[Accelerate energy transition with smarter regulation for faster grid digitalization]

[Vítor Marques, Entidade Reguladora dos Serviços Energéticos, (351) 213033224, vmarques@erse.pt][1]
[Paulo Moisés Costa, Instituto Politécnico de Viseu, INESCTEC Porto, CISED, (351) 232480524, paulomoises@estv.ipv.pt]
[Nuno Bento, Instituto Universitário de Lisboa (ISCTE-IUL), DINÂMIA'CET, (351) 916416087, nuno.bento@iscte.pt]

Abstract

This paper aims to improve the understanding about the most appropriate regulatory approaches to incentivize the adoption of the new technology innovations needed to modernize the distribution networks and enable the energy transition. There is a large set of new technologies, such as technologies related to advanced metering infrastructure (smart metering and communication), substation and feeder automation and low voltage microgrids, which have positive externalities, going beyond the provision of basic network activities or the improvement of quality of service. These externalities have a value for the grid that needs to be accounted for, challenging traditional regulatory models, which tend to overlook the indirect benefits of investments. We characterize a group of representative innovative investments in the grid, considering their expected gains and functionalities that namely enable the development of new services and reinforce efficiency and resilience, while preserving the social and economic affordability.

Then, we develop a decision model, which assesses the changes in the firms' incentives to invest in new technologies under different regulatory schemes. Two representative regulatory settings have been compared: TOTEX; and hybrid regulatory schemes. We compare this model with the profile of the different types of innovations under survey. The results show that a TOTEX regulatory scheme, which fully emulates a competitive situation, more effectively promotes innovative investments or processes that bring benefits in reducing total network costs than cost plus or other regulatory schemes. This result is still valid if the innovative technology lead to an increase in OPEX, provided that total costs decrease. However, for technologies, whose benefits go beyond the network activities, the results show that there is no a one size fit all regulatory scheme, and a case-by-case approach should be preferred.

1 Introduction

To deliver the international targets to decarbonize the economy by the middle of the century, an energy transition is necessary that will have pervasive consequences in a large number of sectors. Changes in the electricity network will be critical to allow a greater integration of renewable energy production, more energy efficiency, higher share of electric mobility and a more active participation of consumers (IEA, 2021). This movement requires a transformation in the activities of the electrical networks, particularly stimulated by the investment in new technologies in the distribution networks.

Technological change has been a central aspect in energy transitions (Smil, 1994; Grubler, 2012). Technological change in complex systems like the electricity systems to a large extent constrains the level and the quality of service provision, their costs and associated externalities. Analysing the historical patterns of technological change in energy, Wilson and Grubler (2014) identify four major drivers of the transformative power of technology: i) clustering of interrelated individual technologies and spillovers to other applications beyond their initial use; ii) continuous improvements of performances and costs resulting from innovation investments (e.g, Research and Development (R&D) expenditures) and diffusion (including learning economies, scale economies, scope economies); iii) key role of consumers and energy end-use; and iv) rapid rates of capital turnover contrasting with the general tendency for inertia in the energy systems. In fact, the historical slow rates of change of energy systems have been widely reported (e.g. Grubler, 2003, GEA; 2012) and attributed to several factors (capital intensity, long lifetime of the capital stock, extended experimentation and learning time, time needed for enacting externalities). In particular, this stems from the long periods that energy technologies pass in formation before market growth that are the most often above two decades (Bento & Wilson, 2016). Hence the importance of addressing the challenges faced by emergent technologies in the formative period, which is more determined by technology characteristics such as substitutability than the initial price (Bento et al., 2018).

Transforming the current electricity distribution networks to enable the energy transition requires an adequate direction and sustained support of technology innovation. The regulatory contexts of the network activities of the

---

[1] The results and comments presented in this paper are entirely the authors' responsibility and should not be in anyway associated to the official opinions of ERSE or other institution.

electricity sectors generally provide relatively high and stable returns, compared to other sectors (BCG, 2020, CEER, 2020). Yet, the power utilities in Western countries have not stood out positively in relation to other sectors, in terms of the evolution of innovation and productivity (Mac Kinsey, 2017; OECD, 2020; Jamasb, 2005; IEA, 2020).

Regulation has an important role in the implementation of innovations in the electricity networks (Lind et al., 2019; Galus, 2017; Faerber et al., 2018). Several authors argue that the path for promoting innovation in networks can be sustained on the direct financing of innovation through tariffs or own funds (Damian et al., 2008; Jamasb and Pollit, 2015). Others suggest mixed approaches, based on incentive-based regulation that emulate a competitive context, in which investment returns are not fully guaranteed and may require greater funds allocation in innovation to “survive” (Jenkins and Arriaga, 2017; Cambini, et al., 2016). But these analyses overlook the specificities of several network innovations, whose intangibility and spillovers alter the profile of costs and returns over time.

Regulation should consider the specificities of the new needs required to the networks and differentiate according to the results of the new technologies (Tuballa, 2016; Galus, 2017; Grubler et al., 2018). In the few studies that analyse the implications of different regulatory approaches in the promotion of cost saving technologies like SGs, it is shown that investment benefits more from an incentive based regulation than a “cost plus”, even if the former is typically associated with overinvestment (Marques et al., 2014; Brown & Sappington , 2018). Still, it has not been shown the effect of dynamic impact of the savings in capital costs. For example, investments in SG technologies that allow reduction of planning and network management costs may have a distinctive regulatory treatment than those with positive externalities, whose effects go beyond the network activity. Those investments may have an impact on the entire energy system and on the whole economy, such as: accommodating an higher share of renewable energy sources which may be decentralized and variable, supporting the dissemination of the electric mobility, energy efficiency and demand side management, electricity theft reduction, fewer power outages, air quality improvement, diversification of the services provided by the grid, enabling new business models, improved security of supply, among other, that should be considered in the regulatory process.

Therefore, we address the following question: what is the most suitable regulatory model to promote investment in the new technologies that are needed to modernize the electricity distribution network? A central proposition in our study is that the different effects coming from innovation should receive different regulatory approach.

We develop a decision model that explicitly considers the profile of benefits and costs of the technology innovations, including their spillovers to the electricity system. We then apply this model to analyse the investment in three new grid technologies (Advanced Metering Infrastructure, Substation and Feeder Automation, and microgrids) that have been widely recognized as important milestones in the (short-term) digitalization and modernization of the distribution networks (see e.g. Dileep, 2020).

The rest of the paper evolves as follows. The next section presents the benefits of the grid innovations. Section 3 reviews the literature and develops the decision model. Section 4 applies the model against the technology innovations under analysis. Section 5 presents the main results and discuss about the theoretical and policy implications as well as presents a research agenda.

