Regulating electricity distribution networks under technological and demand uncertainty

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ABSTRACT

The regulation of electricity distribution networks faces new challenges, as consumer preferences for network services change, distributed energy resources are connected in increasing number, and advanced information and communication technologies become ubiquitous. This work discusses how, within this new context, national regulatory authorities in Great Britain and Italy already employ advanced regulatory instruments for establishing firms' allowed revenues under technological and demand uncertainty. Identified areas of improvement are then addressed via the proposal of an original regulatory approach. This builds on elements from practice and academia and formulates the *ex-post* regulatory estimate of efficient total expenditures in a modular manner. As illustrated with an example and thoroughly discussed in the paper, this approach preserves the desirable features of the existing mechanisms and adds to them in several ways. The main contribution regards the efficient treatment of benchmark errors, which occur when regulators fail to anticipate the emergence of a new cost saving technology or network management practice. Providing incentives for cost efficiency while granting firms the freedom to innovate is, indeed, crucial at a time when, as described by EU Directive 2019/944, the complexity of the tasks carried out by distribution operators continues to increase.

1. Introduction

Technological innovations, often driven by de-carbonization policies, are transforming the way electricity distribution networks are operated and utilized (Burger et al., 2019). The diffusion of Distributed Energy Resources (DERs) requires networks to handle bidirectional power flows. Advanced metering, together with changes in market design, create opportunities for end-users to become more responsive to economic and operational signals, often via providers of aggregation services or within energy communities. The integration of Information and Communication Technologies (ICTs) into more traditional activities of the electricity sector modifies the way networks are operated in real-time, making distribution grids increasingly similar to transmission grids.

The number and amplitude of these changes is so large that the EU Parliament has recently redefined the tasks of distribution system operators – Articles 31 to 39 in the EU Directive 2019/944 (EU, 2019a).

Also, a rather large number of studies has looked at the problem of designing efficient distribution tariffs in this new context (Pérez-Arriaga and Bharatkumar, 2014; Nijhuis et al., 2017; Abdelmotteleb et al., 2018; Azarova et al., 2018; Brown and Sappington, 2018; Pollitt, 2018; Schittekatte et al., 2018; Küfeoğlu and Pollitt, 2019).

On the contrary, not much attention is being paid to the process leading to the definition of a firm's revenue allowance (distribution tariff design is only concerned with the recovery of a firm's allowed revenues). This process presents a number of well-known challenges, mostly deriving from a regulator's inability to observe firms' cost opportunities and levels of managerial effort (Laffont and Tirole, 1993). Asymmetric information creates possibilities for strategic behaviour and rent extraction and, for this reason, regulation in practice has traditionally balanced incentives towards productive and allocative efficiency (Joskow, 2008).

However, also setting a firm's allowed revenues is more difficult today than in the past, due to the growing uncertainty over end users'

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preferences for network services (the number and type of users who will connect/disconnect to the distribution grid), and over the rate of adoption of technological innovations, which renders regulatory estimates of efficient network costs more prone to errors. Failing "to anticipate the emergence of new cost saving technologies or network management practices … that shift the efficient frontier" (Jenkins and Perez-Arriaga, 2017, p. 65) is an example of a 'benchmark error'. Failing to foresee changes in relevant cost drivers, such as the rate of DER penetration, or the number of new connections, constitutes a 'forecast error'. In both cases, the risk of significant rent extraction by the regulated firms and/or the risk that firms become unable to finance the necessary investments, are expected to increase (Jenkins and Perez-Arriaga, 2017).

In fact, anecdotal evidence indicates that a regulatory transformation might also be underway, with the goal to revise the process leading to the definition of the allowed revenues of a network operator. Two cases are of particular interest, one regarding Great Britain's Office of Gas and Electricity Market (OFGEM), and one regarding the Italian regulatory authority, ARERA – *Autorità di Regolazione per Energia Reti e Ambiente* (OFGEM, 2010a; 2010b; ARERA, 2016; 2017a). OFGEM's RIIO (setting Revenues using Incentives to deliver Innovation and Outputs) model and ARERA's TOTEX (Total Expenditures) approach both illustrate how regulators combine advanced regulatory instruments to deal with information asymmetry (a menu of contracts), with 'uncertainty mechanisms' to address forecast errors.[2] Nevertheless, issues regarding benchmark errors and innovation incentives remain comparatively underexplored. As novel technologies available to a network operator become more numerous, for instance, in the context of smart grids, this constitutes an important gap in the current practice and in the literature as well (Jenkins and Perez-Arriaga, 2017).

Focusing on the question of how a regulator can provide incentives for firms to spend efficiently, while enabling technological change, the present work proposes to intervene on the formulation of the annual regulator's estimate of a firm's efficient TOTEX and, specifically, to structure it in a modular way. Each module would capture a certain 'activity' conducted by the firm, such as the replacement/addition of network components (e.g., a medium voltage feeders) or the introduction of a non-wire solution for old (reduction of losses, voltage regulation) as well as new (data management, procurement of products and services) functionalities (EU, 2019).

The advantages of a modular structure are two. First, it enables the regulator to adjust the regulatory TOTEX estimate during the tariff period to, e.g., the actual number of medium voltage feeder replaced/added in a year, hence to minimize the impact of forecast errors. The incentives for the firm to innovate derive, instead, from the monetary values of the activities, which are designed to grant firms the freedom to explore and adopt innovative solutions as new system operation techniques emerge over time. This is true, however, only within certain boundaries, defined by regulators. Outside of those boundaries (as the efficient frontier changes significantly) the firm's remuneration also changes, ensuring that efficiency gains are reflected in the allowed revenues (that they are shared with consumers). The ability of the proposed approach to help the regulator in managing benchmark errors while, at the same time, encouraging firms to innovate in both network planning and operation, is the main contribution of this proposal.

The remainder of the paper is organized as follows. Section 2 briefly discusses the relevant literature and provides some background on the process leading to the definition of a firm's revenue allowance. Section 3 and Section 4, respectively, introduce the proposed approach and illustrate its application via a numerical example. Section 5 discusses the

approach's incentive properties. Section 6 concludes and derives policy implications.

2. Literature review and conceptual background

Starting with Schmalensee (1989), the economic literature has often investigated the incentive properties of alternative regulatory schemes in the presence of high levels of uncertainty regarding both cost-reduction opportunities and future costs. Some of the main insights derived from this theoretical line of work are summarized below. Also, the more practical aspects of the process leading to the definition of a firm's revenues allowance are briefly presented. This is instrumental to clarify the contribution of the present work.

2.1. Literature review

Incentive regulation and its relation to investment and innovation has been the subject of numerous theoretical studies – for surveys, see Vogelsang (2002; 2012). For instance, a line of studies has evolved from Dobbs (2004)'s contribution, where the regulated firm's decision to invest is studied under the assumption that the evolution of product demand and technology are governed by stochastic processes (i.e., using real option analysis). The paper by Evans and Guthrie (2012) adds to this work by incorporating economies of scale and addressing the choices of scale and timing of a regulated monopolist making investment decisions under uncertain demand and capital prices. Modelling capacity expansion under stochastic demand, Willems and Zwart (2018) also address the concern that firms subject to high-powered inventive schemes might postpone investment in durable assets, especially under high uncertainty.

While such studies provide important insights regarding the effect of uncertainty on investment efficiency, or the optimal regulatory mechanisms under certain sets of assumptions, they offer little guidance for the regulatory practice. In fact, as Vogelsang (2012) notes, the literature on the relationship between regulation, investment and innovation suggests many different case-specific outcomes. In light of this, a general recommendation to preserve an efficient investment level of ordinary investment (from a regulator's perspective, ordinary investments are those with well-known costs), is that incentive regulation in practice, in particular high-powered incentive schemes, is accompanied by adjustments (a higher price cap/rate-of-return, a surcharge for real options, etc.) in the 'tightness' of the regulation (Vogelsang, 2012). As for innovative investments (those with little-known, uncertain costs as well as an uncertain effect on final demand), the recommendation for the regulatory practice is, if potential benefits from innovation are larger than those from regulation, 'no regulation' (regulatory holidays).

Another relevant strand of literature (also reviewed in Vogelsang, 2012), has looked at the effect of regulatory commitment on investment. Generally speaking, commitment is good for investment decisions (increases the incentives to invest and decreases the cost of capital), particularly for innovations having a potential for high profits or high losses. In turn, a lack of commitment can deal better with technological changes and correct mistakes. In sum, commitment needs balancing, for instance, by means of updates of price cap regulation, using rate of return criteria (Vogelsang, 2012).

In light of the above, the approach proposed in this work fits well with this second line of literature, as it strengthens the regulatory commitment under incentive regulation. Also, similarly to the other regulatory approach described in the literature (Jenkins and Pérez-Arriaga, 2017) or found in practice (OFGEM, 2010a; 2010b; ARERA, 2016; 2017a), it relies on rate-of-return criteria in the definition of the allowed revenues. In fact, to properly discuss the contribution of the proposed approach, the next section summarises how this process is carried out in practice.

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[2] Uncertainty mechanisms enable regulators to manually or automatically adjust allowed revenues during the tariff period, so that both costs to consumers and firms' cashflows remain under control, despite the unpredictability, for instance, in the timing and volume of load or generation connections.

2.2. Establishing a firm's revenues allowance

The process of establishing a firm's revenue allowance consists of two phases: an *ex-ante* one, at the start of a multi-year tariff period, and an *ex-post* one, during the tariff period. For instance, in the case of RIIO, the process leading to the definition of the so-called Price Control (the *ex-ante* phase) normally takes up to 30 months and the Price Control period (the *ex-post* phase) lasts eight years (OFGEM, 2010a).

