Greater than the sum: on the regulation of innovation in distribution networks with externalities

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Abstract

To modernise distribution networks and enable the energy transition, we need to understand the most appropriate regulatory approach to incentivise the adoption of technology innovations in the grid. An increasing set of new technologies have positive externalities beyond the provision of basic network activities or improvement of the quality of service. These technologies provide an additional value for the transformation of the grids, challenging traditional regulatory models which tend to overlook the indirect benefits of investments. We develop a decision model to assess firms' incentives to invest in new technologies under different regulatory schemes that consider externality effects. Results show that regulatory schemes, under which companies retain all the losses and gains of achieving (or not) efficiency targets, more effectively promote innovative investments that reduce network costs. However, no one-size-fits-all scheme exist for technologies whose benefits go mostly beyond the network activities, and a case-by-case approach should be preferred.

Keywords: regulation, incentives, innovation, externalities, electricity distribution networks.

1 Introduction

Decarbonise the economy by the middle of the century imposes an energy transition that will have pervasive consequences in many sectors. It requires a transformation in the electrical networks to allow greater integration of renewable energy generation, more energy efficiency, a higher share of electric mobility, and more active participation of consumers (IEA, 2021). Transforming the current electricity distribution networks to enable the energy transition needs an adequate level of innovation and investment.

Various technological innovations have become available recently to support the transformation of electricity distribution networks. Digitalisation is considered essential in facilitating clean energy transition (IEA, 2022). Automation and digitalisation have become relevant topics, combining information and communication technologies with the more conventional infrastructures. Those technological innovations help the integration of new demands (e.g., electric mobility) or the development of already established concepts such as distributed energy resources (e.g., Dileep, 2020) that, most of the time, are renewable resources. Technologies supported by automation and digitalisation emerge as the more relevant concepts from the viewpoint of the utilities and network operators in the shorter term (Dileep, 2020).

Under certain circumstances, technology innovations can even reduce the need for traditional network investments. That may be reached by reducing the electricity demand , which is also the most efficient way to meet the energy

[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.

and climate targets (Grubler et al., 2018). Distributed solar generation, depending on the location and network pricing, can either reduce (Cohen et al., 2016) or increase (Wolak, 2018) the need for network investment. Another alternative to traditional network investment is electricity storage. Electricity can be stored near consumption points and released in moments of network congestion and/or peaks of demand. This reinforces the system's reliability while avoiding further network expansion).

Regulation has an important role in the implementation of innovations in electrical networks (Lind et al., 2019; Galus, 2017; Faerber et al., 2018), as well to ensure, in a broader perspective, that the changes in its business model, which are foreseeable, will meet customers' evolving needs (Peterson and Ros, 2018) The regulatory contexts generally provide relatively high and stable returns compared to other industries (BCG, 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 (MacKinsey, 2017; OECD, 2020; IEA, 2020).

There is a debate about the best approach to stimulate the adoption of new technologies in the networks that encompass entirely different perspectives. However, most of these analyses have overlooked the role of externalities for the system resulting from grid modernisation. This modernizationallows for the development of new greener services, such as demand-side management or electric mobility, which is of utmost importance for decarbonisation.

Therefore, this paper addresses the following question: what is the most suitable regulatory model to incentivise the investment in the new technologies needed to modernise the electricity distribution network? A central proposition in this study is that the different effects coming from innovation should receive a different regulatory approach. Thus, we develop a decision model that explicitly considers the profile of the benefits and costs of the technology innovations, including their spillovers. The results obtained are then considered to analyse the investment in three new technology innovations in the grid: Advanced Metering Infrastructure; Substation, Feeder Automation; and microgrids. Those technologies have been widely recognised as important milestones in the (short-term) digitalisation and modernisation of the distribution networks (see, e.g., Dileep, 2020).

The rest of the paper evolves as follows. The following section presents the benefits of three representative innovations in distribution networks. Section 3 reviews the literature. Section 4 develops the decision model. Section 5 applies the model against the technology innovations under analysis. Section 6 proposes a general regulatory framework to address the investment in network innovation considering two dimensions, externalities and technological risks, and their impacts on the regulator's action in terms of scope and power of the incentive regulatory schemes. Section 7 presents the main results before discussing their theoretical and policy implications, along with the limitations and open questions for future research.

2. Innovation in the grids: benefits inside and outside the electricity sector

The use of intelligent monitoring, communication, control, and self-healing technologies are the core for the modernisation of the distribution network. This should respond to the new demands for more reliable, resilient, secure, efficient, and flexible infrastructures. The modernisation of the distribution networks is, in particular, a crucial step in responding to the increasing demands of electricity and services from the digital society while reducing the environmental impacts at the lowest cost.

Over the past few years, various innovative technologies have been developed to enhance the performance of the electrical sector. These technologies also help in the integration of new concepts such as electric mobility or to reinforce the development of already established ideas, like distributed generation (DG) (Dileep G., 2020; Spiliotis K. et al., 2016; Bayindir R. et al., 2016).

In the European regulatory context, some of those technologies can only be implemented by utilities since they are focused on network operation and development. Others will be implemented by network users (in particular by consumers, energy aggregators, services, retailers, etc.) since they are out of the scope of network activities. 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 that are implemented by utilities, the Advanced Metering Infrastructure

(AMI), the Advanced Substation and Feeder Automation (ASFA), and the microgrids (µG) concepts appear as the more relevant from the viewpoint of the utilities. Table 1 shows a short description of these three technologies.