2. Innovation on grids: benefits inside and outside electricity sector

Over the past few years, various technologies (including components and functions) have been developed to enhance the performance of the electrical sector as well as to help the integration of new concepts (electric mobility) or reinforce the development of already established concepts (distributed generation – DG) (Dileep G., 2020; Reuver M. et al, 2016; Spiliotis K. et al, 2016; Kuiken D. and Más H., 2016; Bayindir R. et al, 2016).

Some of those technologies, given its intrinsic relation to the investment and operation of the electrical networks may be more likely to be promoted by utilities. Others, due to their characteristics more focused on network users, will tend to be fundamentally promoted by them (in particular by consumers, energy aggregators and/or services, retailers, etc.). The latter case includes the concepts of vehicle to grid, virtual power plants, self-consumption (including collective self-consumption and energy communities), home and building automation, and energy storage. Concerning the technologies, components, and functions more likely to be promoted by utilities, the Advanced Metering Infrastructure (AMI), the Substation and Feeder Automation (SFA) and the microgrids (μG) concept appear as the more relevant from the viewpoint of the utilities. It is important to stress that the integration of the technologies (the ones promoted by utilities and the ones promoted by the network users) allows to increase the potential of the smart grids to contribute to the emergence of a more efficient, more environmentally friendly, more reliable, more robust and safer electrical system.

Table 1 shows a short description of technologies that are likely to be promoted by utilities, including the main resources (hardware and software) that are requested makes it possible to make the technologies functional in practice.

Table 1 – Short description of technologies that are likely to be promoted by utilities

Technology	Short description
Advanced metering infrastructure (AMI)	AMI incorporates a set of features that provide an intelligent two-way connection between utilities and consumers, including the loads and the generation and storage systems installed on the consumers' side. The main resources used in the AMI are the smart meters and the two-way communication platform, which allows exchanging information related to electricity consumption data (remotely collected), electricity prices, network services requests, etc. Specific software is also requested in order to implement a functional AMI system.
Substation and feeder automation (SFA)	SFA uses specific hardware and software resources to endow electrical networks with intelligence that allows a continuous monitoring, control, protection, data acquisition about network assets, and the execution of various automated actions. The SFA allows gathering data from different sensors and sends these data to a central computer which manages the data and controls devices in the field remotely. Several hardware components may be used in SFA, namely sensors (smart relays, phasor measurement units, voltage and current measurement units, remote fault indicators which are sensors able to detect current and voltages levels on feeders that are outside usual operating boundaries, etc.), actuators (circuit brakers, capacitor bank switches, voltage regulators, reclosers, load tap changer controllers, etc.), communication platforms (SCADA equipment) and even some assets that are not network' actives such as the consumers ability to change the consumption, storage systems, vehicle to grid units, or distributed generation. Concerning software, a wide range of applications can be used, including scada software, communication protocols (e.g., IEC61850 for substation automation and communication with intelligent electronic devices), online and offline applications for monitoring and diagnostics of main substations and line equipment, including transformers, circuit brakers, relays, cables, capacitors, switches, bushings., etc.
Microgrids (μG)	The concept of μG has been developed to ease the integration of microgeneration in low voltage networks. A μG is an association of a LV distribution network, microgenerators, loads and storage devices, having some local coordinated functions. This entity can operate interconnected with the distribution network or isolated from it (using local resources) when an outage or power quality problems occur in the upstream network. The establishment of a μG implies the installation of control equipment, as well as a communication platform. Control equipment includes a μG central controller, microgeneration controllers and load controllers (CL). The μG controllers carry out the control of the active and reactive powers produced by microgeneration systems and energy storage systems. The load controllers control the loads by, for example, interrupting them when necessary. The central controller has the mission to manage the micro-network, providing the operating points for the load and generation controllers, to optimize the technical and, when applicable, economic performance of the μG.

As expected, implementing these technologies implies investment and potentially costs for operation and maintenance. On the other hand, these technologies have the potential to reduce operating and maintenance costs and even investments in networks (by extending the useful life of resources already installed), as explained in tables 2 to 5.

Table 2 – Benefits resulting from AMI

Technology	System benefits	Benefits outside the system	
		Environmental	**Other services**
Advanced metering infrastructure (AMI)	- lower billing costs due to a more autonomous system (the costs of training, insurance, vehicles, and other fixed cost expensed on manual meter reading are eliminated); - lower costs related to billing complaints, once the AMI system provides a more timely and accurate billing procedure; - potential infrastructure cost savings once the AMI may help in avoid or delay investments related to peak-load and integrated and responsive voltage regulation. Note that AMI can help in load flow, peak-load and voltage levels monitoring and management, particularly when coordinated with SFA; - lower costs related to the theft of electricity (depending on the way those costs are inputted); - potential reduction on network operation costs, once AMI allows obtaining useful information to define a more suitable network operation, which may reduce losses and improve voltage profiles; - lower electricity quality monitoring costs (provided that the meters have this function);	- benefits resulting from avoided emissions related to: - a better operation of the networks, namely due to potential better management of the load flows (namely if the AMI System is integrated with the SFA system) and to the development of Demand Response technologies and actions, which may improve the efficiency and the load control abilities. - energy efficiency in delivery and use of electricity; - the faster integration of distributed renewable generation; - the ability to create a emissions market system due to the ability of AMI to provide detailed measurement and recording capabilities.	- **Consumers:** - potential lower energy costs once AMI is able to provide information on electricity prices ((including real time pricing)) and consumption patterns, which affords the consumers the opportunity to make intelligent decisions in controlling the energy usage and costs. This includes the control of appliances (that may be achieved by Home and Building Automation Systems), electric cars charging and other decisions, including Demand Response. Moreover, AMI can accelerate the development of new choices about prices and services by the retailers; - potential income resulting from a more active participation in electricity markets, as well as in providing system services (e.g., voluntary reward programs for reduced consumption). - electricity cost savings resulting from energy sharing in collective self-consumption activity - **Retailers/aggregators:** - development of new pricing strategies, which that can help in attracting new customers ; - possibility of developing new activities such as aggregating production and electricity consumptions; - **Society:** - Enables energy and services markets, encouraging both the investment and the innovation; - More efficient usage of electricity, and higher integration of self-generation based on renewable resources contributing to less dependence on energy imports;