2.2.1. The ex-ante phase

The *ex-ante* phase consists of four steps. The process begins with the regulated firms submitting a Business Plan (BP), where they assess their costs for the multi-year tariff period. Given the firm's assessment, the regulator carries out an *ex-ante* estimate of the efficient total expenditures (TOTEX). This can rely on a Reference Network Model (RNM), as in Jenkins and Pérez-Arriaga (2017) - hereinafter JPA, or on a comparative cost assessment, as in Great Britain.[3]

Note that in the former case, using the firm's provided forecast of network uses (e.g., load growth) the regulator estimates the efficient investment and maintenance expenditures over the tariff period (multi-year estimate). This includes the overnight cost of new and replacement network investments and as well as the cost of preventive and corrective maintenance.[4] These costs are then converted into an annual investment schedule with associated annual maintenance costs. The regulator's *ex-ante* estimate of efficient TOTEX is thus a *vector* of annual total expenditures.

The second step of the *ex-ante* phase sees the regulator defining two important aspects of the firm's remuneration. One is the share of the TOTEX which will be capitalized into the Regulated Asset Value (RAV), vs. the portion which is considered as fully expended every year (also known, respectively, as slow and fast money). Keeping this proportion fixed allows firms to make the optimal, cost-saving choices between capital vs. operational expenditures (CAPEX vs. OPEX), without impacting their return on equity.[5] The other fundamental regulatory decision is the definition of an incentive compatible menu of profit-sharing contracts also known, in practical applications, as the Information Quality Incentive (IQI) matrix. By defining a continuum of profit (and loss) sharing factors between the firm and the network users, together with additional income adjustments to ensure incentive compatibility, such menu stimulates firms to reveal their cost type and to improve productive efficiency (e.g., Cossent and Gómez, 2013).

The third step is where, using the firm's and the regulator's *ex-ante* estimates of TOTEX, as well as the menu of contracts, the regulator defines the firm's *ex-ante* allowed revenues for each year of the regulatory period. As in the standard RPI-X approach, the main components of the *ex-ante* allowed revenues are defined by the return on the RAV, the depreciation allowance, the operating cost allowance, and taxes. To ensure regulatory stability, the main financial parameters – the Weighted Average Capital Cost (WACC), depreciation profile and

capitalisation rate – are set for the duration of the tariff period.

The fourth step is of particular interest for the present work. To conclude the *ex-ante* process, JPA propose to use a number of automatic adjustment factors (so-called 'delta-factors'). These account for deviations from the initial forecast of the evolution of network uses and will be applied annually to correct, via a given formula, the firm's *ex-ante* allowed revenues. Note that to calculate the delta factors the regulator would need to employ the RNM "to estimate network costs for a range of uncertainty scenarios designed to capture the likely range of potential evolution of load, DG penetration, or other important cost drivers" (Jenkins and Pérez-Arriaga, 2017, p. 19). Once the efficient network costs are calculated under each scenario, a multivariate linear regression analysis is employed to determine the change in TOTEX associated with a change in each of the cost drivers. In practice, the delta factors correspond to these estimated regression coefficients. While such adjustments take care of forecast errors, JPA suggest that potential benchmark errors (due, for instance, to a defect in the RNM), can be mitigated by adhering more closely to firms' realised costs. Nevertheless, they also indicate that the question of the regulation's sensitivity to benchmark errors would require further investigation. This is one the main points addressed by the present paper.

So-called 'revenue adjustments' are possible also in the OFGEM case, when unexpected changes in network uses emerge. In practice, this uncertainty mechanism can be deployed automatically or be manually assessed. Firms are expected to propose, in their BPs, which expenditures might require this type of intervention and in which form. For instance, automatic adjustments have been proposed in the electricity transmission sector in relation to new connections (POYRY, 2017). To automatically adjust the *ex-ante* allowed revenues to reflect the actual number of connections provided by the firm, a unit cost was defined *ex-ante*, per substation, kilometre of overhead lines, and so on. While this uncertainty mechanism finds a direct correspondence in JPA's proposal, in OFGEM's case revenue adjustments are not estimated by the regulator.

An important feature of ARERA's TOTEX approach to regulate the roll-out of the second generation of smart meters, is the decision to consider the expenditures pertaining to the installation and commissioning of the smart meters separately from those related to the Automated Meter Management (AMM) systems (installation of data concentrators, realization of back-end systems, etc.).[6] This enables the regulator to closely monitor the deployment of smart meters *ex-post*, via a so-called Progress Control Mechanism (PCM). Specifically, meter-related *ex-post* allowed revenues are a linear function of an *ex-ante* 'expenditure baseline per meter' multiplied by the number of meters actually installed in the same year. This prevents firms from earning unfair returns in case of delays in the roll-out. Moreover, penalties apply to operators failing to achieve at least 95% of their annual target in meter installations. Such penalties take the form of a reduced remuneration of the equipment that was not installed in due time.

2.2.2. The ex-post phase

In the JPA approach, the *ex-post* process requires the regulator to estimate, at the conclusion of each year, the annual *ex-post* allowed revenues. This calculation accounts for delta factors as well as for the efficiency incentive (derived from the IQI matrix). In a similar way, during the tariff period, OFGEM monitors firms to determine the so-called 'maximum revenue allowance' in any year (corresponding to the *ex-post* revenue allowance). On top of the efficiency incentive, revenue adjustments are made, if necessary, to account for uncertainty mechanisms. The procedure applied in the Italian case is similar but includes, instead, the PCM.

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[3] While the advantages and disadvantages of benchmarking vs. RNMs are thoroughly discussed in the literature (Jamasb and Pollit, 2008; Jamasb and Söderberg, 2010; Domingo et al., 2011), it is clear that both require specific competencies, as well as human and technical resources. Once a regulatory authority has invested in one or the other, switching costs are probably rather high.

[4] Investments are typically required in several network components: Low and Medium Voltage feeders, Primary and Secondary Substations, and quality-related equipment (protection devices, voltage regulators, etc.).

[5] This method was introduced by OFGEM in 2009 (OFGEM, 2009). When the share of TOTEX defined as slow money is fixed, the actual share of OPEX and CAPEX can depart from this value, without impacting the RAV (which is constructed using slow money, among other things) and which, in turn, is used to calculate the annual regulatory allowance for the repayment of debt and equity. Under RIIO, the capitalisation rate reflects the historical split of OPEX vs. CAPEX.

[6] Note that more than 90% of the capital expenditures foreseen for the 2G (second generation) system of the largest distribution and metering operator in Italy are due to the meters.

2.3. Remarks

To sum up, the regulator's estimate of efficient total expenditures (a vector of annual total expenditures determined *ex-ante* by the regulator) is a quantity prone to errors. When conducted, for instance, via a Reference Network Model (RNM), this estimate depends on a forecast of network uses (made by the firm) and it is based on current technology's costs. Given the uncertainty in the demand for network services, as well as in technological change, errors derive from events that are not predictable, neither by the regulator, nor by the firm. It is to account for these forecast and benchmark errors (caused by the unpredictability of, respectively, demand growth and technological change) that regulators introduce uncertainty mechanisms. Additionally, limitations in the regulator's modelling approach (e.g., inaccuracies in the RNM), can also contribute to errors in the determination of the efficient frontier (i.e., to the benchmark error).

In fact, particularly under demand and technology uncertainty, "regulators risk establishing a multi-year *ex-ante* revenue trajectory that is poorly aligned with realised costs, leading to either substantial rents (if revenues are too generous) or increased risk that firms will not be able to adequately finance necessary investments (if revenues are too low)" (Jenkins and Perez-Arriaga, 2017, p. 65). A possible remedy is to conduct periodic updates, based on actual costs and rate-of-return regulation criteria (Vogelsang, 2012). However, frequent *ex-post* revisions create significant "regulatory uncertainty that may raise the cost of capital for utilities and undermine incentives to manage productive efficiency" (Jenkins and Perez-Arriaga, 2017, p. 65).

Hence, the idea to introduce uncertainty mechanisms *ex-ante*, and ensure regulatory stability: OFGEM's revenue adjustments, ARERA's Progress Control Mechanism, and JPA's delta factors are all defined *ex-ante*.[7] Such adjustments, however, address mainly forecast errors. As for addressing benchmark errors, the literature's suggestions for the regulatory practice are two: *(i)* to combine, via a carefully chosen weighting factor, the regulator's and the firm's *ex-ante* estimate of total network expenditures in the definition of the *ex-ante* TOTEX baseline (see Section 4); and *(ii)* to prudently select the profit-sharing factor (benchmark type errors in the allowed revenues decrease for lower profit-sharing factors). Note that both solutions focus on benchmark errors deriving from a limitation in the regulator's model. Differently, the uncertainty mechanism proposed in this work address (in addition to 'forecast' errors) benchmark errors deriving from technological change.

3. Whole system indicator approach: an introduction

Generally speaking, the proposed method follows rather closely the approaches analysed so far. In fact, the Whole System Indicator (WSI) approach includes the same main elements: *(i)* a benchmarking (or engineering) model for estimating efficient network expenditures with a forward-looking approach; *(ii)* an incentive compatible menu of contracts to elicit a disclosure of accurate expenditures and provide incentives for cost efficiency; *(iii)* a fixed share of fast vs. slow money to avoid distortions in the use of OPEX and CAPEX; *(iv)* and an uncertainty mechanism, to accommodate demand and technological uncertainty.

As illustrated in Table 1, the first three steps of the *ex-ante* process are also common to the observed experience, while the fourth step is original. In fact, the WSI's peculiarity lays in the idea of formulating the "*ex-post* regulatory estimate of the efficient TOTEX" (as explained in Section 4, this is instrumental to calculate the annual *ex-post* allowed revenues) in a modular manner. As each module captures a certain 'activity' conducted by the firm, the regulator will need to define, in step four of

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[7] Both JPA and OFGEM are concerned with uncertainties which derive from factors beyond the control of the distribution operator (externally-driven forecast errors). ARERA is primarily concerned, instead, with potential deviations from the deployment schedule (firm-driven forecast errors).