Table 1 – Short description of innovative technologies

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 primary 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 to implement a functional AMI system.
Advanced Substation and Feeder Automation (ASFA)	The ASFA goes beyond the automation that has existed for a few decades, fundamentally aimed at the remote control of some network resources. In fact, ASFA can use decision-making algorithms that, upon the occurrence of certain events, determine autonomous actions (without the need for direct human intervention) as, for example, the self-healing of the network after a fault or the voltage regulation. Therefore, ASFA uses specific hardware and software resources to endow electrical networks with intelligence that allows continuous monitoring, control, protection, data acquisition about network assets, and the execution of various autonomous automated actions. The ASFA gathers data from different sensors and sends these data to a central computer that manages the data and controls devices in the field remotely. Several components of hardware may be used in ASFA, namely: sensors (smart relays, phasor measurement units, voltage and current measurement units, remote fault indicators that detect current and voltages levels on feeders that are outside usual operating boundaries, etc.); actuators (circuit breakers, capacitor bank switches, automatic voltage regulators, reclosers, load tap changer controllers, etc.); fast communication platforms (possibly on optical fibre), including SCADA equipment; and even some assets outside the network, such as storage systems, vehicle to grid units, or distributed generation (DG). Concerning software, a wide range of applications can be used, including Scada software, communication protocols, online and offline applications for monitoring and diagnostics of primary substations, and line equipment, including transformers, circuit breakers, relays, cables, capacitors, switches, bushings., etc. The Digital Twin (DT) technology, which is rapidly developing, will play a vital role in this autonomous automation. DT technology consists of the digital representation of the physical system that supports decision-making on actions to implement in the physical system. In other words, it is an SW that collects information about the physical system and has a digital representation (model) of that system that allows predicting what happens when an event or set of circumstances occurs. That is, DT creates a dynamic digital model that mirrors the physical substation and feeders system, allowing the continuous comparison between the behaviour of the real monitored and the simulated scenarios (Brosinsky et al, 2018) and (Pan et al, 2020)].
Microgrids (µG)	The concept of µG has been developed to ease the integration of microgeneration in low voltage (LV) networks. A µG is an association of a LV distribution network, microgenerators, loads, and storage devices, with 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 and a communication platform. Control equipment includes a µG central controller and microgeneration and load controllers. The µG controllers control the active and reactive powers produced by microgeneration 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 optimise the technical and, when applicable, the economic performance of the µG. It is essential to emphasise that the ownership of microgrids varies according to the existing context, and three fundamental models can be found: µG owned by third parties (consumers, service companies, etc.); µG owned by the network operators; and µG held in a hybrid model (Valta, et al, 2018; Marnay et al, 2015; Vanadzina, et al, 2019). In this work, we assume the uGs owned by network operators, created as a solution to enhance gains in

	reliability and quality of service of their networks or even to integrate more DG. In this ownership model, the utility company invests and owns the μG to support its operation, where these investments are economically feasible. That is, the utility will invest in μG when this is cheaper than building new network resources (lines, for instance) to ensure compliance with required constraints (for example, reliability and energy quality levels).

These three technologies can reduce operating and maintenance costs and even network investments (e.g., extending the useful life of already installed resources). But they also bring economic benefits beyond network activities. Tables 1 to 4 identify the more relevant benefits inside and outside the network and the costs resulting from the establishment of AMI, ASFA and uG. It is important to stress that the benefits and costs of investing in these innovative technologies depend on the investment's characteristics and context. For example, investing in a μG can produce substantially higher reliability-related benefits if it is established in a weak network area than if it is established in a network area with high-reliability indices. A similar situation occurs for the investment in ASFA. Likewise, the investment in ASFA, for example, depends on the system implemented, particularly concerning the hardware and software resources that prove necessary.

Table 2 – Benefits and costs resulting from AMI

Technology	Network benefits	Benefits outside the network		Investment and, operation & maintenance costs
		Environmental	Others	
AMI	- lower billing costs due to a more autonomous system; - 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 avoid or delay investments and integrated and responsive voltage regulation - lower costs related to the theft of electricity; - potential reduction on network operation costs once AMI allows obtaining helpful information to define a more proper network operation.; - lower electricity quality monitoring costs.	- benefits resulting from avoided emissions related to: - a better operation of the networks, namely due to potential better management of the load flows and to the development of Demand Response technologies; - energy efficiency in delivery and use of electricity; - the faster integration of distributed renewable generation; - the ability to create a market of emissions.	**- Consumers:** - potential lower energy costs once AMI can provide information on electricity prices and consumption patterns. ; - potential income resulting from more active participation in electricity markets, as well as in providing system services; - electricity cost savings resulting from energy sharing in collective self-consumption activity. **- Retailers/aggregators:** - development of new pricing strategies), which can help in attracting new customers; - possibility of developing new activities such as aggregating production, consumption, or storage capacity. **- Society:** - More efficient electricity usage and higher self-generation integration based on renewable resources contribute to less dependence on energy imports.	The deployment of a suitable AMI implies costs related to investment and costs related to the operation and maintenance of the system. The investment costs are mainly related to: - the smart devices to be installed at user points; - the communication network; - the installation of the devices and communication systems. - the needed software for data collection, analysis and storage; Data collection, analysis, storage, and system management result in operation and maintenance costs. Another cost that can be important is associated with the necessary updating of security systems against cyberattacks, which will have to be maintained over the years.

Table 3 – Benefits and costs resulting from ASFA

Technology	Network benefits	Benefits outside the network		Investment and, operation & maintenance costs
		Environmental	Others	
ASFA	- lower financial losses related to energy not distributed and compensations for violation of quality of service indicators. As well, ASFA allows a faster and more automated and autonomous network reconfiguration after a fault/outage situation; - optimisation of assets and efficient operation of the network; - more intelligent asset management, including better planning of preventive and corrective maintenance; - the ability to prevent potential failures, detect and predict disturbances, fluctuations and monitor equipment health; - improved management of distributed energy resources, including microgrid operation and storage management; - easier accommodation of (DG) storage systems in a plug-and-play regime.	Avoided emissions resulting from: - a more efficient operation of the networks; - more easy and coordinated integration of DG, mainly renewable generation; - lower downtime of renewable-based distributed generators due to network unavailability.	- **Consumers:** - a more reliable system and high-quality electricity, which is needed for the digital society ; - a more secure system, reducing the possibility of power blackouts. **- Society:** - a higher integration of DG , including self-generation, contributing to less dependence on energy imports.	The implementation of an ASAF includes investment costs in hardware and software resources, namely: - sensors: smart relays, phasor measurement units, voltage and current measurement units, remote fault indicators (that detect current and voltages levels on feeders that are outside usual operating boundaries), etc.; - actuators: circuit breakers, capacitor bank switches, automatic voltage regulators, reclosers, load tap changer controllers, etc.; - fast communication platforms (possibly on optical fibre); - SCADA equipment; - a wide range of software applications, including SCADA software, online and offline applications for monitoring and diagnostics of primary substations and line equipment (including transformers, circuit breakers, relays, cables, capacitors, switches, bushings., etc.), communication protocols, and Digital Twin software platforms. The maintenance costs are related to the equipment installed to establish the ASAF. Although the ASAF is expected to have a markedly autonomous operation, operational costs related staff needed to operate the system will exist. Another cost that can be important is related to the necessary updating of security systems against cyberattacks, which will have to be maintained over the years.