Table 3 – Benefits resulting from SFA

Technology	System benefits	Benefits outside the system	
		Environmental	**Other services**
Substation and feeder automation (SFA)	- lower financial loss related to not distributed energy and to compensations for violation of quality of service indicators, once SFA allows to improved reliability and resilience of the electrical system. In fact, SFA may help in knowing the type of the faults (permanent or not), its location, and whether the circuit breakers and relays operated correctly. As well, SFA allows a faster and automated network reconfiguration after a fault/outage situation (by detecting and locating failures/outages more accurately and quickly), ensuring the self-healing of the networks, and minimizing downtime; - optimization of assets and efficient operation of the network, allowing to build less new infrastructures, transmit more power through existing systems and thereby spend less to operate and maintain the grid; - more intelligent asset management, including better planning of preventive and corrective maintenance (e.g. the diagnosis and analysis software may include functions to monitor network assets producing event reports and suggesting repair actions, which facilitates the maintenance crews, operators and engineers work in consistently and quickly estimate the performance, recognize shortage situations and outline probable causes for abnormal functioning), and definition of additions and replacements of equipment); - ability to prevent potential failures, detect and predict disturbances, fluctuations and catastrophic events and to monitor equipment health; - improved management of distributed energy resources, including microgrid operation and storage management; - easier accommodation of distributed generation, storage systems in a plug and play regime.	Avoided emissions resulting from: - a more efficient operation of the networks; - a more easy and coordinated integration of DG, mainly renewable generation; - lower downtime of renewable based distributed generators, due to network unavailability;	- **Consumers:** - more reliable system (less interruptions and lower times to restore the service) and high-quality electricity which is needed for the digital society. This allows to save money lost on outages and power quality problems; - more secure system, reducing the possibility of power blackouts; ´ - **Society:** - higher integration of distributed generation (namely renewable generation), including self-generation, contributing to less dependence on energy imports;

Table 4 – Benefits resulting from µG

Technology	System benefits	Benefits outside the system	
		Environmental	**Other services**
µG	- avoided reliability related investments due to improved reliability indices resulting from the abilities of µG to both isolate from upstream network and to control internal generation and load, even when interconnected to the upstream network. The reliability improvements may be felt by internal consumers (number and duration of the interruptions) as well as by external consumers (duration of the interruptions) due to the ability of µG to help in network reconfiguration actions by changing its internal load and/or generation levels; - reduction in the income resulting from not distributed energy, once µGs contribute for outage duration reduction; - Possible obtention of grid services from the µGs, namely congestion relief, reactive power and voltage control support, frequency regulation and load following, black start, etc.	- Higher integration of DG, namely based on renewable resources: emission reduction and dependence reduction climate change	**Consumers:** - less financial costs related to power outages; reduction on the costs that results from power outages - not loss generation in self productions **LV distributed generators:** - not loss generation **Society:** - more resilient system, being better prepared to face severe situations resulting from weather conditions, terrorist attacks, etc. - job creation, particularly at local level, as well as creating new business opportunities; - stimulation of innovation through research into more effective renewable energy technologies or smart power systems.

Some of the benefits presented on tables 2 to 5, resulting from the AMI, SFA and µG technologies, remain within the electrical system (e.g. lower billing costs, potential infrastructure cost savings, lower costs related to the theft of electricity, potential reduction on network operation costs). Other benefits stay outside the system (e.g. the encouragement on both the investment and the innovation, the avoided emissions related to electricity generation, the employment in new economic activities).

3. Defining effective regulatory scheme

3.1 Theoretical overview

Before presenting the results of our analysis, some basic notions of regulatory methodologies for the definition of companies' allowed revenues are presented in this section.

Beyond the fact that they provide essential goods, network activities of the electricity sector, like electricity distribution and transmission activities, are natural monopolies characterized by decreasing long run marginal costs, justifying their need to be regulated (Marques et al, 2014), namely by defining allowed revenues to be recovered through access tariffs.

Therefore regulatory methodologies influence and restrain companies' options for managing their resources. Generally, the European regulatory context of electricity network companies (CEER, 2020) is conducive to the recognition of investment costs, and cost control concerns are mainly present for operating costs.
Apparently, this solution would be the best to encourage investments, whose returns are not guaranteed, and consequently conducive to innovative investments.
However, as will be seen, the greater or lesser adequacy of the regulatory methodology depends on the characteristics of the innovative investment.

Most of regulatory methodologies that define allowed revenues aims to address asymmetric information issue i.e., the lack of information by regulators about cost function. In the regulatory "game", the regulated firm will know more about its economic environment than does the regulator (Joskow, 2000). To address this issue, namely to overtake situation where companies do not strive to control costs and improve quality of service, regulators emulate competitive environment through incentive bases regulation approaches.
If the main objective of the regulatory scheme is to control costs i.e., an input based regulation is applied, the revenue (revenue cap) or the price (price cap) is fixed for a regulatory period, and all the gains are kept by the firm. In that case, some economic rents can be created or at the opposite the economic sustainability of the form can be threaten, since the regulator can fix too high or too low price/revenue level (Schmalensee, 1989).
On the other hand, if the main targets of the regulator are focused on the allocative efficiency and it seeks to control the profit of the activity and to ensure a minimum level of investment, a cost plus type regulation, like a rate-of-return, is applied. This type of regulatory scheme is a more traditional approach, simple to apply, but with some major drawbacks, namely associate to cost inefficiency.
In other to take advantage of the different issues Laffont and Tirole (1993) define a menu of contract that regulators that offer to companies with cost-sharing provisions.
However, with some exceptions (like Ofgem) regulators do not generally apply this kind of sophisticated regulatory approach, preferring to adopt more simple hybrid methodologies that mix these two types of regulatory approaches, trying to avoid the main drawbacks of both.

Typically, the hybrid approaches treat differently OPEX (Operational Expenditures) and CAPEX (Capital Expenditure), namely, as referred before, by imposing incentive based regulation with efficiency targets to the OPEX and cost plus type regulation (like rate-of-return) to the CAPEX.
But, nowadays some regulators apply regulatory approaches that do not treat companies' costs differently, in terms of targets and allowed revenues, depending on their nature, namely depending on whether they are OPEX or CAPEX. This regulatory approach is called TOTEX (Total Expenditure) methodology.
This methodology also does not guarantee cost recovery. However, the Totex-type methodology allows full retention of earnings for the company. The situation is close to a market situation, with the substantial difference that, in the case of companies/activities with public service concessions, regulators or the State ensure that companies will not be insolvent. In this way, the risk for companies is mitigated, constituting, mainly, a lower or higher profitability.

Finally, the more and more regulation ceases to only focus on direct cost control, to also act to lead network company to provide better services and to ensure the environmental sustainability of the sector, that is, regulation has not only been input-based oriented, but also output-based oriented (Cambini et al, 2014).

For this purpose, regulators enable electricity network companies to obtain revenues if they are successful to achieve regulatory goals associated to different kind of outputs like: quality of service, network resilience, dissemination of information to consumers, energy efficiency, sustainability and environmental protection, etc. The British regulatory scheme RIIO (Revenue= Incentives+ Innovation+Outputs) developed by Ofgem is a well-known example of these regulatory approach.

Therefore, innovation can be seen as an end by itself, but it can also be understood as a means to ensure that companies are able to effectively provide the services that regulators and consumers want (CEER, 2017).

The analysis that will be developed in the next section intends to shed some light on how innovation may or may not naturally appear in the network activities of the electricity sector, depending on the regulatory methodology adopted.

