission (2014b)	26.42	10.47
energy_int	Eurostat (2014c)	255.86	165.05
renewable_share	Eurostat (2014b)	21.03	21.34
entry_regulated	Conway and Nicoletti (2007)	0.61	0.49
pub_ownership	Conway and Nicoletti (2007)	61.12	36.37
price_residential	Eurostat (2014e)	13.76	4.84
latitude_capital	Csgnetwork (2014)	49.18	7.13
hhi_concentration	European Commission (2014a)	2.94	2.48
Instruments			
num_dso_capita	European Commission (2014a)	8.08	8.29
el_cons_capita	Eurostat (2014a)	1.89	1.58
neg_util	Gutierrez et al. (2013)	5.78	3.85
not_accept_infra	Gutierrez et al. (2013)	55.25	10.58
wtp_weighted	Gutierrez et al. (2013)	5.01	4.93
financialfreedom	Heritage Foundation (2014)	66.40	15.59
pct_verticalint	Conway and Nicoletti (2007)	34.41	37.97
investmentfreedom	Heritage Foundation (2014)	70.60	12.78
reliab_not_satisf	Gutierrez et al. (2013)	10.01	9.39
pct_households_N	European Commission (2014b)	31.11	9.93
elprice_regulated	European Commission (2014b)	0.56	0.50
pop_density	Eurostat (2014f)	148.19	225.45
price_industry	Eurostat (2014g)	7.69	2.80

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