Table 4 – Benefits and costs resulting from µG

Technology	Network benefits	Benefits outside the network		Investment and, operation & maintenance costs
		Environmental	Others	
µG	- avoided reliability-related investments due to improved reliability indices resulting from the abilities of µG to both isolates from the upstream network and control internal generation and load, even when interconnected to the upstream network.; - reduction in the loss resulting from not distributed energy, once µGs contribute to outage duration reduction - possible obtention of grid services from the µGs, including congestion relief, reactive power and voltage control support, frequency regulation etc.	- Higher integration of DG, namely based on renewable resources.	**Consumers:** - fewer financial costs related to power outages; reduction in the costs that result from power outages; - not loss generation in self productions. **LV distributed generators:** - not loss generation. **Society:** - a more resilient system, better prepared to face difficult situations; - job creation, particularly at a local level.	For the establishment of a µG, by evolving an existing network, some investments must be made, namely in: - management and control equipment (microGrid central controller (MGCC), generator controllers (GC), and the load controllers (LC)); - communication systems, needed to allow communication between MGCC, LC and GC. - energy storage devices to ensure the success of islanding and subsequent isolated operation of the µG; - suitable protection schemes, able to respond suitably in the presence of low short-circuit currents that may exist, namely when the µG operates in isolated mode; - a static switch, able to ensure high-speed isolation of the µG, to be installed on the interconnection point between the µG and the main network. Besides the investment cost (including project and installation), operation and maintenance costs must also be considered. The maintenance costs are related to the new equipment installed to establish the µG. The operation costs result from the operation of the µG and include losses in storage systems, eventual staff needed to operate the µG, etc.

3. Literature overview

When the main target of regulators of natural monopolies, such as European electricity distribution, is allocative efficiency, they generally employ a cost-plus type regulation, like a rate-of-return, when they define regulated companies' allowed revenues. This regulatory scheme seeks to control the activity's profit and ensures a minimum level of investment. This is a more traditional regulatory approach, which is simple to apply. However, it has some drawbacks because it may induce cost inefficiencies. Therefore, regulators emulate a competitive environment through incentive-based regulation approaches to address this issue. Incentive-based regulation also allows regulators to deal with the asymmetric information context about companies' costs they have to face (Joskow, 2000).

Thus, when the main objective of the regulatory scheme is to promote cost efficiency, an incentive-based regulation is applied, which is input-oriented. That is, the revenue (revenue cap) or the price (price cap) is fixed for a regulatory period, being all the gains or losses kept by the firm (Schmalensee, 1989). However, an incorrect calibration by the regulator of the cost efficiency's targets leads to the creation of economic rents or, on the opposite, may jeopardise the economic sustainability of the firm.

Another regulatory approach is based on a menu of contracts with different cost-sharing provisions (Laffont and Tirole, 1993). Despite the theoretical merits of this approach in incentivising cost efficiency and reducing information asymmetry, regulators do not apply this sophisticated regulatory approach apart from a few exceptions (e.g., Ofgem). In contrast, regulators more often adopt more straightforward hybrid methodologies, mixing the regulatory approaches based on price/revenue cap and rate-of-return, aiming to avoid the main drawbacks of both. Typically, the hybrid approaches treat OPEX (Operational Expenditures) and CAPEX (Capital Expenditure) differently by imposing incentive-based regulation with efficiency targets to the OPEX and cost-plus type regulation to the CAPEX[2].

In 2009, Ofgem enlarged its incentive-based regulation to the TOTEX (Total Expenditure), applying a regulatory approach that does not treat companies' costs differently, depending on their nature. Within this TOTEX approach, OPEX and CAPEX savings will face the same efficiency incentive (Jenkins and Pérez-Arriaga, 2017). More recently, some other European regulators also apply this approach, though usually in more simplistic regulatory schemes (CEER, 2018).

The role of incentive-based or performance-based regulation (PBR) versus cost-plus to incentivise investments at the lowest cost is still a matter of debate. Makholm (2018) and Kaufman (2019) discuss the evolving conditions of PBR application in a changing electricity industry.Costello (2020) alerts for the limits of PBR in setting the adequate benchmark. Notwithstanding, Sappington and Weisman (2021) sustain that PBR better replicates the competitive process, namely if the regulators rely more on carefully designed plan options to mitigate the information advantage of the regulated utility.

Other authors (Jenkins and Pérez-Arriaga, 2017 and Bovera et al., 2021) highlight the risks of poor calibration in PBR schemes due to the technological and demand uncertainties around the evolution of new factors, such as distributed generation, that bring technological and demand uncertainties. However, since European electricity distribution network companies provide an essential service, regulators will always strive to mitigate the 'companies' risk. Therefore, even if regulators apply tight regulation on electricity distribution network companies, allowing low-profit rates, their sustainability will not be compromised.

This context is especially risk-averse, so promoting innovation may be quite challenging. Note, for example, that the promotion of innovation is often associated with deregulation (Vogelsang 2012), which obviously cannot occur in activities that are natural monopolies and provide essential services, as is the case of electricity distribution and transmission.

The debate about the best approach to stimulate innovation in these activities encompasses completely different perspectives. 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 (Jamasb and Pollit, 2015) or, in a more general term, an explicit innovative stimulus (Mirzenami, 2021). However, here too, the effectiveness of this approach faces the issue of asymmetric information that can be overcome by applying, whenever it is possible, competitive or cooperative approaches (Mirzenami, 2021).

Some authors suggest mixed approaches based on incentive-based regulation because they 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). Following the seminal work of Cabral and Riordan (1989), some studies show that investment benefits more from an incentive-based or PBR than from a "cost-plus", even if the latter is typically associated with overinvestment (Marques et al., 2014; Brown & Sappington, 2018). This relationship will depend on some regulatory parameters, such as the length of the regulatory period (Biglaiser

[2] Based on the CEER “Report on Regulatory Frameworks for European Energy Networks” (2020), we estimate that for a sample of 27 countries, two-thirds apply a combination of incentive regulation on OPEX and rate-of-return on CAPEX, 15% apply cost-plus on both OPEX and CAPEX and the rest apply incentive type regulation for both OPEX and CAPEX.

and Riordan, 2000) and the degree of performance sharing between consumers and the companies (Costa et al., 2017).