Table 1

High-level comparison of the JPA approach with the GB and the Italian cases, and with the WSI approach.

	JPA approach	GB Case	Italian Case	WSI approach
	Ex-ante phase			
1.	Firms provide **forecast of network uses** and **later** submit BP with estimate of total network expenditures	Firms submit BP with **forecast of network uses** and estimate of total network expenditures	Firms submit BP with **forecast of asset deployment** and estimate of total network expenditures	Firms submit BP with **forecast of network uses** and estimate of total network expenditures
	Regulator estimates efficient total network expenditures, via **RNM**	Regulator estimates efficient total network expenditures, via **benchmarking**	Regulator **assesses efficient capital expenditures**	Regulator estimates efficient total network expenditures, via **benchmarking**
2.	Regulator defines share of slow vs. fast money	Regulator defines share of slow vs. fast money	**Not yet applicable**	Regulator defines share of slow vs. fast money
	Regulator designs IQI matrix	Regulator designs IQI matrix	Regulator designs IQI matrix	Regulator designs IQI matrix
3.	Regulator calculates *ex-ante* revenue allowance	Regulator calculates *ex-ante* revenue allowance	Regulator calculates *ex-ante* revenue allowance	Regulator calculates *ex-ante* revenue allowance
4.	Regulator identifies **automatic** adjustment factors, via **RNM**	Regulator identifies **automatic** and **manual** adjustment factors using **firms' proposals**	Regulator designs **Progress Control Mechanism** (PCM)	Regulator identifies **activity indicators** and their **monetary values**
	Ex-post phase			
5.	Regulator and firms carry out *ex-post* process using **automatic adjustment factors** and efficiency incentive	Regulator and firms carry out *ex-post* process using **automatic/ manual adjustment factors** and efficiency incentive	Regulator and firms carry out *ex-post* process using **PCM** and efficiency incentive	Regulator and firms carry out *ex-post* process using **WSI** and efficiency incentive

Note: Differences across approaches in bold fonts.

the *ex-ante* phase, the so-called *activity indicators* as well as their monetary values per unit of activity, where these are defined by *unitary indices* and *modulation coefficients*.

A network operator's activity is meant to correspond to a physical network component, a technological (non-wire) solution, or a grid functionality which constitutes or physically describes the network and/ or enables its operation. While simple examples of activity indicators in the electricity distribution sector are feeders and substations, others might capture ICT equipment and software for traditional and new (smart) functionalities, such as data management, procurement of products and services (e.g., flexibility), reduction of fault clearing times, voltage regulation (EU, 2019).

Besides being objectively measurable, the main characteristic of an activity indicator is to be under the control, and to result from a direct intervention of the network operator. In this sense, an activity indicator is different from an output, which often refers to the impact of the distributor's activity on the network users, as well as from a cost driver used in a benchmarking assessment (which can include network components, but also energy delivered). Both outputs and cost drivers are influenced by the network operator's activity but, similar to network uses in JPA, also depend on other social, economic and technological conditions, which are not directly controlled by the operator.

The identification of these activity indicators is motivated by the objective to express the *ex-post* regulatory TOTEX estimate exclusively on the basis of the firm's realised activities – thus exempting the regulator from tracking the drivers of these activities.[8] Activity indicators are then associated to a (capital and operational) cost per unit of activity – as done, for example, for the meters in the Italian case. Such costs are referred to as unitary indices and are, in turn, linked to modulation coefficients. As better illustrated in Section 4, modulation coefficients have the function to fine-tune the unitary indices to account for the activities realised by the firm over the year. The sum over all activity indicators, of the unitary indices, multiplied by their modulation coefficient, times the respective realised activities is the WSI.

Assuming for simplicity to have selected four activity indicators for the regulation of an electricity distribution network, namely Primary Substations (PS), Medium Voltage Feeders (MVF), Secondary Substations (SS), and Low Voltage Feeders (LVF), the formulation of the WSI, for a year *y*, is as follows:

$$WSI_y = \alpha \cdot \mu_{PS} \cdot \Delta PS + \beta \cdot \mu_{MVL} \cdot \Delta MVF + \gamma \cdot \mu_{SS} \cdot \Delta SS + \delta \cdot \mu_{LVL} \cdot \Delta LVF \quad (1)$$

where:

α, γ: unitary indices in €/unit for PS and SS, respectively;

β, δ: unitary indices in €/km for MVF and LVF, respectively;

$\mu_{PS}, \mu_{MVL}, \mu_{SS}, \mu_{LVL}$: modulation coefficients, for, respectively PS, MVF, SS and LVF;

$\Delta PS, \Delta SS$: number of new PS and SS realised in year *y*;

$\Delta MVL, \Delta LVL$: length, in km, of new MV and LV feeders realised in year *y*.

While the number of new substations or feeders realised in a year include replacements and network expansions, unitary indices correspond to the state-of-the-art, efficient cost of realizing and maintaining the same substations and feeders they are associated with. Notably, activity indicators do not necessarily coincide with physical assets. Hence, when selecting the activity indicators, a regulator should always consider the feasibility of identifying their unitary cost with a reasonable amount of effort (and to oversee a manageable number of them). As for the network operator, unitary indices represent a reference cost for the activity.

Modulation coefficients will ultimately define the monetary value assigned by the regulator to a specific unit of activity. This value is designed to be larger when the annual realised quantity of an activity is considered efficient and vice versa, and depends on the firm's forecast of network uses, given the current technology or business practice. In the following, the product of a unitary index times the modulation coefficient will be referred to as the Recognised Unitary Value (RUV) associated to an activity indicator.

Once defined, the unitary indices and the modulation coefficients will not be modified over the tariff period. This favours transparency and creates regulatory certainty for the network operators. In fact, it is expected that firms will also recalculate their TOTEX estimates using unitary indices and modulation coefficients, to make informed decisions regarding expected remuneration levels.[9]

Note that not all the activities of a regulated firm can be easily translated into expenditures expressed in terms of unit costs times volume of an activity. The expenditures linked to those activities will continue to be included in the firm's total expenditures as today (as monetary values). The practice of breaking down a firm's expenditures in activities is well established and the WSI should not create a higher risk of double counting or cost-shifting.

4. Whole system indicator approach: a numerical application

The goal of this section is to show how the proposed WSI approach can be applied to calculate the annual *ex-post* allowed revenues of a distribution network operator during the tariff period. Hence, this section focuses on step four of the *ex-ante* phase and on the *ex-post* phase.

The numbers chosen for this numerical example are calibrated on the 2020–2022 BP of the largest Italian distributor (*e-distribuzione*) and rely, for additional information on ARERA's documents (e-distribuzione, 2020; ARERA, 2017b; 2019). The mathematical details of the process up to step three, are reported in Appendix A. The IQI matrix built for this numerical application is reported and commented upon in Appendix B.

4.1. Ex-ante phase – step four – WSI approach

As for step four of the *ex-ante* phase, illustrative numerical figures are chosen for the unitary indices and the modulation coefficients. For simplicity, this example considers the distribution operator activities to be fully captured by the four activity indicators introduced in equation (1): PS, MVL, SS, and LVL. For each indicator, a unitary index is then identified, in Euros per unit. Modulation coefficients are derived, instead, from a so-called RUV curve. To capture the idea that there is an efficient level of activity, the curve is defined as a cubic function of the annual realised quantity of the generic activity indicator, Δx:

$$RUV = f(\Delta x) = -a \cdot \Delta x^3 + b \cdot \Delta x^2 + c \cdot \Delta x + d \quad (2)$$

where *a* is strictly positive.

Having four coefficients, the RUV curve needs four Boundary Conditions (BC) to be calculated. These will be indicated by the regulator to represent:
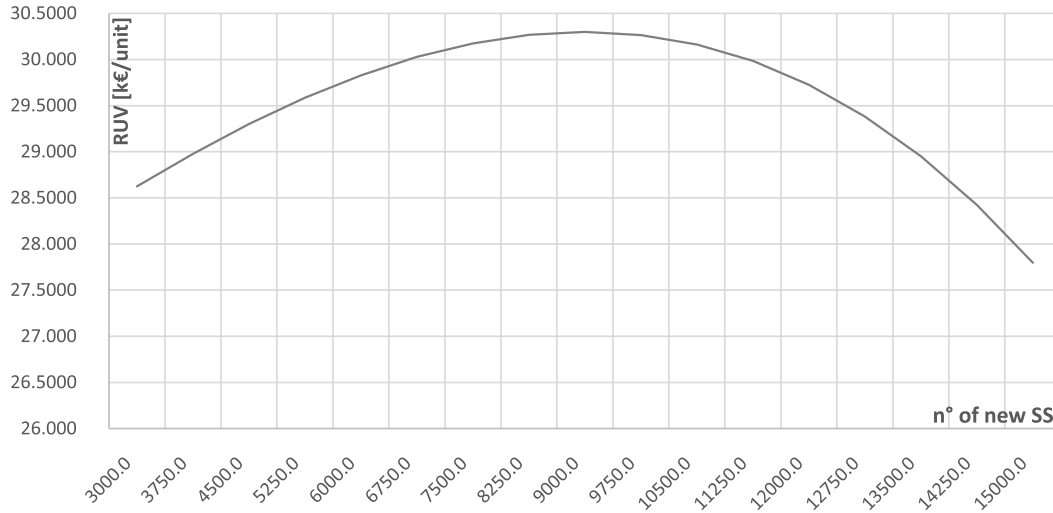
– a minimum and a maximum level of activity and the corresponding RUV (respectively, BC 1: $RUV_1 = f(\Delta x_1)$ and BC 2: $RUV_2 = f(\Delta x_2)$);
– an efficient level of activity and the corresponding RUV which will be normally (but not necessarily) the highest recognised unitary value (BC 3: $RUV_3 = f(\Delta x_3)$ and BC 4: $\frac{df(\Delta x_3)}{dx} = 0$).