3.2 Modelling

To assess how regulatory methodologies address better the need to promote Smart Grids through innovative investments and processes, we developed a decision model that assesses the changes in the firms' incentives to invest in new technologies under different regulatory schemes. The model assumes that companies maximize their expected gains by allocating their resources to OPEX, CAPEX or Innovation, under different regulatory contexts. We compare two representative regulatory settings: TOTEX and hybrid regulatory schemes.
The former considers the total amount of expenditures, irrespectively of their origin; the hybrid schemes refer to a combination of instruments often used in the practice: rate of return for CAPEX and price cap for OPEX and dedicate innovative funds that are integrally recovered through tariffs.

In a both static and dynamic manner, the models account for the relations between the cost structure of the network companies and the different types of SG investments.

This includes the positive externalities that go beyond the operation and planning of the network infrastructure. The model also tests for the effect of different assumptions concerning the sharing of gains between consumers and companies.

The modelling process is based on the following assumptions:

Assumption 1)

The regulatory context is incentive-based type. Therefore, network companies' allowed revenues (defined by the regulator) may be decoupled from the real level of costs.

Assumption 2)

We compare two main representative regulatory settings: TOTEX and specific regulatory approaches for CAPEX and OPEX.

The former considers the total amount of expenditures, irrespectively of their origin. The second approach can be split into: i) hybrid regulatory scheme, that is a combination of instruments often used in the practice, rate of return for CAPEX and incentive based for OPEX, ii) incentive based approach for CAPEX and OPEX with different regulatory targets.

The expected revenues of the regulated company that considers an incentive based approach for TOTEX with different regulatory targets are formalized as follows:

$$-I_{TotexSG} + \sum_{t=1}^{T} \frac{DTOTEX}{(1+r)^t} + \sum_{t=T+1}^{\infty} \frac{(1-\delta)DTOTEX}{(1+r)^t} + \sum_{t=1}^{\infty} \frac{\xi G_{Totex}}{(1+r)^t} \geq 0 \qquad (1)$$

Where:

- T is the next time allowed revenues review period;
- r is the firm's cost of capital;
- $\mathrm{I}_{\mathrm{TotexSG}}$ is the amount invested in innovative technology in a TOTEX regulatory scheme;
- δ is the proportion of TOTEX savings that is transferred to consumers after T
- DTOTEX is the costs decrease in a TOTEX regulatory scheme;
- $\xi\mathrm{G}_{\mathrm{Totex}}$ is the proportion of external benefits due to Innovation that is withheld by the company in a TOTEX regulatory scheme.

The expected revenues of the regulated company that considers an incentive based approach for CAPEX and OPEX with different regulatory targets are formalized as follows:

$$-\boldsymbol{I_{SG}} + \sum_{t=1}^{T} \frac{\boldsymbol{DC}}{(\boldsymbol{1+r})^{t}} + \sum_{t=1}^{T} \frac{\boldsymbol{DI_C}}{(\boldsymbol{1+r})^{t}} + \sum_{t=T+1}^{\infty} \frac{(\boldsymbol{1-\beta})(\boldsymbol{DI_c - I_{SG}}) + (\boldsymbol{1-\alpha})(\boldsymbol{DC_c - DC_{SG}})}{(\boldsymbol{1+r})^{t}} + \sum_{t=1}^{\infty} \frac{\boldsymbol{\xi G}}{(\boldsymbol{1+r})^{t}} \geq \boldsymbol{0} \quad (2)$$

Where:

- I_{SG} is the amount invested in innovative technology;
- DC is the operational cost decrease (that includes depreciation);
- DIC is the reduction of conventional investment due to the innovative investment;
- α is the proportion of the operational costs savings that is transferred to consumers after T;
- β is the proportion of the investment savings that is transferred to consumers after T;
- ξG is the proportion of external benefits due to innovation that is withheld by the company.

The expected revenues of the regulated company that considers a hybrid approach are formalized as follows:

$$-\mathrm{I_{SG}} + \sum_{\mathrm{t=1}}^{\mathrm{T}} \frac{\mathrm{DC}}{(1+\mathrm{r})^{\mathrm{t}}} + \sum_{\mathrm{t=1}}^{\mathrm{T}} \frac{\mathrm{DI_C}}{(1+\mathrm{r})^{\mathrm{t}}} + \sum_{\mathrm{t=T+1}}^{\infty} \frac{\mathrm{r}\gamma(\mathrm{I_{SG}} - \mathrm{DI_C}) + (1-\alpha)\mathrm{DC}}{(1+\mathrm{r})^{\mathrm{t}}} + \sum_{\mathrm{t=T+1}}^{\infty} \frac{\xi G}{(1+\mathrm{r})^{\mathrm{t}}} \geq 0 \quad (3)$$

Where:

- γ is the proportion of the investment expenditure that is accrued on the firm's regulatory asset base after T.

Assumption 3)

The strategy chosen by the regulator is neutral in terms of costs recovery during the regulatory period, so:

$$\mathrm{z\ TOTEX} = \mathrm{xCAPEX} + \mathrm{y\ OPEX} \quad (4)$$

z, x and y are regulatory targets definided for Totex, Opex and Capex, respectively.

$$\begin{cases} If\ \mathrm{DOPEX} \leq \mathrm{x}, \alpha\ = 1 \\ If \mathrm{DOPEX} > \mathrm{x}, \alpha\ < 1 \\ If\ \mathrm{DCAPEX} \leq \mathrm{y}, \beta\ = 1 \\ If\ \mathrm{DCAPEX} > \mathrm{y}, \beta\ < 1 \quad (5) \\ If \mathrm{DTOTEX} \leq \mathrm{z}, \delta\ = 1 \\ If \mathrm{DTOTEX} > \mathrm{z}, \delta\ < 1 \end{cases}$$

Where:

DOPEX= $(DC_c - DC_{SG})$
DCAPEX=$(DI_c - DI_{SG})$

From equation (4), one obtains:

$$\mathrm{Z}\ = \frac{\mathrm{xCAPEX}}{Totex} + \frac{\mathrm{y\ OPEX}}{Totex} \quad (6)$$

Assumption 4)

$$\mathrm{x} \neq \mathrm{y} \neq \mathrm{z} \quad (7)$$

Each goals are different both for the OPEX, the CAPEX and for the TOTEX.

Assumption 5)

The analysis is carried out with reference to the investment level SG = (1-ς) GSG, with GSG being the total resources (OPEX + CAPEX) spent in innovation.

Thus, the resources that are not spent through investments will be spent through OPEX (ς GSG).´

Assumption 6)

Investment that go beyond network quality of service obligations are treated as sector externalities.

Assumption 7)

Regulatory goals are achieved, i.e, companies can withhold some of the gains obtained during the regulatory period.