The degree of risk aversion of the companies is another factor to be taken into account. Since regulated utilities are risk-averse, as they are regulatory protected, an incentive base-regulation may not be effective in promoting innovation if the risk profiles of innovation and the incentive scheme are not aligned (Poudineh et al, 2020). What can be the case if the latter is mainly focused on costs efficiency. Risk aversion together with the uncertainty associated with the results of innovative processes create barriers to innovation and the transition to other technological paradigms. These situations can be overcome by creating strategic niches through protected spaces (determined and restricted application or limited area or jurisdiction) for the development of promising technologies through experimentation (Kemp, 1998). More recently, this experimental approach has been taken up in the regulation of network infrastructures, given the new challenges it faces (Ofgem, 2018; CEER, 2022).

In parallel, the need for regulation to become more output-based oriented and not just input-based oriented has been pointed out (Cambini et al., 2014). The Output-based regulation enables electricity network companies to obtain additional revenues when they successfully achieve regulatory goals. It can also overcome issues related to innovation being an externality for the network company (Bauknecht, 2011). Thus, this kind of regulation avoids the effect of high-powered incentive regulation (high percentage of cost reductions or cost increases retained by firms, Laffont and Tirole, 1993) that may postpone socially efficient investments (Willems and Zwart, 2018). These goals can be associated with outputs such as the quality of service, network resilience, dissemination of information to consumers, energy efficiency, environmental protection, and innovation. British regulatory scheme RIIO, developed by Ofgem, is a well-known example of this regulatory approach (Jamasb, 2020).

Yet, the literature remains limited on including the intangibility and spillovers of several technologies in the network grid that alter the profile of costs and returns over time.

4. Model

Two representative regulatory schemes are compared. On the one hand, the total expenditures (TOTEX) approach, i.e., a technologically neutral,high-powered and input-based regulatory scheme. The regulated 'companies' allowed revenues are defined regardless of the type of costs (OPEX or CAPEX) that these revenues will recover. On the other hand, a hybrid scheme assumes a combination of instruments that can be seen as a medium or low-powered input-based regulatory scheme once the company can only keep the gains achieved beyond regulatory targets for a minor part of its total costs. In this case, we adopted the rate of return methodology for CAPEX[3], the price cap methodology for OPEX, and dedicated innovative funds, integrally recovered through tariffs.

In both static and dynamic manner, the model accounts for the relations between the cost structure of the network companies and the different effects of innovative investments.

4.1 Assumptions

The basic model assumes an incentive-based regulatory context. Hence, the allowed revenues of network companies (defined by the regulator) may be decoupled from the real level of costs.

The expected revenues of the regulated company that considers an incentive-based approach for TOTEX are formalised as follows:

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

Where:

$I_{TotexSG}$ is the amount invested in innovative technology in a TOTEX regulatory scheme;
DTOTEX is the costs variation in a TOTEX regulatory scheme;

[3] That typically represent the majority of the cost of a network distribution company (see, ERSE, 2021).

r is the firm's cost of capital;
T is the next time allowed revenues review period;
δ is the proportion of TOTEX savings that is transferred to consumers after T;
ξG_{Totex} is the proportion of external benefits due to the technology that is withheld by the company in the TOTEX regulatory scheme.

Following Marques et al. (2014), the expected revenues of the regulated company that considers a hybrid approach is formalised as follows:

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

Where:
I_{SG} is the amount invested in innovative technology;
DC_c is the operational cost variation (that includes depreciation) related to conventional infrastructures;
DC_{SG} is the operational cost variation (that includes depreciation) related to SG;
DI_C is the variation of conventional investment due to the innovative investment;
γ is the proportion of the investment expenditure accrued on the firm's regulatory asset base after T;
α is the proportion of the operational costs savings that are transferred to consumers after T;
ξG is the proportion of external benefits due to the innovative technology that is withheld by the company due to the action of the regulator.

Considering the case in which the regulator is neutral in terms of efficiency targets, such as:

$$\text{z TOTEX} = \text{xCAPEX} + \text{y OPEX} \leq \mathbf{0} \quad (3)$$

Where z, x, and y are regulatory targets defined for TOTEX, OPEX, and CAPEX, respectively.
Let us consider a high-powered case in which the regulated company withholds the gains that go beyond regulatory goals:

$$\begin{cases} If\ \frac{\text{DOPEX}}{\boldsymbol{OPEX}} \leq \text{x}, & \alpha = 1 \\ If\ \frac{\text{DOPEX}}{\boldsymbol{OPEX}} > \text{x}, & \alpha < 1 \\ If\ \frac{\text{DCAPEX}}{\boldsymbol{CAPEX}} \leq \text{y}, & \beta = 1 \\ If\ \frac{\text{DCAPEX}}{\boldsymbol{CAPEX}} > \text{y}, & \beta < 1 \\ If\ \frac{\text{DTOTEX}}{\textbf{TOTEX}} \leq \text{z}, & \delta = 1 \\ If\ \frac{\text{DTOTEX}}{\textbf{TOTEX}} > \text{z}, & \delta < 1 \end{cases} \quad (4)$$

Where:
β is the proportion of the investment savings transferred to consumers after T.

DOPEX= $(DC_c - DC_{SG})$
DCAPEX=$(DI_c - I_{SG})$
DTOTEX= DOPEX+ DCAPEX=$(-\mathrm{I_{SG}} + \mathrm{DI_C} - \mathrm{DC_{SG}} + \mathrm{DC_C})$ (5)

Therefore, for the TOTEX model, equation (1), can be presented such as:

$$-\boldsymbol{I_{SG}} + \sum_{t=1}^{T} \frac{(\boldsymbol{DC_c} - \boldsymbol{DC_{SG}})}{(1+r)^t} + \sum_{t=1}^{T} \frac{\boldsymbol{DI_C}}{(1+r)^t} + \sum_{t=T+1}^{\infty} \frac{(1-\delta)(DI_c - I_{SG}) + (1-\delta)(DC_c - DC_{SG}) + \xi G_{Totex}}{(1+r)^t} \geq \mathbf{0} \quad (6)$$