Table 2 provides an example of the regulatory defined, boundary conditions for the activity indicator SS. Assuming a unitary index, γ, fixed at 30 k€/unit, Fig. 1 shows the resulting RUV curve (in €/unit) as a function of the annual realised quantity, ΔSS. As expected, the RUV for a single secondary substation is maximum for a regulatory defined, efficient level of activity and decreases for annual realised quantities above and below it. The modulation coefficients, μ_{SS}, are computed dividing

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[8] For instance, OFGEM (2019) indicates that, in order to set firms' allowed revenues, the regulator needs information from the companies on the activities that they intend to undertake and their associated costs.

[9] The parameters related to the unit cost of an activity can be the same across all firms (or differentiated if the regulator sees a motivation for this to be the case – e.g., contextual or geographical factors). As it is done today, the unit costs can be proposed by the regulated firms and further investigated by the regulator. Differently, because they are calibrated on the efficient volume of an activity, the modulation coefficients need to be defined for each firm separately. However, to ensure fairness across regulated firms the RUV curve (see Section 4) should be the same across firms. The form of this function is to be determined by the regulator who can choose to provide more or less incentives for the firms to deliver the *ex-ante* efficient volume of an activity or to allow more flexibility around such predefined volume.

Table 2
Boundary conditions for the RUV curve – Secondary Substations.

Unitary index: 30 k€/unit	ΔSS	RUV
Minimum activity level	0	27
Maximum activity level	16,000	26.8
Efficient activity level	9000	30.3

For the purpose of this example, the firm's realised TOTEX, $X_{y,ex-post}$, are assumed equal to those illustrated in Table 6. The regulator uses this information, together with the above *ex-post* annual TOTEX baseline, $X_{y,WSI}$ to calculate the yearly efficiency incentive, I_y:

$$I_y = SF \cdot \left(X_{y,WSI} - X_{y,ex-post} \right) \tag{4}$$

Fig. 1. Recognised Unitary Value for the activity indicator Secondary Substations.

the RUV by the annual realised quantity, and follow the same trend (Figure C.1, **Appendix C**). In other words, the boundary conditions determine the profile of the curve, creating an incentive for the operator to deliver the efficient level of activity. In this example, the modulation coefficients μ_{SS} vary between 0.90 and 1.01, which correspond to RUVs between 26.8 and 30.3 €/unit, and identify an efficient level of activity of around 240 SSs a year (Table 3).[10]

To illustrate the effect of the defined parameters on the *ex-post* annual, regulatory TOTEX estimate (the WSI), Table 3 (column five) shows the Recognised Cumulated Value (RCV) for the activity indicator under observation. As expected, this increases with the annual realised quantity of secondary substations, but with an S shape (Figure C.2 in **Appendix C**).

4.2. Ex-post phase – WSI approach

The calculation of the *ex-post* annual regulatory TOTEX estimate (of the WSI for each year of the tariff period) occurs via equation (1). To illustrate this process, we assume a tariff period of 5 years and the annual realised quantities per activity indicators given in Table 4. The latter is the only information required *ex-post* for this estimation and needs to be provided, at the end of each year, by the regulated firm. The annual WSIs over the tariff period, WSI_y, are reported in the last column of Table 4. An example of this simple calculation is given in Table 5 for the first year of the period: according to eq. (1), the annual WSI is simply the sum of the RCV for every activity indicator.

Once the annual WSI is known, the regulator calculates the *ex-post* annual TOTEX baseline, $X_{y,WSI}$, for the same year (Table 6). This is obtained using a weight defined *ex-ante* ($\omega = 0.66$), and the firm's *ex-ante* TOTEX estimate, $X_{y,firm}$, in the following way:

$$X_{y,WSI} = WSI_y \cdot \omega + X_{y,firm} \cdot (1 - \omega) \tag{3}$$

where the sharing factor SF is also fixed *ex-ante*. Recall that a high sharing factor corresponds to a high-powered incentive scheme (a value of 1 corresponds to a revenue cap) and entails a higher risk for the regulated firm.

The annual *ex-post* allowed TOTEX, $X_{y,\,allowed}$ is obtained as:

$$X_{y,allowed} = X_{y,ex-post} + I_y \tag{5}$$

and it is also reported in Table 6.

Finally, the annual *ex-post* revenue allowance, $R_{y,allowed}$, is computed, using *ex-ante* defined values for the capitalization rate, σ, (e.g., 0.70), the WACC (e.g., 7.09%) and the regulatory asset life (e.g., 40 years).[11]

5. Discussion of the WSI approach

The objective of this section is to discuss the properties of this proposal. A few different issues are addressed: the incentives provided to the regulated firms, the advantages for the regulator, economic efficiency, and a few implementation aspects.

5.1. Incentives provided to the regulated firms

With regard to the incentives provided to the regulated firms, two aspects are important. First, to account for the firm's opportunistic behaviour, the proposal relies on the IQI matrix. Since its incentive properties are well-known from the literature, they are only briefly summarized in **Appendix B**. Second, the WSI is designed to provide incentives to adopt a single innovative technology when this presents lower unit costs (unitary indices are fixed for the regulatory period). Given that the desirable outcomes associated with a certain activity are clearly specified, firms presented with a reference cost, are encouraged to adopt a new technology, whenever this choice results in lower expenditures per unit of activity.

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[10] Unitary indices, boundary conditions, and modulation coefficient curves for the activity indicators PS, MVF and LVF can be found in **Appendix C**.

[11] More details on this calculation are given in Table C4 in **Appendix C**.

Table 3
Recognised cumulated value – secondary substations.

Number of realised SS	Modulation coefficient	Unitary index	Recognised Unitary Value	Recognised Cumulated Value
ΔSS	μ_{SS}	γ [k€/unit]	k€/unit	k€
3,000	0.95	30	28.63	85,877
3,750	0.97	30	28.98	108,668
4,500	0.98	30	29.30	131,848
5,250	0.99	30	29.58	155,321
6,000	0.99	30	29.83	178,975
6,750	1.00	30	30.03	202,687
7,500	1.01	30	30.18	226,315
8,250	1.01	30	30.27	249,708
9,000	1.01	30	30.30	272,695
9,750	1.01	30	30.27	295,093
10,500	1.01	30	30.16	316,706
11,250	1.00	30	29.98	337,319
12,000	0.99	30	29.73	356,707
12,750	0.98	30	29.38	374,628
13,500	0.97	30	28.95	390,826
14,250	0.95	30	28.42	405,030

Table 4
Firm's realised quantities over the tariff period and annual WSI.

Year	Primary substations	MV feeders	Secondary substations	LV feeders	WSI$_y$
	ΔPS	ΔMVF	ΔSS	ΔLVF	[M€]
1	44	4,800	11,250	13,040	**4,892**
2	31	5,400	12,000	11,800	**5,340**
3	54	3,900	10,500	10,700	**3,980**
4	40	6,000	9,375	10,100	**5,678**
5	58	6,500	9,875	13,650	**6,295**

Table 5
Ex-post annual regulatory TOTEX estimate, or annual WSI for year 1.

	Realised quantities	Unitary index [k€/unit]	Recognised Unitary Value [k€/unit]	Recognised Cumulated Value [k€]
Primary substations	44	1,000	999	43,967
MV feeders [km]	4,800	800	803	3,856,191
Secondary substations	11,250	30	30.0	337,319
LV feeders [km]	13,040	50	50.2	654,247
WSI$_1$ [k€]				**88,702**

Table 6
Annual firm's realised TOTEX and *ex-post* annual allowed TOTEX.

Year		1	2	3	4	5
Firm's *ex-ante* TOTEX estimate [M€]	$X_{y,firm}$	4974	5237	4202	5577	5235
Annual WSI [M€]	WSI_y	4892	5340	3980	5678	6295
TOTEX baseline [M€]	$X_{y,WSI}$	4920	5305	4055	5644	5935
Firm's realised TOTEX [M€]	$X_{y,ex-post}$	4748	5237	3981	5820	5437
Efficiency incentive [M€]	I_y	1.53	0.56	0.82	-1.35	3.46
Ex-post allowed TOTEX [M€]	$X_{y,allowed}$	4824	5266	4014	5743	5642
Ex-post revenue allowance [M€]	$R_{y,allowed}$	1877	2232	1995	2764	2953

Note that when the unitary cost of a certain activity decreases, the benefit of such cost decrease remains with the firm, as long as the amount of that activity remains at the *ex-ante* efficient level. If the firm decides to deliver more of the same, less costly technology, the modulation coefficients ensure that such benefits are shared with consumers (the RUV curve is bell-shaped). In fact, an innovation will constitute an advantage for a network operator adopting more of the new technology, only up to the point where the RUV of a given activity indicator is higher than the cost sustained by the firm to deliver and maintain a new unit of that activity. An example of such an occurrence regards a hypothetical technological innovation in materials used to manufacture overhead cables (making them more expensive than in the past). This allows for the use of such cables in numerous situations where their mechanical characteristics (strain-strength and thermal capacity) where considered insufficient in the past (e.g., provided an unacceptable level of supply reliability), thus requiring the use of even more expensive underground cables. In this case, it is in the interest of the firm and of the regulator to favour the adoption of the new technology.[12] Hence, a revision of the calibration of the modulation coefficients might also be requested by the firm. In doing so, firms should be obliged to demonstrate also the benefits ensured to the end-users, i.e. to justify the request on the basis of a CBA (recall that the regulator has the possibility to approve it or deny it).