Assumption 8)

The investment decision (type of investment) is not influenced by the regulatory framework:

$\mathbf{-I_{TotexSG} = -I_{SG}}$, $\mathbf{DTOTEX}=\mathbf{DC + DI_C}$ and $\boldsymbol{\xi G_{Totex}} = \boldsymbol{\xi G}$ (8)

3.3 Results

The analysis was carried out bearing in mind several regulatory contexts. For that purpose, the following simulation were performed:

i) Totex methodology is compared with the traditional hybrid methodology, for two situations:

  a) The regulator defines goals that are achieved by the company which witholds the benefits that goes beyond the goals:
    i. Static evaluation, the weight of cost structure does not change
    ii. Dynamic assessment, the weight of cost structure changes

ii) Case study, for a situation of profit sharing between regulated and regulators.

3.3.1 Comparing Totex and hybrid methodologies

Regulated company withholds gains that go beyond regulatory goals:

If DOPEX>x, $\alpha < 1$

(9)

If DCAPEX>y, $\gamma < 1$

If DTOTEX>z, $\delta < 1$

For simplicity, one considers that company will withhold all gains achieves.

Therefore, $\gamma = 0$, $\alpha = 0$ and $\delta = 0$.

As the analysis is carried out for the same type of innovative investments, the portions of the revenues obtained before the review of the regulatory parameters, as well as resulting from the externalities of innovative investments are the same:

$$\left\{-\mathrm{I}_{\mathrm{SG}}; \sum_{t=1}^{T} \frac{\mathrm{DC}}{(1+r)^{t}} + \sum_{\mathrm{t}=1}^{\mathrm{T}} \frac{\mathrm{DI}_{\mathrm{C}}}{(1+\mathrm{r})^{\mathrm{t}}}; \sum_{\mathrm{t}=\mathrm{T}+1}^{\infty} \frac{\xi G}{(1+\mathrm{r})^{\mathrm{t}}}\right\} = \left\{-\mathrm{I}_{\mathrm{SG}}; \sum_{t=1}^{T} \frac{DC\mathrm{TOTEX}\quad \mathrm{iC}}{(1+r)^{t}}; \sum_{\mathrm{t}=\mathrm{T}+1}^{\infty} \frac{\xi G}{(1+\mathrm{r})^{\mathrm{t}}}\right\} \quad (10)$$

Therefore, the comparison between methodologies will only take into account the portion of allowed revenues, unrelated to innovation externalities, defined after the review of regulatory parameters. The reduced models are as follows:

Totex model

$$\mathrm{DTOTEX} = \mathrm{DCAPEX} + \mathrm{DOPEX} = (-\mathrm{DI}_{\mathrm{SG}} + \mathrm{DI}_{\mathrm{iC}} - \mathrm{DC}_{\mathrm{SG}} + \mathrm{DC}_{\mathrm{C}})) \ (11)$$

The reduced form of model 1), considering only the components of allowed revenues, unrelated to externalities, defined after the review of regulatory parameters, will be as followed:

$$\frac{(1-\delta)(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{DI}_{\mathrm{C}})+(1-\delta)(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{DC}_{\mathrm{iC}})}{r(1+\mathrm{r})^{\mathrm{T}}} = \frac{(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{DI}_{\mathrm{C}})+(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{DC}_{\mathrm{iC}})}{r(1+\mathrm{r})^{\mathrm{T}}} \quad (12)$$

Since $\delta = 0$

Hybrid model

The reduced form of model 3), considering only the portion of allowed revenues, unrelated to externalities, defined after the review of regulatory parameters, will be as followed:

$$\frac{r(\mathrm{D}I_{\mathrm{SG}}-\mathrm{D}I_{\mathrm{iC}})+(1-\alpha)(-\mathrm{DOPEX}_{\mathrm{SG}}+\mathrm{DOPEX}\quad_{\mathrm{iC}})}{r(1+\mathrm{r})^{\mathrm{T}}} = \frac{r(\mathrm{D}I_{\mathrm{SG}}-\mathrm{D}I_{\mathrm{iC}})+(-\mathrm{DOPEX}_{\mathrm{SG}}+\mathrm{DOPEX}\quad_{\mathrm{iC}})}{r(1+\mathrm{r})^{\mathrm{T}}} \quad (13)$$

I) <u>Static analysis</u>

In this section, we perform a static analysis, assuming the maintenance of the weight of OPEX and CAPEX after the innovative investment.

Using the reduced form of the models, the comparison of the two regulatory methodologies, assuming transfer of gains, that is, α = 0, gives the following results:

$$\frac{(\mathrm{D}I_{\mathrm{SG}}-\mathrm{D}I_{\mathrm{iC}})}{(1+\mathrm{r})^{\mathrm{T}}} + \frac{(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{DC}_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}} - \frac{(-\mathrm{D}I_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{iC}})+(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{DC}_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}} = \frac{(DI_{SG}-DI_{C})}{(1+r)^{T}} - \frac{(-DI_{SG}+DI_{C})}{r(1+r)^{T}} \quad (14)$$

We will analyse expression (18) for two situations.

First, innovative investment expenditures are greater than the reductions that they allow for conventional investments amounts, i.e, $\mathbf{D}\boldsymbol{I}_{\mathbf{SG}} - \mathbf{D}\boldsymbol{I}_{\mathbf{C}}$ >0 e $-\mathbf{D}\boldsymbol{I}_{\mathbf{SG}} + \mathbf{D}\boldsymbol{I}_{\mathbf{C}}$ <0, therefore:

$$\frac{(\mathbf{D}\boldsymbol{I}_{\mathbf{SG}}-\mathbf{D}\boldsymbol{I}_{\mathbf{C}})}{(\mathbf{1+r})^{\mathbf{T}}} > \frac{(-\mathbf{D}\boldsymbol{I}_{\mathbf{SG}}+\mathbf{D}\boldsymbol{I}_{\mathbf{C}})}{\boldsymbol{r}(\mathbf{1+r})^{\mathbf{T}}} \quad (15)$$

In this case, the gains with hybrid methodology (left side of the inequality) are greater than Totex or incentive targets both on CAPEX and OPEX.

However, in that case innovative investments could only be considered rational if the external gains that they achieve will be enough to recover the raise of net cost they induce in network activity performed by the company.

The second situation happens when expenditures with innovative investments are lesser than the reductions that they allow in conventional investments, therefore ($\mathbf{D}\boldsymbol{I}_{\mathbf{SG}} - \mathbf{D}\boldsymbol{I}_{\mathbf{C}}$) <0 e ($-\mathbf{D}\boldsymbol{I}_{\mathbf{SG}} + \mathbf{D}\boldsymbol{I}_{\mathbf{C}}$) >0:

$$\frac{(\mathrm{D}I_{\mathrm{SG}}-\mathrm{D}I_{\mathrm{C}})}{(1+\mathrm{r})^{\mathrm{T}}} < \frac{(-\mathrm{D}I_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}} \quad (16)$$

In this case, the gains obtained with the hybrid methodology (right side of the inequality) are smaller than the gains with Totex or incentive base both for CAPEX and OPEX.

Since r <1, the gain obtained in this situation with a Totex or incentive base both for CAPEX and OPEX is clearly higher than the losses obtained with these methodologies in the previous situation.