This equation can be slightly changed to consider a broader situation where CAPEX and OPEX have different regulatory targets:

$$-\boldsymbol{I}_{\mathbf{TotexSG}} + \sum_{t=1}^{T} \frac{(DC_c - DC_{SG})}{(1+r)^t} + \sum_{t=1}^{T} \frac{DI_C}{(1+r)^t} + \sum_{t=T+1}^{\infty} \frac{(1-\beta)(DI_c - I_{SG}) + (1-\alpha)(DC_c - DC_{SG}) + \xi G_{Totex}}{(1+r)^t} \geq \mathbf{0} \quad (7)$$

For simplicity, let us assume that benefits beyond network quality of service obligations are treated as sector externalities. Therefore, under a regulatory framework technology-neutral that does not influence the decision about the type of investment, we obtain:

$-\mathbf{I}_{\mathbf{TotexSG}} = -\mathbf{I}_{\mathbf{SG}}$ and $\boldsymbol{\xi G_{Totex}} = \boldsymbol{\xi G}$ (8)

4.2 Model specifications

For simplicity, one considers that the company will withhold all the gains achieved, i.e., the targets set by the regulator for the regulatory period are feasible, and the gains that go beyond regulatory goals are not shared with the consumers (see formulation (4)). Therefore:

$\alpha = 0, \beta = 0$, and $\delta = 0$ (10)

Moreover, one considers that the company withholds all the investment expenditure accrued on the firm's regulatory asset base.

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, and resulting from the externalities of innovative investments, are the same. Therefore:

$$\left\{-\mathrm{I}_{\mathrm{SG}}; \sum_{t=1}^{T} \frac{(DC_c - DC_{SG})}{(1+r)^t} + \sum_{t=1}^{T} \frac{\mathrm{DI_C}}{(1+r)^t}; \sum_{t=T+1}^{\infty} \frac{\xi G}{(1+r)^t}\right\} = \left\{-\mathrm{I}_{\mathrm{TotexSG}}; \sum_{t=1}^{T} \frac{DC\mathrm{TOTEX} \quad \mathrm{iC}}{(1+r)^t}; \sum_{t=T+1}^{\infty} \frac{\boldsymbol{\xi G_{Totex}}}{(1+r)^t}\right\} \quad (11)$$

Hence, the comparison between methodologies will only consider the portion of allowed revenues, regardless of innovation externalities defined after reviewing regulatory parameters. The reduced models are as follows:

TOTEX model

The reduced form of equations (7) and (8), considering only the components of allowed revenues, unrelated to externalities, defined after the review of regulatory parameters, will be as follows:

$$\frac{(1-\delta)(-\mathrm{I_{SG}} + \mathrm{DI_C}) + (1-\delta)(-\mathrm{DC_{SG}} + \mathrm{DC_C})}{r(1+r)^{\mathrm{T}}} = \frac{(1-\beta)(-\mathrm{I_{SG}} + \mathrm{DI_C}) + (1-\alpha)(-\mathrm{DC_{SG}} + \mathrm{DC_C})}{r(1+r)^{\mathrm{T}}} = \frac{(-\mathrm{I_{SG}} + \mathrm{DI_C}) + (-\mathrm{DC_{SG}} + \mathrm{DC_C})}{r(1+r)^{\mathrm{T}}} \quad (12)$$

Since $\delta = 0$, $\beta = 0$ and $\alpha = 0$.

Hybrid model

The reduced form of equation (2), considering only the portion of allowed revenues, unrelated to externalities, defined after the review of regulatory parameters, will be:

$$\frac{r\gamma(I_{SG}-DI_C)+(1-\alpha)(-DC_{SG}+DC_C)}{r(1+r)^T}=\frac{(I_{SG}-DI_C)}{(1+r)^T}+\frac{(-DC_{SG}+DC_C)}{r(1+r)^T} \quad (13)$$

Since $\alpha = 0$ and γ=1.

4.3 Static analysis

We perform static analysis without considering the changes in OPEX and CAPEX due to the innovative investment.

Using the reduced form of the model, the comparison of the two regulatory methodologies, i.e., the difference between formulation (13) (Hybrid) and (12) (Totex), gives the following result:

$$\frac{(I_{SG}-DI_{iC})}{(1+r)^T}+\frac{(-DC_{SG}+DC_C)}{r(1+r)^T}-\frac{(-I_{SG}+DI_{iC})+(-DC_{SG}+DC_C)}{r(1+r)^T}=\frac{(I_{SG}-DI_C)}{(1+r)^T}-\frac{(-I_{SG}+DI_C)}{r(1+r)^T} \quad (14)$$

We will analyse expression (14) for two situations. In the first one, we assume that the expenditures on innovative technologies are greater than the reductions in conventional investments amounts they allow, i.e., $\boldsymbol{I_{SG}-DI_C}$ > 0. In such circumstances:

$$\frac{(\boldsymbol{I_{SG}-DI_C})}{\boldsymbol{(1+r)^T}}>\frac{(\boldsymbol{-I_{SG}+DI_C})}{\boldsymbol{r(1+r)^T}} \quad (15)$$

In this case, the gains with hybrid methodology (left side of the inequality) are more significant than in TOTEX or incentive base. However, in that case, innovative investments could only be considered rational if the gains that go beyond the cost reduction more than compensate for the rise in the net cost they induce, which the company bears, that is:

$$(\boldsymbol{I_{SG}-DI_C})<\boldsymbol{\xi G} \quad (16)$$

The second situation happens when expenditures with innovative investments are lower than the reductions they allow in conventional investments, therefore $(\boldsymbol{I_{SG}-DI_C})$ <0:

$$\frac{(I_{SG}-DI_C)}{(1+r)^T}<\frac{(-I_{SG}+DI_C)}{r(1+r)^T} \quad (17)$$

In this case, the gains obtained with the TOTEX (right side of the inequality) are higher than those with the hybrid methodology. Once r <1, the gain obtained in this situation with a TOTEX is higher than the losses obtained with these methodologies in the previous case.

The two previous situations lead to the conclusion that if an innovative investment decreases conventional investments, the best option is to apply a TOTEX methodology.

On the other hand, if the innovative investment does not decrease network investment costs but provides other benefits that are higher than the its costs, it seems reasonable to value the benefits and the degree of externalities to define the most effective regulatory approach (see section 6).

4.4 Dynamic analysis

We consider now that the relation between OPEX and CAPEX can vary following the innovative investment in the medium to long run.