More importantly, the WSI provides incentives to explore alternative technical solutions, as new system operation techniques emerge over time. This is possible because firms can substitute, for instance, one physical asset with another (or with a non-wire alternative) and still maintain the annual, expected flow of revenues. The adoption of innovations often requires a system-wide change, hence the WSI's focus on giving regulated firms the flexibility to modify several activity indicators at the same time.

To illustrate the incentive to innovate at the system level recall that the WSI uses monetary values for the activity indicators which change with the realised quantity (the RUVs). This entrusts firms with a certain flexibility to substitute one activity indicator with another. For example, to stay with the activity indicators used in the numerical example, the firm might use less PS and more MVF than planned. In fact, the *Total* recognised unitary value (the sum of the RUVs for PS and for MVF) does not change (within certain limits) when different combinations of activities are selected by the firm. In other words, the firm has an incentive to explore alternative solutions as new system operation techniques emerge over time.

Let us consider, the curve depicted on the left-hand side of Fig. 2. This represents, for a generic distribution operator, the number of new MVF to be realised per new PS, according to the *ex-ante* schedule.

Assume now that, in light of a technological change, the same firm chooses, *ex-post*, to increase the quantity of new MVF while decreasing that of new PS. Indeed, if the regulation did not allow some flexibility in the number of MVF per PS, this decision could penalise the firm, by lowering the RUVs for the two indicators.[13] This flexibility, to substitute one activity indicator for another quite freely, is illustrated on the right-hand side of Fig. 2.

To explain this, it is useful to look first at the surface in Fig. 3, representing the sum of the RUVs for PS and for MVF (hereinafter $Total_{RUV}$), for different quantities and combinations of the two. As expected, $Total_{RUV}$ decreases as the number of realised quantities moves away from the efficient level of activity. This is captured by the changing colour of the surface, with lighter grey indicating the highest $Total_{RUV}$ and darker grey the lowest. The right-hand side of Fig. 2 is obtained by projecting this three-dimensional surface on a two-dimensional plane, where the contour lines identify iso-$Total_{RUV}$ curves. These show that, although within certain boundaries, firms do have the possibility to choose different activity indicators combinations, while maintaining the $Total_{RUV}$ unchanged. At the same time, iso-$Total_{RUV}$ curves with lower values show how regulation adapts to a change in the technological efficient frontier, and share the efficiency gains with the end-users.

In other words, under the WSI approach regulated firms gain in flexibility, that is they do not need to strictly adhere, every year, to the (time and quantity) schedule foreseen *ex-ante* in order to maintain the expected flow of revenues, thus, any gains associated with cost efficiency improvements.

5.2. Addressing uncertainty

The proposed approach presents features that help regulators to manage uncertainties. The modular structure of the WSI, whereby unitary indexes are multiplied by the number of realised quantities, enables the regulators to adjust the *ex-post* annual regulatory TOTEX estimate to the firm's annual realised activities during the tariff period. This minimizes the impact of forecast errors, both those driven by a firm decision to modify the timing and scope of its BP, as well as those driven by unforeseen changes in end-user demand and preferences for network services (which will be reflected in the level of activity selected by the regulated firm). Moreover, for the reasons illustrated above with the help of Fig. 3, the WSI approach offers a solution to benchmark errors, specifically when unexpected changes in technological approaches lead to a substitution of an activity with another (e.g., a wire vs. a non-wire solution).

All in all, this helps regulators ensuring that the *ex-post* annual regulatory TOTEX estimate remains in line with actual expenditures under demand and technology uncertainty. Recall that the difference between the *ex-post* annual regulatory TOTEX estimate (i.e., the WSI) and the *ex-post* realised TOTEX is used to estimate the efficiency incentive (the portion of over/under spend shared by with consumers) that derives from the IQI matrix.

From the regulator's perspective, preserving the incentive for firms to adopt innovative technological solutions, while protecting end-users from excessive rent extractions, is a highly valuable feature in current and future regulatory scenarios and can be quite relevant as well, when the same regulated firm serves different territories, each requiring tailored approaches. Also, looking forward, the ability of network regulation to deal not only with uncertainties (in technological innovations as well as network uses), but also with increased complexity is crucial (Cambini et al., 2020). The modular structure of the WSI allows for flexibility in this regard as well. As the number of activities included in the WSI increases also the possible mix of technological solutions that

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[12] Suppose, that the overnight capital cost for an overhead cable is 50 k€/km, while for an underground cable is 75 k€/km. Thanks to a rapid technological development, new material for overhead cables are commercialised. The new cables are able to ensure better supply reliability; however, the cost of the new overhead cables is higher (55 k€/km).

[13] In other words, the proposed approach could prevent the firm to adopt a new, more efficient technological solution, resulting in a missed opportunity not only for the network operator but for the end-users as well.
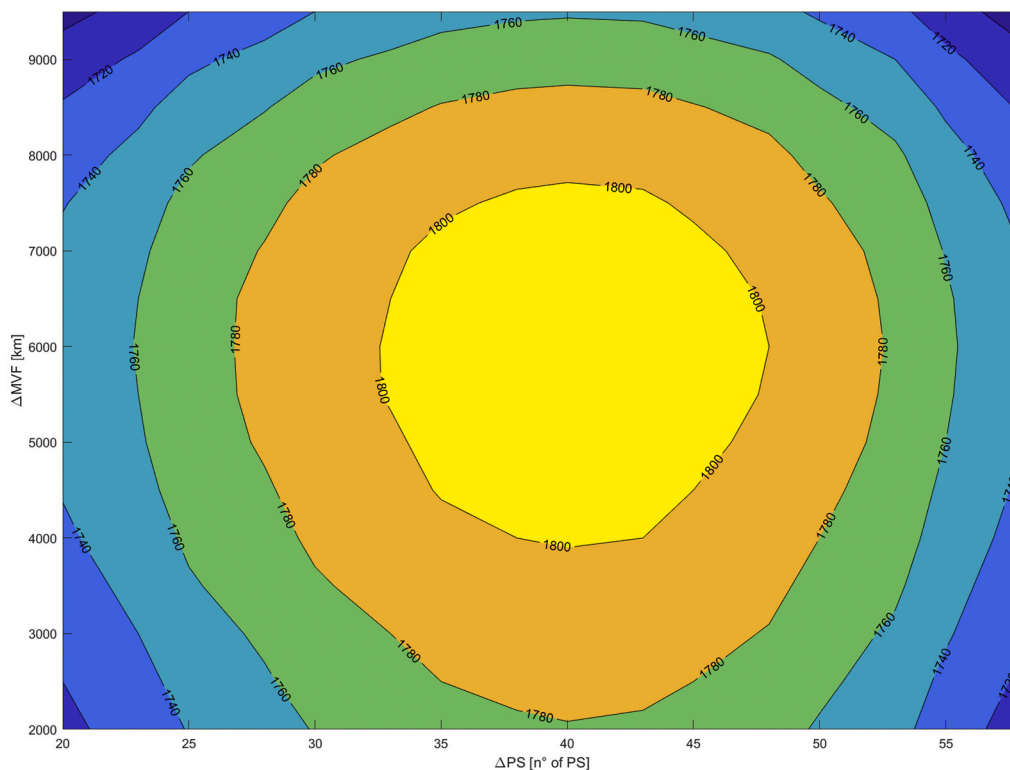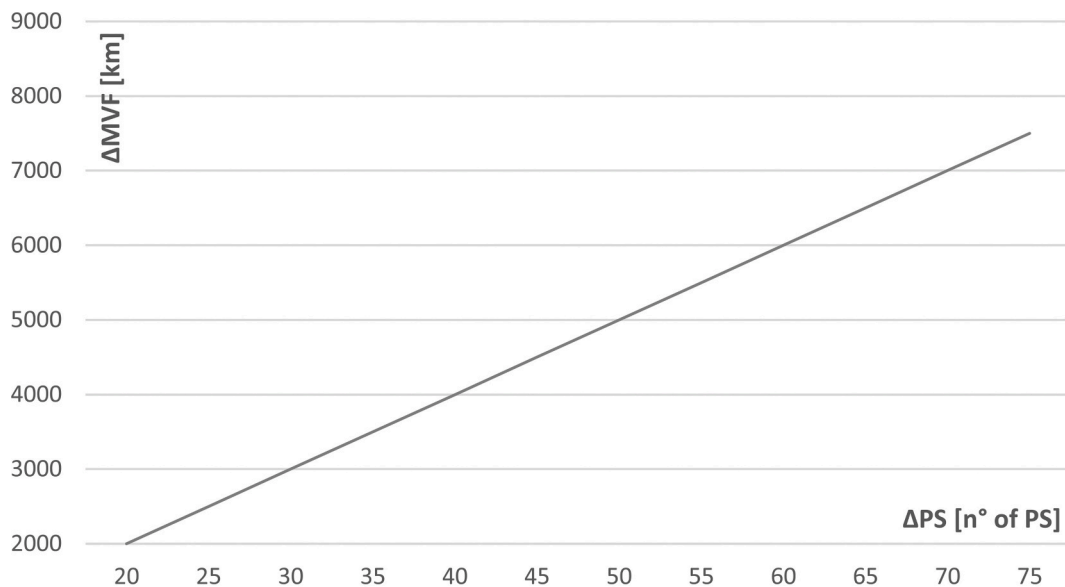
Fig. 2. Flexibility of the WSI approach: PS vs. MVF. On the right-hand side, numbers indicate TotalRUV (in k€/unit).

can be adopted by a firm will increase, leaving to the firm even greater freedom to innovate. This can be particularly useful in the context of smart grid solutions.