Bearing in mind these two situations, one can conclude that if an investment in SG do not decrease network investment costs, but brings benefits that are higher than the costs they produce in the network, it is natural that its cost is fully recognized, i.e., hybrid approach is more appropriate. However, if the benefits go beyond the sector users (consumers), it has to be weighed whether only part of the investment costs (in proportion to the benefit that stay in this activity) or all costs should be recovered through tariffs.

If an investment in SG decrease conventional investments, then the best option is to apply a TOTEX methodology.

II) <u>Dynamic analysis</u>

For this dynamic analyses, one considers that the relation between OPEX and CAPEX varies with the innovative investment. Therefore, we will test hypotheses of gains by varying the relation between both type of costs.

For that dynamic analysis, we first consider that both conventional OPEX and CAPEX decrease with the innovative investment:

- $\mathrm{f}(\mathrm{C}_{\mathrm{SG}})$ increases with I_{SG}, therefore $D_{\mathrm{f}(I_{\mathrm{SG}})} = \frac{D_{\mathrm{C}_{\mathrm{SG}}}}{D_{I_{\mathrm{SG}}}}>0$
- $\mathrm{g}(\mathrm{C}_{\mathrm{c}})$ decreases with I_{SG}, therefore $D_{\mathrm{f}(I_{\mathrm{SG}})} = \frac{D_{\mathrm{C}_{\mathrm{Ic}}}}{D_{I_{\mathrm{SG}}}}<0$ (17)
- $\mathrm{h}(\mathrm{I}_{\mathrm{ic}})$ decreases with I_{SG}, therefore $D_{\mathrm{h}(I_{\mathrm{SG}})} = \frac{D_{\mathrm{I_c}}}{D_{I_{\mathrm{SG}}}}<0$

We will again compare the TOTEX and hybrid regulatory approaches. However, comparing these two functions, the common components are eliminated, which include OPEX components. Therefore:

$\mathrm{u}(\mathrm{I}_{\mathrm{SG}})= \frac{\left(D_{I_{\mathrm{SG}}}-D_{\mathrm{I_c}}\right)}{(1+\mathrm{r})^{\mathrm{T}}}$, for Totex (or incentive applied in Capex and Opex) (18)
$\mathrm{v}(\mathrm{I}_{\mathrm{SG}})= \frac{\left(-D_{I_{\mathrm{SG}}}+D_{\mathrm{I_c}}\right)}{r(1+\mathrm{r})^{\mathrm{T}}}$, for Hybrid (19)

The functions derivative are:

$D_{\mathrm{u}(I_{\mathrm{SG}})} = \frac{(1-D_{\mathrm{I_c}})}{(1+\mathrm{r})^{\mathrm{T}}} > 0$, for Totex (or incentive applied in both Capex and Opex) (20)
$D_{\mathrm{v}(I_{\mathrm{SG}})} = \frac{(-1+D_{\mathrm{I_c}})}{r(1+\mathrm{r})^{\mathrm{T}}} < 0$, for Hybrid (21)

Thus, assuming that both conventional CAPEX and OPEX decrease with the innovative investment, one can conclude that Totex is beneficial for the company.

We also consider that only conventional OPEX decreases with the innovative investment, as follows:

- $\mathrm{f(C_{SG})}$, decreases with I_{SG}, therefore $D_{\mathrm{f}(I_{\mathrm{SG}})} = \frac{D_{\mathrm{C_{SG}}}}{D_{I_{\mathrm{SG}}}} > 0$
- $\mathrm{g(C_c)}$, decreases with I_{SG}, therefore $D_{\mathrm{f}(I_{\mathrm{SG}})} = \frac{D_{\mathrm{C_c}}}{D_{I_{\mathrm{SG}}}} < 0$ (22)
- $\mathrm{h(I_c)}$, increases with I_{SG}, therefore $D_{\mathrm{h}(I_{\mathrm{SG}})} = \frac{D_{\mathrm{I_c}}}{D_{I_{\mathrm{SG}}}} > 0$

Using the same approach as in the previous assumption, we obtain the following derivatives:

$D_{\mathrm{u'}(I_{\mathrm{SG}})} = \frac{(1-D_{\mathrm{I_c}})}{(1+\mathrm{r})^{\mathrm{T}}} > 0$, if $\frac{D_{\mathrm{I_c}}}{D_{I_{\mathrm{SG}}}} < 1$, for Totex (23)
$D_{\mathrm{v'}(I_{\mathrm{SG}})} = \frac{(-1+D_{\mathrm{I_c}})}{r(1+\mathrm{r})^{\mathrm{T}}} < 0$, if $\frac{D_{\mathrm{I_c}}}{D_{I_{\mathrm{SG}}}} < 1$, for Hybrid (24)

Thus, there are gains for the company with TOTEX, provided that the increase in conventional investments resulting from innovative investments are lower than the increase in innovative investments.

3.3.1 Case study: situation of profit sharing between regulated and regulators

After highlighting the advantage of Totex, compared to hybrid regulation, this section evaluate the impacts of applying different regulatory targets for OPEX and CAPEX (“block” approach), considering a typical case in terms of cost structure and regulatory targets.

Considering the relations previously defined, we have:

$$\delta = \frac{\gamma\,\mathrm{I}}{TOTEX} + \frac{\alpha\,\mathrm{C}}{TOTEX} \equiv$$
$$\delta = \frac{\gamma\,\mathrm{I}}{I + C} + \frac{\alpha\,\mathrm{C}}{I + C} \equiv$$

$\delta\mathrm{I} + \delta\mathrm{C} = \gamma\,\mathrm{I} + \alpha\,\mathrm{C} \equiv$ (24)

And considering the adaptation of formula (13):

$$\frac{(1-\gamma)(-\mathrm{DI_{SG}}+\mathrm{D}I_{\mathrm{C}})+(1-\alpha)(-\mathrm{DC_{SG}}+\mathrm{D}C_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}} \quad (25)$$

As said, we assume a case that is quite representative of the cost structure of network activities, where CAPEX has typically a biggest relative weighting than OPEX:

$\frac{\mathrm{I}}{I+C} = \frac{2}{3}$ and $\frac{\mathrm{I}}{I+C} = \frac{1}{3}$; $\gamma = 0{,}75$ and $\alpha = 0{,}5$

Therefore, $\delta = 7/12$

This situation corresponds to a situation in which most of the regulatory risk is borne by OPEX, which corresponds, in general, to what happens in most regulatory schemes.