We first consider that both conventional OPEX and CAPEX decrease with the innovative investment:

- $f(C_{SG})$ increases with I_{SG}, therefore $D_{f(I_{SG})} = \frac{D_{C_{SG}}}{D_{I_{SG}}} > 0$
- $g(C_c)$ decreases with I_{SG}, therefore $D_{g(I_{SG})} = \frac{D_{C_c}}{D_{I_{SG}}} < 0$ (18)
- $h(I_c)$ decreases with I_{SG}, therefore $D_{h(I_{SG})} = \frac{D_{I_c}}{D_{I_{SG}}} < 0$

We will again compare the TOTEX[4] and hybrid regulatory approaches, eliminating the common components. Therefore:

$u(I_{SG}) = \frac{(I_{SG} - D_{I_c})}{(1+r)^T}$, for TOTEX (19)

$v(I_{SG}) = \frac{(-I_{SG} + D_{I_c})}{r(1+r)^T}$, for Hybrid (20)

The functions derivative are:

$$D_{u(I_{SG})} = \frac{1}{(1+r)^T} \times \frac{D_{I_{SG}}}{D_{I_{SG}}} - \frac{1}{(1+r)^T} \times \frac{D_{I_c}}{D_{I_{SG}}} = \frac{1 - \frac{D_{I_c}}{D_{I_{SG}}}}{(1+r)^T} \quad (21)$$

Assuming, for simplicity, $\frac{D_{I_c}}{D_{I_{SG}}} = D_{I_c}$, we obtain:

$\frac{(1 - D_{I_c})}{(1+r)^T} > 0$, for TOTEX (22)

Using the same approach for $D_{v(I_{SG})}$, we have:

$D_{v(I_{SG})} = \frac{(-1 + D_{I_c})}{r(1+r)^T} < 0$, for Hybrid (23)

Thus, assuming that conventional CAPEX and OPEX decrease with the innovative investment, one can conclude that TOTEX benefits the company.

We consider a second case in which the innovative investment only decreases conventional OPEX, as follows:

- $f(C_{SG})$, increases with I_{SG}, therefore $D_{f(I_{SG})} = \frac{D_{C_{SG}}}{D_{I_{SG}}} > 0$
- $g(C_c)$, decreases with I_{SG}, therefore $D_{g(I_{SG})} = \frac{D_{C_c}}{D_{I_{SG}}} < 0$ (24)
- $h(I_c)$, increases with I_{SG}, therefore $D_{h(I_{SG})} = \frac{D_{I_c}}{D_{I_{SG}}} > 0$

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

$D_{u(I_{SG})} = \frac{(1 - D_{I_c})}{(1+r)^T} > 0$, if $\frac{D_{I_c}}{D_{I_{SG}}} < 1$, for TOTEX (25)

$D_{v(I_{SG})} = \frac{(-1 + D_{I_c})}{r(1+r)^T} < 0$, if $\frac{D_{I_c}}{D_{I_{SG}}} < 1$, for Hybrid (26)

Thus, there are gains for the company with TOTEX, provided that the increase in conventional investments resulting from innovative investments remains lower than the increase in innovative investments. This situation is foreseen in several projects of digitalisation of the grid.

[4] TOTEX case also encompasses incentive applied both in CAPEX and OPEX.

5. Illustrating the application of the model

In this section, we compare those grid technology innovations concerning the potential to avoid operation and management (O&M) costs and investment costs and frame them into our model's results. The creation of network externalities is also compared, illustrating the implications of suitable regulatory approaches.

The conventional distribution networks must evolve into more flexible systems. The modernisation of distribution networks, converting them from conventional passive systems to active, intelligent distribution systems, is a central issue in such a context. Technology innovations such as AMI, ASFA, and µG are crucial for modernising the grids (see more details in Section 2, tables 2 to 4).

The investment in AMI, ASFA, and µG technologies can reduce the operation and maintenance costs of the electric networks and even the need for investments in network expansion. However, the extent of the (external) benefits obtained with each technology is different. Figure 1 stylistically compares the avoided costs against investment levels required for the surveyed technologies. Figure 2 presents the relative positioning of the technologies concerning the relationship between the benefits produced that stay within the network activity and the benefits that will take place outside this activity (see tables 2 to 4 for more details).

Figure 1 – Grid innovation 'technologies' potential to avoid costs

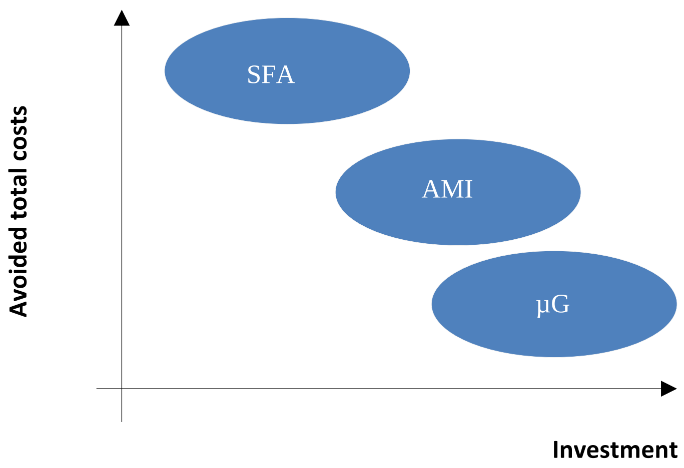
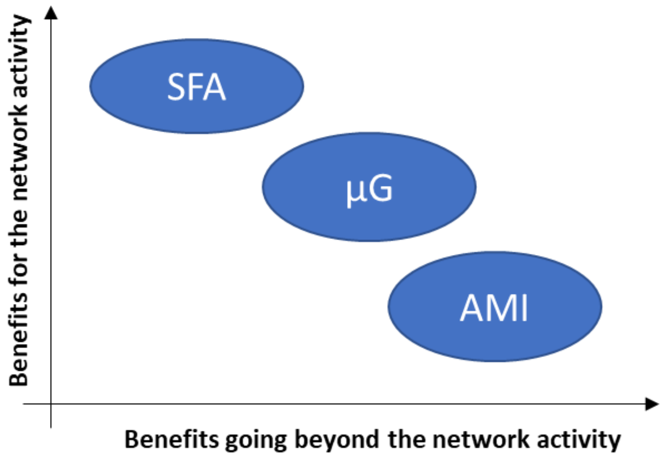


Figure 2 –Grids innovation 'technologies' weight of externalities



When comparing the potential to reduce costs with the lowest investment, SFA is the dominant technology (Figure 1). This is mainly because SFA allows the networks to self-heal (in a fast and autonomous manner) after a fault/outage situation. Moreover, SFA technologies make possible a more intelligent asset management concerning the better planning of maintenance actions. SFA allows for better asset management (e.g. with functions to monitor network assets produce event reports, suggest repair actions, and recognise shortage situations) and prevents unnecessary investments. In more formal terms, SFA can avoid unnecessary OPEX and CAPEX costs, applying inequalities (17), (22) and (23) from section 4. In addition, SFA presents multiple external benefits in terms of the contribution for the efficiency of the grid and for the growth of the share of renewable energies in the electricity mix. Therefore, SFA can be better promoted through a high-powered TOTEX regulatory approaches .