5.3. Economic efficiency

A relevant aspect of the WSI proposal is whether it improves economic efficiency. By addressing the issue of information asymmetry via a menu of contracts, the proposed approach creates incentives for firms to present accurate cost estimations and to reduce expenditures. Also, by eliminating trade-offs between CAPEX and OPEX, it minimizes distortions in the use of capital. Furthermore, the WSI is designed to maintain the regulatory revenue trajectory aligned with realised costs under demand and technology uncertainty, while favouring dynamic efficiency (allowing firms the flexibility to innovate). Finally, because the WSI is completely defined *ex-ante*, it avoids the distortions that derive from regulatory uncertainty.
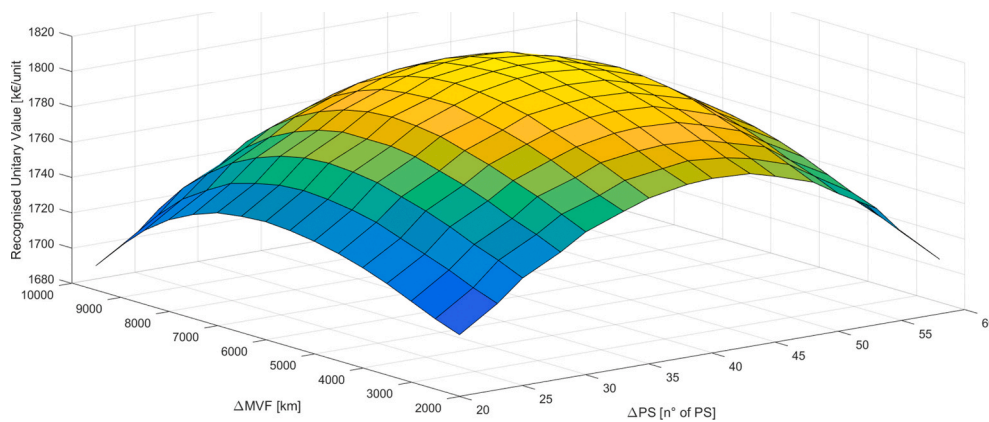
Fig. 3. TotalRUV (in k€/unit) as a function of different quantities of PS and MVL.

5.4. Implementation aspects

Before concluding, two minor remarks, and a major one, are in order. Starting with the major one, it is evident that the implementation of the WSI clearly requires quite some work in the *ex-ante* phase. Note that this work would substitute a step (step 4 in Table 1) which is already carried out, although in a different manner, in practical approaches (by OFGEM or ARERA), or approaches proposed in the literature (Jenkins and Pérez-Arriaga, 2017). The selection of the activity indicators and the calibration of the parameters (unitary indices and modulation coefficients) is a new task, but it would still require regulators and firms to use the same information which is normally collected and processed during the *ex-ante* phase. Using this information in a different way, would require however a change of perspective, that should be addressed by the regulator, for instance, via several rounds of consultation with network operators and users alike.

In fact, a common practice in regulation is to apply a new approach in a controlled setting (e.g., to a specific activity of the network operator such as, for instance, the roll-out of second generation of smart meters in Italy). This can trigger a trial and error cycle that enables all interested parties to gain sufficient experience to widen the scope of the regulatory approach over time. For instance, the WSI approach could be implemented first for to calculate the expenditures related to those activities carried out by the firm, which are easily expressed in terms of volumes times a unit cost, such as the replacement of existing network assets and/or new investments (e.g., in feeders, transformers, meters), as well as those activities which are associated with large uncertainties, such as network reinforcement for new consumer connections or connections of Distributed Generation. Not only the volume of activity related to latter two is difficult to predict, but it can also be achieved via traditional interventions (larger capacity transformers, new cables) or via innovative technical solutions (ICT and consumer management) which reduce the need for traditional investments.[14] The scope of the WSI approach can then be expanded over time.

Conversely, the *ex-post* process whereby the regulator adjusts the TOTEX baseline to account for the actual evolution of network uses (JPA's and OFGEM's adjustment factors) or for the actual deployment of the physical asset (ARERA's PCM) becomes rather straightforward. In fact, the regulatory estimation of the *ex-post* annual TOTEX, i.e., the calculation of annual WSI, only requires information on the realised quantity for each activity indicator, everything else being fixed *ex-ante*.

As for the minor remarks, of course, an additional advantage of keeping the number of realised quantities in the calculation of the annual WSI, is the opportunity for regulators to monitor the roll-out of a

given asset – a feature similar to the one implemented by ARERA with the PCM. In fact, the calibration of modulation coefficients can also be geared to enforce the delivery of a certain level of activity, in cases where this might be necessary. Finally, it is worth noticing that the proposed approach focuses only on the definition of the allowed revenues. A well-functioning regulatory framework will also include incentives for the regulated firms to meet performance standards on selected outputs, such as Quality of Service, network losses, network resilience and, recently, innovation (OFGEM, 2010a; 2012; 2017; Olivieri et al., 2012; Lo Schiavo et al., 2013). These can provide additional funds (on top of the allowed revenues) to realize selected innovation projects, or to facilitate the roll-out of innovative technologies which showed the potential to provide benefits to consumers and/or the environment.

6. Conclusions and policy implications

The regulatory approach proposed in this work aims to support policy makers and energy regulators to adequately cope with the changing nature of electricity distribution networks – a result of the uncertainties brought forward by the increased penetration of DER, the related changes in consumers' preferences for network services, and the widespread availability of ICT innovations.

Anecdotal evidence shows that two national regulatory authorities, OFGEM in the UK and ARERA in Italy, have already responded to the new challenges, by adopting advanced regulatory instruments (menu of contracts), and introducing specific incentives for innovation. A comparative analysis of these practical cases, in light of the recent work by Jenkins and Perez-Arriaga (2017), highlights, however, the potential for further improvement.

The methodology for establishing the allowed revenues of electricity distribution networks proposed in this work builds on the observed experience, i.e., it is similarly designed to respond to the traditional regulatory challenges linked to information asymmetry. In addition, it enables regulators to specifically address two further issues. By resorting to a modular structure for the estimation of the regulatory TOTEX during the tariff period, the proposed approach has the potential to reduce forecast errors (those related to a regulator's inability to correctly predict the rate of DER penetration, or to foresee a change in the number customers connected to the grid). Benchmark errors (those linked to the inability of the regulator to predict the future availability of innovative practices and equipment to operate the grid) are more difficult to manage and no *ex-ante* regulation will eventually be able to comprehensively account for uncertainties in technological change. Nevertheless, the proposed approach is specifically designed to be less sensible to benchmark errors than existing (practical and academic) solutions and, at the same time, to encourage firms to explore and adopt innovations (albeit, within certain boundaries).

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[14] To keep the focus on equation (1), this option is not included in the numerical example presented in Section 4.

From a broader policy perspective, this work highlights that several actions are needed to enable the decarbonization of the European energy sector, while ensuring customer participation and affordability (EU, 2018; 2019a; 2019b). Among those, an adequate regulation of the energy infrastructure is crucial. In particular, distribution network regulation needs to change and become capable to provide incentives for cost efficiency while, at the same time, effectively address the increasingly complexity of planning and operating the grid.

In this context, the flexibility introduced by the WSI approach appears extremely valuable. For this reason, further work is needed to study the combined effect on firms of the full set of incentives (to disclose information, spend efficiency, and innovate) included in the current proposal. This could also support the development of implementation guidelines, not only for the calibration of the regulatory parameters, but for the choice of the activity indicators as well, a key aspect for the well-functioning of the WSI approach.

CRediT authorship contribution statement

Filippo Bovera: Conceptualization, Methodology, Formal analysis,

Validation, Writing - original draft, Writing - review & editing. **Maurizio Delfanti:** Conceptualization, Investigation, Writing - original draft. **Elena Fumagalli:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Luca Lo Schiavo:** Conceptualization, Supervision. **Riccardo Vailati:** Conceptualization, Supervision.

Declaration of competing interest

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

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Appendix A. Establishing a firm's revenue allowance

This Appendix A summarises the regulatory process presented in JPA and provides a definition for the variables and terms used in their work. For the sake of clarity, the same terminology is adopted in this work as well.

Ex-ante phase – step 1

Using the firm's provided forecast of network uses (e.g., load growth, DER penetration) the regulator estimates the efficient investment and maintenance expenditures over the tariff period (multi-year estimate). This includes the overnight cost of new and replacement network investments and as well as the cost of preventive and corrective maintenance. These costs are then converted into an annual investment schedule with associated annual maintenance costs. The regulator's *ex-ante* estimate of efficient total expenditures (TOTEX) is thus a *vector* of annual total expenditures, which can also be summarized, using a Net Present Value (NPV) calculation, into the NPV of regulator's TOTEX.

Ex-ante phase – step 2

● The regulator implements a TOTEX-based approach to capitalizing expenditures into the Regulated Asset Value (RAV). This involves determining a parameter, σ fixed over the tariff period and referred to as slow money share or capitalization rate. This indicates which portion of TOTEX will be capitalized into the RAV (slow money, S). The remainder of the TOTEX, known as fast money, F, will be expensed annually.