For Totex methodology, we have:

$$\frac{(1-\delta)(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})+(1-\delta)(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{iC}})}{r(1+\mathrm{r})^{\mathrm{T}}}=\frac{(5/12)(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})+(5/12)(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}}=\frac{(5/12)[(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})+(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{C}})]}{r(1+\mathrm{r})^{\mathrm{T}}} \quad (26)$$

For “Block” methodology, we have:

$$\frac{\left(\frac{3}{12}\right)(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})+\left(\frac{6}{12}\right)(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}} \quad (27)$$

Comparing both:

$$\frac{(5/12)[(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})+(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{C}})]}{r(1+\mathrm{r})^{\mathrm{T}}}-\frac{\left(\frac{3}{12}\right)(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})+\left(\frac{6}{12}\right)(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}}=$$

$$\frac{\left(\frac{2}{12}\right)(-\mathrm{DI}_{\mathrm{SG}}+\mathrm{D}I_{\mathrm{C}})-\left(\frac{1}{12}\right)(-\mathrm{DC}_{\mathrm{SG}}+\mathrm{D}C_{\mathrm{C}})}{r(1+\mathrm{r})^{\mathrm{T}}}>0 \quad (28)$$

Therefore, for that situation Totex is also more beneficial, as long as $-\mathrm{DI}_{\mathrm{SG}} + \mathrm{D}I_{\mathrm{C}}>0$, i.e, investment in SG globally decreases the need to invest.

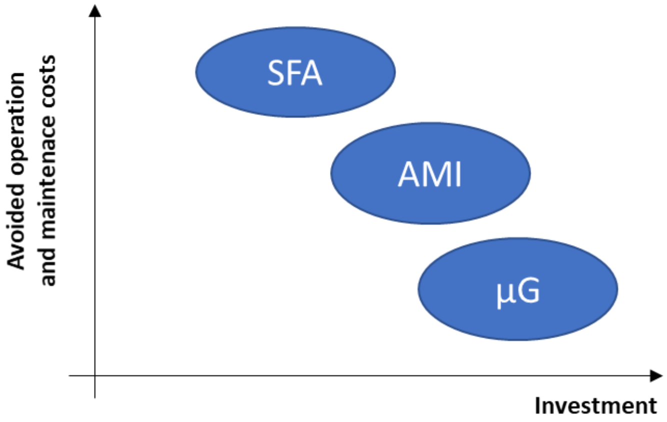
4. Discussion and conclusion

This paper addresses a gap in the literature about the consideration of the innovation’s external benefits when defining the regulation of the investment in new technologies for electricity grids. These externalities are an important element for changing the electricity grid, which is crucial in the energy transition context. In such context, regulatory schemes must be adequately adapted to the specificities and advantages of each type of innovative investment or process. Therefore, this paper pave the way to improve the understanding of the most suitable regulatory approaches to incentivize the adoption of the new technologies that are needed to modernize the electricity distribution networks.

Totex-type methodologies are more effective in promoting innovation than other methodologies, generally applied by regulators, which distinguish regulatory approaches according to the nature of the cost and being generally more demanding for OPEX than CAPEX. The paper distinguishes from the previous literature, which also suggests the superiority of incentive-based regulation for the promotion of cost saving technologies in Smart Grids or for distributed energy resources integration (Marques et al., 2014; Brown & Sappington, 2018), by explicitly address Totex regulatory approach, and the positive externalities resulting from innovative investments. Those externalities include the improved capacity to absorb increasing penetrations of decentralized and renewable generation, the higher ability to accommodate more load demand, and the integration of the electrical mobility, which are crucial for decarbonization.

TOTEX regulatory approach effectively promote technologies such as the SFA, which are characterized by the ability to allow significant operating costs decrease while imposing a relative low investment cost when compared to the AMI and μG (microgrids) technologies, as shown in Figure 1.

Figure 1 –SG technologies cost efficiency



The AMI technologies may also benefit from the use of a TOTEX regulation once they are able to reduce operating costs and avoid new investments. However, their benefits clearly spill over from the sector, in a more significant way than the SFA and µG technologies (see Figure 2). The combination of these two situations justifies the fact that the costs related to AMI technologies (such as the smart meters and the needed communication platform), may be directly recovered through tariffs, once the cost-benefit analysis is positive. In that case, it has to be weighed, whether only part of the cost (in proportion to the benefit that stay in this activity) or all cost should be recovered through tariffs. The roll-outs of smart meters that have been implemented in several European countries are an example of this (Geels et al., 2021).

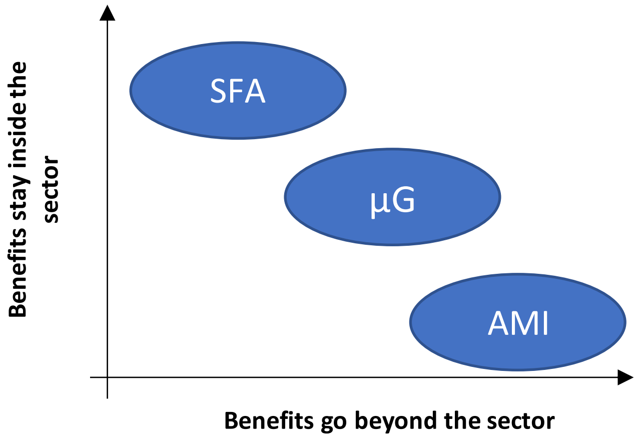
Bearing in mind that the benefits associated with these technologies derive mainly from the type of services they can provide to consumers, the recovery of their costs may be directly associated to the services they provide. Thus, the regulatory methodology that seeks to promote these technologies is less input-based oriented, and more output-based oriented instead. Such regulatory approach is followed by some regulators, such as the Portuguese regulator (ERSE) with its ISI[2] regulatory scheme.

Regarding µGs, although these investments make it possible to control costs and their benefits are mainly internal to the sector, these are, in general, locally restricted. Thus, the socialization of the costs of investments in µGs through regulatory tariffs must be balanced taking into account the gains obtained. However, the scale effect of these benefits in the integrated management of the network may arise, with the generalization of such projects. This justifies that such investments can be monitored through pilot projects and that regulatory “sand-boxes” can be developed, in order to evaluate the net gains, for the whole network, of such kind of experiences.

---

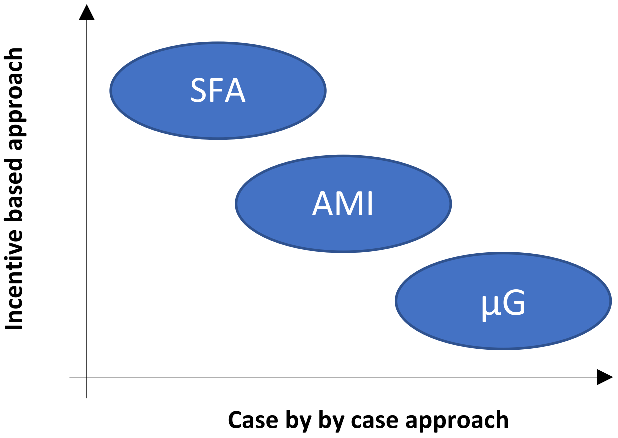
[2] Incentive for the Integration of Low Voltage installations into Smart Grids

Figure 2 –SG technologies externalities



In conclusion, this paper shows that in the energy transition context, when regulatory concerns embrace many targets, regulatory schemes must be adequately adapted to the specificities and advantages of each type of innovative investment or process. The models presented allow to analyze the advantages of a TOTEX regulatory approach to promote innovation which reduces the future needs of investment in the network, comparing with traditional schemes (hybrid or cost plus). It was possible to foresee that incentive based regulation, in particular TOTEX, will be more effective in promoting SFA-type technologies, while a case-by-case analysis will be more appropriate for µG's technologies. AMI technologies lie on the middle of these two regulatory approaches. Figure 3 illustrates the paper’s main findings.