AMI technologies (such as the smart meters and the needed communication platform), combined with ASFA, can help monitor and manage load flows, peak load and voltage levels, helping to avoid or delay investments and enabling responsive voltage regulation. Moreover, AMI technologies can avoid billing costs, through the digitalization of the metering processes. However, their benefits spillover from cost reduction and even from the network activity (see Figure 2 and Table 2). Therefore, for AMI technologies inequalities (14), (15) and (26) from section 4 apply and a high-powered TOTEX regulatory approach is not recommended.

The information that can be provided to consumers about electricity prices and their consumption profiles can enable consumers to make intelligent decisions in controlling energy use, controlling their costs and appliances, charging electric vehicles and other decisions, including the demand response actions. In addition, AMI can accelerate the development of new pricing and service options by retailers. To assess whether the costs of AMI technologies must be recovered through tariffs, a cost benefit analysis may be previously performed (see inequality (16) from section 4). Whenever this cost benefit analysis is positive, AMI technologies' costs may be included into the regulated companies' allowed revenues (in dedicated funds) to be recovered through tariffs. In that case, it is essential to assess whether only part of the cost (in proportion to the benefit that remains in this activity) or all costs should be recovered through tariffs. The roll-out of smart meters implemented in several European countries is an example of such an approach (Geels et al., 2021). Bearing in mind that the benefits of these technologies derive mainly from the type of services that they can provide to consumers, the recovery of their costs may be directly associated with 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 (see section 3).[5]

Regarding µG, the investment in such technology makes it possible to control costs, and their benefits are mainly internal to the network activity (see Figure 2 and Table 4). However, these benefits are often locally restricted. µG

[5] This approach was followed by the Portuguese regulator to "promote smart services", through the linking of the allowed revenues with the services provided by smart meters (ERSE, 2019).

improves the reliability of the service for both internal consumers (through the number and duration of the interruptions) and external consumers (duration of the interruptions) due to the ability of μG to assist in network reconfiguration actions by changing its internal load and/or generation levels. However, μG require much more significant investments for similar operating cost reduction levels, making it difficult to be promoted through nationally defined high-powered regulatory approaches such as TOTEX (see, section 4) . Thus, the socialisation of the costs of such investments through regulatory tariffs must be balanced with the gains obtained in terms of, e.g., the improvements in the flexibility and security of the system. In addition, the benefits resulting from the integrated management of the (distributed) networks may be scaled by generalising such projects. Thus, the μG's investments can be monitored through pilot projects (Kemp, et al., 1998); regulatory "sandboxes", i.e., a temporary regulatory framework (CEER, 2022) can be developed to evaluate the net gains for the whole network of such kinds of experiences.

6. General regulatory model proposed to promote innovation

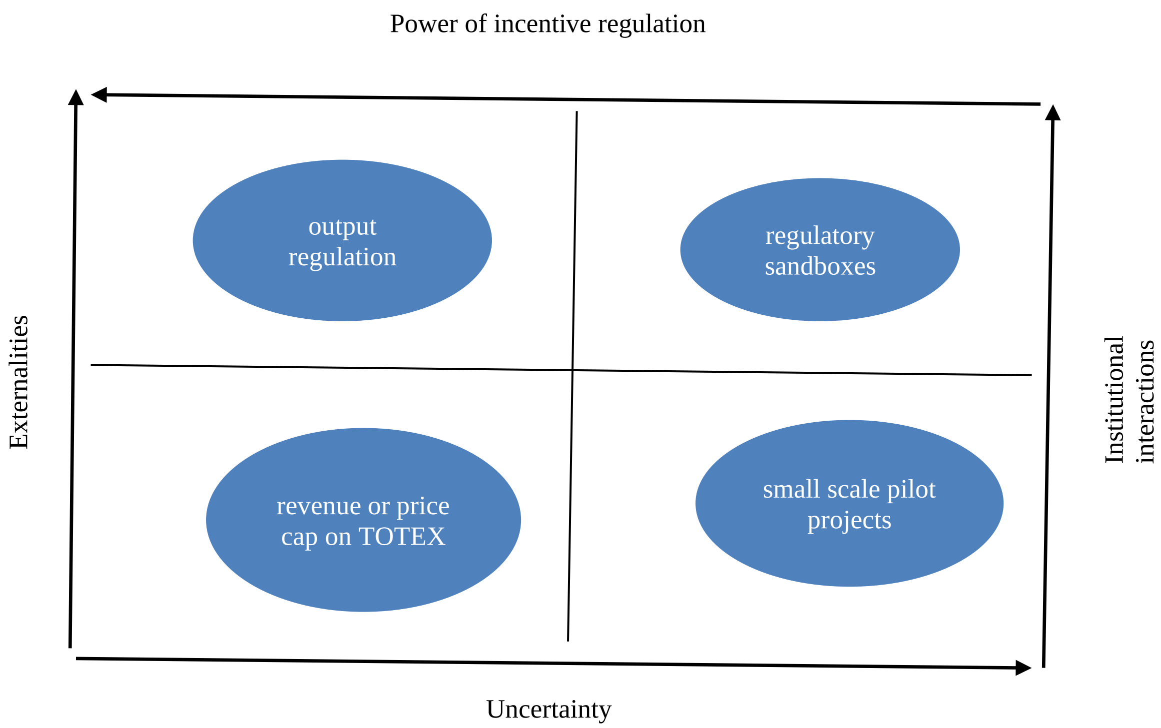
The definition of a practical regulatory framework to promote innovation in network activities implies assessing effects at different dimensions. First, the externalities, i.e., the benefits that go beyond the network activity, are an important dimension to be considered when setting the regulatory scheme to promote innovation. The externalities of the innovative investment can be assessed at different levels: network operator level; network users level; societal level (beyond network users). This dimension is associated with the regulator's capacity to implement innovation and the degree to which more or less collaborative actions with other institutions or, more specifically, policymakers can be implemented.