● The regulator constructs an incentive compatible menu of profit-sharing contracts, often referred to as the IQI matrix (Information Quality Incentive matrix). Following the method introduced by Cossent and Gómez (2013), this requires the regulator to define four discretionary parameters:

a) ω, the weight of the regulator's estimate of efficient TOTEX relative to the firm's estimate;

b) SF_{ref}, the reference value of the profit-sharing factor (also known as the reference value of the efficiency incentive rate), i.e., the value of the *SF* for a ratio, $\theta_{ex-ante}$, equal to 1; the latter corresponds to the ratio of the NPV of firm's TOTEX (see point 4b) below) over the NPV of regulator's TOTEX;

c) SF_{roc}, the rate of change of the profit-sharing factor with changes in the ratio $\theta_{ex-ante}$;

d) AI_{ref}, the reference value of the Additional Income, i.e., the value of the *AI* for a ratio, $\theta_{ex-ante}$, equal to 1.[15]

Ex-ante phase – step 3

Given *(i)* the firm's *ex-ante* estimate of TOTEX, $X_{y,firm}$ (a *vector* of annual TOTEX submitted as part of the Business Plan); *(ii)* the corresponding NPV of the firm's TOTEX; *(iii)* the regulator's *ex-ante* estimate of efficient TOTEX, $X_{y,\ reg}$; and *(iv)* the IQI matrix, the regulator:

● Calculates the *ex-ante* annual TOTEX baseline, $X_{y,ex-ante}$ as:

$$X_{y,\ ex-ante} = X_{y,reg} \cdot \omega + X_{y,firm} \cdot (1 - \omega) \tag{A.1}$$

● Identifies the value of the sharing factor (*SF*, which will remain fixed for the tariff period) and the additional income allowance (*AI*) corresponding to the ratio, $\theta_{ex-ante}$.

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[15] Following Cossent and Gómez (2013) and JPA, Table A1 provides the equations that are necessary to create an IQI-matrix from the four parameters.

- Calculates the *ex-ante* allowed revenue baseline, $R_{y, ex-ante}$ for each year of the tariff period,[16] as:

$$S_y = X_{y,ex-ante} \cdot \sigma \tag{A.2}$$

$$F_y = X_{y,ex-ante} - S_y \tag{A.3}$$

$$G_y = G_{y-1} - E_y + S_y \tag{A.4}$$

$$D_y = G_y \cdot Life^{-1} \tag{A.5}$$

$$RAV_y = (Life - Age) \cdot Life^{-1} \cdot G_y \tag{A.6}$$

$$C_y = RAV_y \cdot WACC \tag{A.7}$$

$$R_{y,ex-ante} = F_y + D_y + C_y + AI \tag{A.8}$$

where:

    G is the total gross value of in-service assets;
    E is the gross value of assets reaching the end of useful life;
    D is the annual capital depreciation allowance;
    Life is the regulatory asset life;
    Age is the average age of assets;
    C is the annual allowance for repayment of debt and equity;
    and *WACC* is the weighted average cost of capital.

Ex-ante phase – step 4

The regulator calculates the automatic adjustment factors (or delta factors) to manage uncertainty in the evolution of network uses. See JPA for all the details on this.

Ex-post phase

At the end of each year of the tariff period, the firm submits a report on actual expenditures, referred to as the firm's realised TOTEX, $X_{y, ex-post}$, together with the actual evolution of network uses. The latter is used by the regulator to adjust, if necessary, the *ex-ante* annual TOTEX baseline (please refer to JPA for details on how this is carried out using delta factors). The TOTEX baseline after adjustments for forecast errors is referred to as the adjusted TOTEX baseline, $X_{y, adjusted}$. The ensuing process involves the following:

- The regulator uses the adjusted TOTEX baseline (or the *ex-ante* annual TOTEX baseline if there are no forecast errors) together with the firm's realised TOTEX, to calculate the efficiency incentive, I_y:

$$I_y = SF \cdot \left(X_{y, adjusted} - X_{y,ex-post} \right) \tag{A.9}$$

- The regulator calculates the *ex-post* annual allowed TOTEX, $X_{y,allowed}$ as:

$$X_{y,allowed} = X_{y,ex-post} + I_y \tag{A.10}$$

- Following the same procedure as in step 3 above, the regulator calculates the *ex-post* revenue allowance, $R_{y,allowed}$
- Finally, the regulator corrects the firm's revenue allowance in future N years (where N is the duration of the tariff period) to equalise the collected revenues with the *ex-post* allowed revenues. See JPA for all the details on this.

Table A.1
Parameters and formulas for the construction of the IQI matrix – Source: Jenkins and Perez-Arriaga (2017), Appendix B.

Symbol	Description	Constraint/Formula
Discretionary parameters		
ω	Weight of the regulator's estimate of efficient TOTEX relative to the firm's [p.u.]	[0,1]
SF_{ref}	Reference value of the profit-sharing factor [p.u.]	[0,1]
SF_{roc}	Rate of change of the profit-sharing factor	<0
AI_{ref}	Reference value of the additional income [% of regulator's estimate]	–
Initialization parameters		
AI_{int}	Intercept of additional income	

(continued on next page)

[16] This is also referred to as the *ex-ante* revenue allowance or as the *ex-ante* allowed revenues.

Table A.1 (*continued*)

Symbol	Description	Constraint/Formula
		$AI_{int} = AI_{ref} - 100 \cdot SF_{ref} \cdot (\omega - 0.5)$
		$= AI_{ref} - 100\alpha - 100^2\beta$
α	First order factor in AI formula	$\alpha = SF_{ref} \cdot (\omega - 1) + 100 \cdot SF_{roc} \cdot (1 - 2\omega)$
β	Second order factor in AI formula	$\beta = SF_{roc} \cdot (\omega - 0.5)$
Ex-ante **parameters**		
X_{firm}	Firm's *ex-ante* estimate of TOTEX [€]	
X_{reg}	Regulator's *ex-ante* estimate of TOTEX [€]	
$\theta_{ex-ante}$	Ratio of the firm's over the regulator's TOTEX estimate	$\theta_{ex-ante} = X_{firm}/X_{reg}$
$X_{ex-ante}$	*Ex-ante* TOTEX baseline	$X_{ex-ante} = 100\omega + (1 - \omega) \cdot \theta_{ex-ante}$
SF	Profit-sharing factor [p.u.]	$SF = SF_{ref} + (\theta_{ex-ante} - 100) \cdot SF_{roc}$
AI	Additional Income [% of regulator's estimate]	$AI = AI_{int} + \alpha \cdot \theta_{ex-ante} - \beta \cdot \theta^2_{ex-ante}$
Ex-post **parameters**		
$X_{ex-post}$	Firm's realised TOTEX [€]	
$\theta_{ex-post}$	Ratio of the firm's realised TOTEX to regulator's *ex-ante* estimate of TOTEX	$\theta_{ex-post} = X_{ex-post}/X_{reg}$
I	Efficiency incentive [% of regulator's estimate]	$I = (X_{ex-ante} - X_{ex-post}) \cdot SF/X_{reg}$

Appendix B. The IQI matrix

By defining a continuum of profit (and loss) sharing factors between the firm and the network users, together with additional income adjustments to ensure incentive compatibility, an IQI matrix stimulates firms to *(i)* reveal their cost type and *(ii)* to improve productive efficiency. Before discussing such properties, note that following the procedure by Cossent and Gómez (2013), a regulator can construct an IQI matrix by setting only four discretionary parameters. The choices made for the purpose of this work are reported in Table B1. The incentive compatible menu of contracts resulting from these choices is illustrated in Table B2.

With regard to the former property (providing incentives for firms to present accurate forecasts of expected expenditures over the tariff period) Table B2 illustrates the following. Given the ratio, $\theta_{ex-ante}$, of the firm's TOTEX estimate (the firm's BP) over the regulator's TOTEX estimate, the IQI matrix provides three main elements. The first is the *ex-ante* TOTEX baseline, computed as a weighted average of the firm's and the regulator's *ex-ante* TOTEX estimates over the tariff period (the weight, ω, on the regulator's estimate was set at 0.66 in this case). The second is the profit-sharing factor, SF, which linearly decreases with the ratio, $\theta_{ex-ante}$, so that a network operator with a low cost-opportunity will be subject to a high-powered incentive scheme and vice versa. The efficiency incentive, i.e. the product of the profit-sharing factor times the difference between the *ex-ante* TOTEX baseline and the firm's realised TOTEX, will depend on the ratio $\theta_{ex-post}$. Finally, the additional income, *AI*, can be positive or negative and ensures that the IQI matrix is incentive compatible (the AI will be added once, to the *ex-ante* allowed revenues). Each element of the matrix provides an indication of the effects of the efficiency incentive plus the additional income on the *ex-ante* TOTEX baseline. As highlighted by the shaded matrix elements, when the menu of contracts is well designed, regulated firms are better off when their realised total expenditures coincide with their *ex-ante* estimate (given $\theta_{ex-post}$, when this is equal to $\theta_{ex-ante}$). In this way, the incentive to inflate expenditure estimations is mitigated (although not eliminated entirely).

As for the second property (the incentive to improve productive efficiency) Table B1 shows that a well-designed IQI matrix encourages firms to reduce expenditures with respect to their *ex-ante* estimate (given $\theta_{ex-ante}$ firms are better off when they realize a lower $\theta_{ex-post}$) and ensures that such savings will be shared with consumers. Symmetrically, in case of overspending, firms' exposure is also limited by the sharing factor.

Note that to calculate the elements in the lower part of the IQI matrix, the necessary inputs are *AI*, which is defined *ex-ante* (see Appendix A) and the Efficiency Incentive, *I*, which is computed annually as:

$$I = (X_{ex-ante} - X_{ex-post}) \cdot SF/X_{reg}$$

where:

$X_{ex-ante} = 100\omega + (1 - \omega) \cdot \theta_{ex-ante}$ is the *ex-ante* TOTEX baseline;
$X_{ex-post}$ is the firm's realised TOTEX;
SF is the profit-sharing factor;
X_{reg} is the regulator's *ex-ante* estimate of the efficient TOTEX.