Figure 3 – Regulatory approaches



References:
Abundo, M.L. (2016). A Review of the Development of Smart Grid Technologies. Renewable and Sustainable Energy Reviews, Vol. 59. Pages 710-725.
Bayindir R., Colak I., Fulli G., Demirtas K. (2016), Smart grid technologies and applications, Renewable and Sustainable Energy Reviews, Volume 66, Pages 499-516, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.08.002.
Bento, N., Wilson, C. (2016). Measuring the duration of formative phases for energy technologies. Environmental Innovation and Societal Transitions, 21, 95-112.
Bento, N., Wilson, C., Anadon, L. D. (2018). Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies. Energy Policy, 119, 282-293.

Brown D., Sappington D., (2018). Optimal procurement of distributed energy resources. The Energy Journal, 39 (5).

BCG (2020). Accelerating Transformation for an Uncertain Future. The 2020 Power and Utilities Value Creators Report.

Cambini C., Croce A., Bompard E., Fumagali E., (2014). Output-based incentive regulation in electricity distribution: Evidence from Italy, Energy Economics, vol. 45, issue C, 205-216.

Cambini C., Meletiou A., Bompard E., Masera M., (2016). Market and regulatory factors influencing smart-grid investment in Europe: Evidence from pilot projects and implications for reform, Utilities Policy Vol. 40.Pages 36-47.

CEER (2018). Incentives Schemes for Regulating Distribution System Operators, including for innovation -A CEER Conclusions Paper, available on: https://www.ceer.eu/documents/104400/-/-/1128ea3e-cadc-ed43-dcf7-6dd40f9e446b.

CEER (2020). CEER Report on Regulatory Frameworks for European Energy Networks, available on: https://www.ceer.eu/en/1913.

Costa, P. M.,Bento, N., Marques, V., (2017). The Impact of Regulation on a Firm's Incentives to Invest in Emergent Smart Grid Technologies. The Energy Journal, Volume 38.

Dileep G. (2020), A survey on smart grid technologies and applications, Renewable Energy, Volume 146, Pages 2589-2625, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2019.08.092.

Faerber, L.A.., & Balta-Ozkan, N., & Connor, P.M. (2018). Innovative Network Pricing to Support the Transition to a Smart Grid in a Low-Carbon Economy, Energy Policy, 116.Frame D., Hannonb M., Bella K., McArthura S., (2008). Innovation in regulated electricity distribution networks: A review of the effectiveness of Great Britain's Low Carbon Networks Fund. Energy Policy. Vol. 118. Pages 121-132.

Galus, D. M., (2017). Smart Grid Roadmap ans Regulation Approaches in Switzerland, 24th CIRED Conference.

Geels, F. W., Sareen, S., Hook, A., & Sovacool, B. K. (2021). Navigating implementation dilemmas in technology-forcing policies: A comparative analysis of accelerated smart meter diffusion in the Netherlands, UK, Norway, and Portugal (2000-2019). *Research Policy*, *50*(7), 104272.

Grubler, A. (2012). Energy transitions research: Insights and cautionary tales. Energy policy, 50, 8-16.

Grubler, A., & Wilson, C. (Eds.). (2014). Energy technology innovation. Cambridge University Press.

Grubler, A. (2003). Technology and global change. Cambridge University Press.

Grubler, A., F. Aguayo, K. Gallagher, M. Hekkert, K. Jiang, L. Mytelka, L. Neij, G. Nemet and C. Wilson, (2012). Chapter 24 - Policies for the Energy Technology Innovation System (ETIS). In Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1665-1744.

Grubler A., Wilson C., Bento N., Boza-Kiss B., Krey V., McCollum D. L., Valin, H. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. Nature energy, 3(6), 515-527

Jamasb T., Pollitt M. (2015). Why and How to Subsidise Energy R+D: Lessons from the Collapse and Recovery of Electricity Innovation in the UK. Energy Policy, Elsevier, vol. 83, pages 197-205.

Jenkins J., Arriaga I., (2017). Improved Regulatory Approaches for the Remuneration of Electricity Distribution Utilities with High Penetrations of Distributed Energy Resources. The Energy Journal, Vol. 38, No. 3. Pages 63-91.

Joskow P.L. (2000). Economic Regulation edited by Paul. L. Joskow, Elgar Reference Collection

Irena (2019). Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables, International Renewable Energy Agency, Abu Dhabi.

IEA 2020, R&D and technology innovation, available on: https://www.iea.org/reports/world-energy-investment-2020/rd-and-technology-innovation.

Kuiken D., Heyd F. Más (2019). Integrating demand side management into EU electricity distribution system operation: A Dutch example, Energy Policy, Volume 129, Pages 153-160, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2019.01.066

IEA (2021), Net Zero by 2050—A Roadmap for the Global Energy Sector, IEA/OECD, Paris.

Laffont JJ, Tirole J. (1993). A theory of procurement and regulation. Cambridge: MIT Press.

Lind, L.,Cossent, R., Frías, P. (2019). New Business Models Enabled by Smart Grid Technology and their Implications for DSOs, 25th International Conference on Electricity Distribution (CIRED), Madrid.

Marques, V.,Bento, N., Costa, P. M., (2014). The “Smart Paradox”: Stimulate the deployment of smart grids with effective regulatory instruments. Energy, Elsevier, vol. 69(C), pages 96-103.

Mac Kinsey Global Institute (2017). The Productivity Puzzle: a Closer Look at the United States. Mark de Reuver, Telli van der Lei, Zofia Lukszo, How should grid operators govern smart grid innovation projects? An embedded case study approach, Energy Policy, Volume 97, 2016,Pages 628-635, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2016.07.011.

OECD (2020), Highlights from OECD Innovation Indicators 2019, availabe on: https://www.oecd.org/sti/inno/innovation-indicators-2019-highlights.pdf

Spiliotis K., Ramos Gutierrez A.I, Belmans R., (2016) Demand flexibility versus physical network expansions in distribution grids, Applied Energy, Volume 182, Pages 613-624, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2016.08.145

Schmalensee R. Good regulatory regimes (1989). Rand J Econ ;20(3):417e36

Smil, V. (1994). Energy in World History. Westview Press, Boulder, CO.Tuballa, M.L.,