Second, the reduction of uncertainty and in particular of technological risk is the other dimension to be taken into account, as regulated network firms are by nature risk-averse (Mirnezami, 2021) (see section 3). Hence, if the outcome of the innovative investments is uncertain, the regulatory scheme needs to ensure the recovery of the investment costs, otherwise the firms will not have the incentive to realise the investment (Poudineh, 2020). Assessing the gains from the investment in innovationis often a difficult task. For example, the externalities associated with efficiency improvements in the grid has been estimated between -0,32 ¢/kWh and 79,16 ¢/kWh, with an average value of 7,8 ¢/kWh (Sovacool et al, 2021).[6] On top of that, regulators face information asymmetry and regulatory schemes must also be designed to consider potential impacts for consumers (Mirnezami, 2021).

Figure 3 presents a matrix that proposes a general heuristic model to define the most effective regulatory schemes. Th matrix considers the two dimensions mentioned above, externalities and uncertainty, aswell as the types of action of the regulator in terms of the power of the regulatory incentive scheme and institutional interactions.As mentioned in Section 3, the power of the regulatory incentive measures the degree to which benefits (e.g. cost reductions) or losses (e.g. cost increases) are retained by the company, i.e. the (un)certainty in the recovery of the company's costs. The institutional interactions measures the degree to which the regulatory mechanism are designed with or without the collaboration with others entities, public institutions or private stakeholders.

[6]Another example can be given by a study (European Commission, 2020) on the deployment of smart meters in the EU which estimates a range for energy savings between 2% and 10%.

Figure 3 – Effective regulatory schemes to promote innovative investments



We limit the action of the regulator to promote innovative investments in the network up to the point where the foreseen positive net benefits are maintained within the network activity. Beyond this limit, that corresponds to situations in which most of the benefits are clearly not directly enjoyed by consumers (not only domestic consumers, but also undertakings), as macroeconomic or environmental benefits that are more transversal to the whole of society. Under these circumsptances, the investment's costs should not be solely beared by the consumers through network tariffs. However, the regulator can still play a collaborative role with policymakers to help them defining effective policies to promote innovation, for example by helping them implementing national R&D and deployment funds.

The lower left corner of the matrix addresses the situation in which the innovative investments provide direct benefits to companies in terms of cost reduction and are less risky, such as the ASFA. As seen in Section 5, these investments can be better promoted through high-powered, input-based regulatory schemes such as TOTEX. This regulatory framework can be developed by the regulator without interaction with other sectoral regulators or government institutions.

The upper left corner of the matrix corresponds to innovative investments whose benefits are almost certain, but which affect consumers more directly than network companies, such as AMI, as they can provide better quality of service, energy savings and prices control, etc. In these cases, output based high-powered regulatory schemes that allow costs recovery (see Section 5) are more appropriate. Since there are some externalities, the design of the regulatory scheme can be can be carried out in interactions between the regulator and others public institutions.

When the impacts of the innovative invesments are uncertain, more cautious regulatory approaches are recommended to address booth the companies risk aversion and the asymmetric information issues. If the innovative investment or process effects are uncertain but clearly focused on the network activity, a pilot project can be carried out, i.e., a small-scale preliminary in-field developed inside the network activity (Kemp, et al 1998). This corresponds to the lower right corner of the matrix. On the other hand, if the impacts are uncertain and have externalities that change the cost function of the network activity (upper right of the matrix), "regulatory sandboxes" can be implemented. This could be done in collaboration with other public institutions, to allow promoters (not just operators networks, but also IT providers, market players, research centers, etc.) to test new products or services (CEER, 2022).

7. Conclusion and Policy Implications

The modernisation of distribution networks is crucial for decarbonisation. The conventional distribution networks must evolve into more flexible systems. Such modernised systems bring benefits that go beyond the traditional operation activity targets. This raises new challenges for the regulator who has to implement a favorable context for network operators to actively search to accomplish the new technical, environmental, and economic objectives. The referred modernisation requires a transformation in the electrical distribution networks, mainly stimulated by the investment in new technologies. However, most of these new technologies provide benefits that have the characteristics of externalities, meaning that network operators do not perceive all the social benefits of the investment.

The effect of the externalities in the definition of the regulatory framework remains largely absent from the literature on the regulatory strategies. This paper addresses this gap by developing a conceptual model that analyses the investment incentives in new network technologies under different regulatory settings. The model explicitly differentiates the main specificities of the technological innovations regarding their impact on costs and externalities. To illustrate the applicability of the model, we discuss the results against the characteristics of three technology innovations, which are representatives of the modernisation of the electrical distribution networks. We assess the adequacy of the regulatory schemes, namely in terms of cost avoidance versus investment required and degree of externalities. Therefore, this paper improves the understanding of the most suitable regulatory approaches to incentivise the adoption of the new technologies that are needed to modernise the electricity distribution networks.

The results show that the regulatory schemes should adapt to the specificities and advantages of each type of innovative investment. The analysis clearly shows that a strong incentive regulation is more beneficial whenever the innovation decreases overall investment needs. The comparison with the technologies surveyed further highlighted some of the findings from the model. In contrast, an experimental and small-scale based regulatory approach is more appropriated for new technologies with more localised effects, uncertain results or a higher share of spillovers.

Based on the results of our model and on a survey of the literature, we propose a general heuristic model to help define the most effective regulatory schemes, considering two dimensions: the externalities of investments, and uncertainty of the investment (from the perspective of both network operators and the regulator, including technology risk). These two dimensions are crossed with the action of the regulator in relation to the power of the incentive regulatory schemes and the interactions with other institutions or stakeholders. The results have implications for regulators and policymakers. Since some innovative investments may generate large externalities (even with characteristics of public goods), but may have few direct impacts on the network operation improvement, these investments would be sub-optimally implemented by distribution operators without an external intervention. In this case, the boundaries between regulators' and policymakers' roles are unclear, raising the need for interactions between both parties. Shall the costs of those investments be recovered through network tariffs, or shall they be recovered in proportion to the benefits they provide to the regulated activity? In the latter case, how will the remaining costs be recovered? Addressing these issues opens a prolific road for further research.

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