Table B.1
IQI matrix for WSI approach: discretionary parameters

Discretionary parameters		
Weight of the regulator's estimate of efficient TOTEX relative to the firm's	ω	0.66
Reference value of the profit- sharing factor		0.40

Table B.1 (*continued*)

Discretionary parameters		
	SF_{ref}	
Rate of change of the profit-sharing factor	SF_{roc}	-1
Reference value of the additional income	AI_{ref}	1%

Table B.2
IQI matrix for WSI approach: Pay-off per 100 € of total expenditures.

Ratio of firm's TOTEX estimate to regulator's TOTEX estimate [%]	$\theta_{ex-ante}$	75	80	85	90	95	100	105	110	115	120	125
Ex-ante TOTEX baseline [% of regulator's estimate]	$X_{ex-ante}$	91.50	93.20	94.90	96.60	98.30	100.00	101.70	103.40	105.10	106.80	108.50
Profit-Sharing Factor [p.u.]	SF	0.65	0.60	0.55	0.50	0.45	0.40	0.35	0.30	0.25	0.20	0.15
Additional income [% of regulator's estimate]	AI	3.4	3.1	2.7	2.2	1.6	1.0	0.3	-0.5	-1.4	-2.4	-3.4
Ratio of firm's realised TOTEX to regulator's TOTEX estimate [%]	$\theta_{ex-post}$	Efficiency Incentive plus Additional Income [% of regulator's estimate]										
	75	14.1	14.0	13.6	13.0	12.1	11.0	9.6	8.0	6.1	4.0	1.6
	80	10.9	11.0	10.9	10.5	9.9	9.0	7.9	6.5	4.9	3.0	0.9
	85	7.6	8.0	8.1	8.0	7.6	7.0	6.1	5.0	3.6	2.0	0.1
	90	4.4	5.0	5.4	5.5	5.4	5.0	4.4	3.5	2.4	1.0	-0.6
	95	1.1	2.0	2.6	3.0	3.1	3.0	2.6	2.0	1.1	0.0	-1.4
	100	-2.1	-1.0	-0.1	0.5	0.9	1.0	0.9	0.5	-0.1	-1.0	-2.1
	105	-5.4	-4.0	-2.9	-2.0	-1.4	-1.0	-0.9	-1.0	-1.4	-2.0	-2.9
	110	-8.6	-7.0	-5.6	-4.5	-3.6	-3.0	-2.6	-2.5	-2.6	-3.0	-3.6
	115	-11.9	-10.0	-8.4	-7.0	-5.9	-5.0	-4.4	-4.0	-3.9	-4.0	-4.4
	120	-15.1	-13.0	-11.1	-9.5	-8.1	-7.0	-6.1	-5.5	-5.1	-5.0	-5.1
	125	-18.4	-16.0	-13.9	-12.0	-10.4	-9.0	-7.9	-7.0	-6.4	-6.0	-5.9

Appendix C. WSI Numerical application

Table C.1
Boundary conditions for the RUV curve – Primary Substations.

Unitary index: 1000 k€/unit	ΔPS	RUV [k€/unit]
Minimum activity level	0	950
Maximum activity level	63	900
Efficient activity level	40	1000

Table C.2
Boundary conditions for the RUV curve – Medium Voltage Feeders.

Unitary index: 800 k€/km	ΔMVF	RUV [k€/unit]
Minimum activity level	0	680
Maximum activity level	10,000	720
Efficient activity level	6000	810

Table C.3
Boundary conditions for the RUV curve – Low Voltage Feeders.

Unitary index: 50 k€/km	ΔLVF	RUV [k€/unit]
Minimum activity level	0	45
Maximum activity level	20,000	42
Efficient activity level	13,500	50

Table C.4
Calculation of the *ex-post* revenue allowance.

Year		0	1	2	3	4	5
Ex-post allowed TOTEX [M€]	$X_{y,allowed}$		4,824	5,266	4,014	5,743	5,642
Efficiency Incentive [M€]	I_y		1.53	0.56	0.82	-1.35	3.46
REVENUE ALLOWANCE CALCULATION							
Slow money [M€]	S_y		3,376	3,686	2,810	4,020	3,949
Total gross value of in-service assets [M€]	G_y	47,450*	49,640	52,086	53,593	56,274	58,816
Average age of assets [years]	Age	19.50*	19.55	19.60	19.65	19.70	19.74
Regulatory Asset Value [M€]	RAV	24,333*	25,380	26,567	27,269	28,565	29,784
Fast money [M€]	F		1,447	1,580	1,204	1,723	1,693
Depreciation allowance [M€]	D		1,241	1,302	1,340	1,407	1,470
Additional Income [M€]	AI		73	78	60	83	88
Allowance for repayment of debt and equity [M€]	C		1,799	1,884	1,933	2,025	2,112
Ex-post revenue allowance [M€]	$R_{y,allowed}$		4,560	4,844	4,537	5,238	5,362

* Assumptions made to initialize figures.

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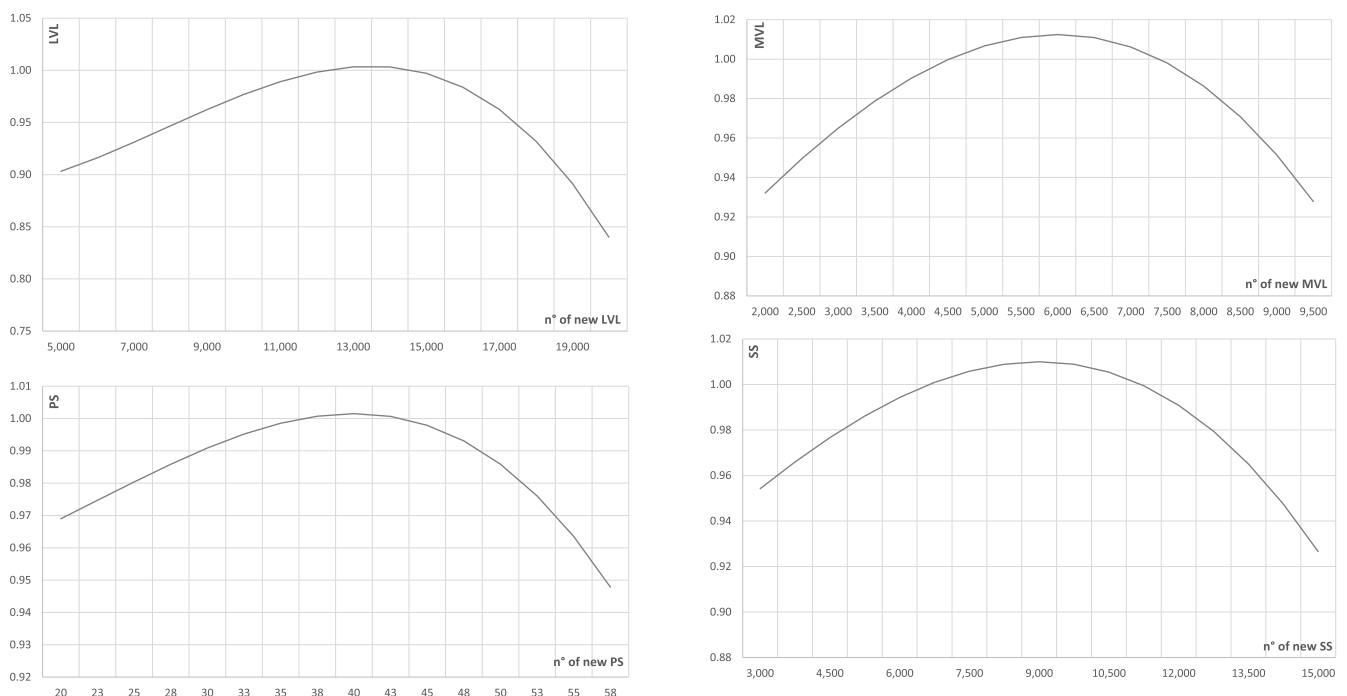
Fig. C.1. Modulation coefficient curve for Primary Substations (PS), Secondary Substations (SS) Medium Voltage Feeders (MVF) and Low Voltage Feeders (LVF).
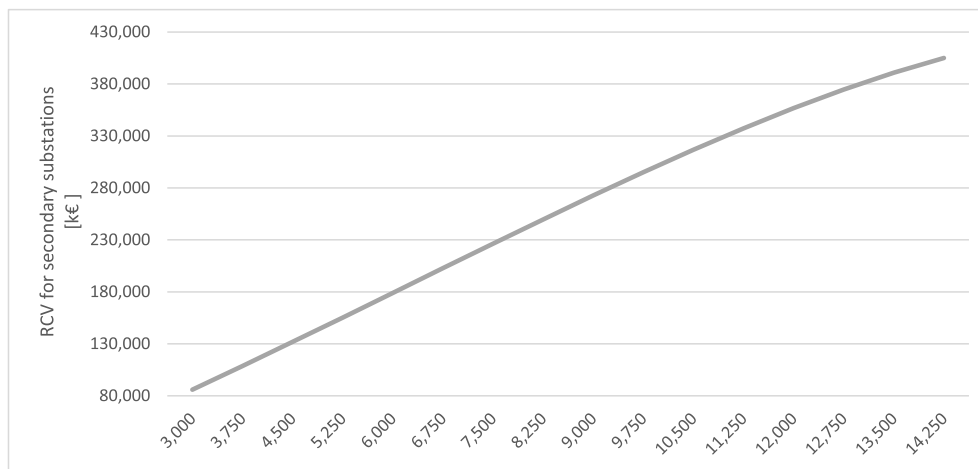
Fig. C.2. Recognised Cumulated Value (RCV) for secondary substations vs. annual realised quantities (*ΔSS*).

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