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COMPETITION AND REGULATION WITH SMART GRIDS

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Abstract

In the last few decades, liberalization and energy transition have deeply reshaped crucial segments of the electric industry (e.g., power generation, energy trading and retail supply) in several countries around the world posing. The development of smart grids is considered a solution to face the new challenges that arise by such dynamics. Our critical analysis of interdisciplinary literature and governmental documents highlights that input-based or output-based regulation is not implementable in the case of smart grids because of unclear definition of smart performance. Thus, we introduce a new definition of grid smartness that is based on the volatility of market energy prices and flows and we develop a simple industrial-organization model of the electric market to analyze the impact of smart grids on competition and to assess the incentives of distribution system operators to invest in smart grids. We find that smart-grid investments foster the aggregate supply of energy, though with controversial effects on suppliers' profits. We also find that the investments in smart grids implemented by the distribution system operators is suboptimal because they fail to internalize positive externalities on energy consumers and producers.
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1 Introduction

The liberalization processes have deeply changed the economic functioning of the electricity sector during the past twenty years in several countries across the world. In the same time span, environmental concerns led governments to pursue policies fostering investments in *renewable energy sources* and *distributed energy resources.* The latter take usually the form of small production plants that inflow power directly into local, medium-voltage distribution grids. The most important economic implication of such dynamics has been the progressive enlargement of the number and types of operators that are involved in the different segments of energy production, trade and distribution.

The arising competitive and regulatory framework is characterized by new technological and economic challenges. The traditional electric infrastructure was not built to support *bi-directional* power flows. Accordingly, power plants are connected with a "fit and forget" approach that does not take into account potential system instability – i.e., supply-demand power unbalances on the grid – that are often associated to investments in distributed and renewable energy sources. Besides security and efficiency considerations, electric system instability may substantially increase market risk for operators, in particular for small firms.

The described dynamics of the electric industry requires infrastructural improvements of transmission and distribution networks. A solution to these new challenges is conventionally identified in technical devices, methods and services (e.g., smart inverters, batteries, bi-directional meters) that may improve the management of the connection of new renewable plants. The introduction of such technological innovations should lead to the development of *smart grids* (SGs) that refers to *"the modernization of the electricity delivery system so that it monitors, protects, and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage transmission network and the distribution system, to industrial users and building automation systems, to energy storage installations, and to end-use consumers, and their thermostats, electric vehicles, appliances, and other household devices"* (Joskow, 2012).

Though SGs are commonly considered a strategic objective of energy policies across the world and, particularly, in the EU countries, a major obstacle to the implementation of effective regulatory frameworks pursuing such objective is the lack of a suitable answer to the simple question: *what makes grids smart*? Answering this question is essential to identify and assess regulatory frameworks and policies and to understand the behaviors of market operators. A first contribution of this paper is the introduction of a new, economically meaningful definition of *smartness.* Based on a critical review of interdisciplinary contributions to the issue and on a narrative analysis of the most common institutional features of electric industries across the world and, particularly, in the EU countries, we identify the final outcome of investments in SGs in *the reduction of market risks faced by market players*, such as production firms, consumers, and distribution system operators (DSOs) who manage local grids. The latter players also play a crucial role in undertaking investments that may improve the smartness of the local distribution grids.

Based on this new definition of SGs and on the narrative analysis of the institutional functioning of the electric markets, we build a simple model of the electric sector focusing on the functioning of local grids. A second contribution of this work is the analysis of the behavior of operators that enter the electricity market to supply energy and of the DSO that manages the local grid and may be interested in investing in SGs. In particular, we analyze the impact of market price volatility and of investments in SGs – that aim at curbing such volatility – on the behavior of energy suppliers. Then we contrast the optimal level of investments in SGs – that would be attainable under the assumption of a benevolent regulator who can verify the quality of investments in SGs – with the level of investments that the DSO implements in a situation where smartness is unverifiable, which hinders any output-based regulation of investments in SGs. Our analysis shows that investments in SGs foster energy supply but not necessarily increase the willingness of firms to enter the market because of the growth of the competitive pressure induced by SGs. Moreover, we show that the DSO tend to under-invest in SGs, with respect to the optimal level that a benevolent regulator would choose, because it fails to internalize the positive effects of such investments on consumers and, possibly, producers. In the discussion of our results, we analyze possible implications in terms of the design of regulatory frameworks that could support investments in SGs and we highlight avenues for future research.

The remainder of the paper is organized as follows. In Section 2 a new definition of SGs is worked out from a review of contributions from different strands of economics and engineering literatures. Section 3 introduces a stylized model of electric market focusing on the functioning of local grids. The behavior of energy suppliers and of the market equilibrium are analyzed in Section 4, taking as given the investments in SGs. Then Section 5 analyzes the decision to invest in SGs by a perfect regulator in contrast to a DSO who operates in a framework where output-based regulation cannot be effectively implemented. Section 6 draws concluding remarks.

2 What Makes Grids Really Smart?

The development of SGs is expected to generate a number of positive effects on the management of electricity networks to face challenges that arise from the new investments in distributed and renewable energy sources. Accordingly, the ultimate objectives of SGs are the integration in the electric system of these new energy resources, the efficient use of energy, the improvement of service quality, the extension of facilities' service-life, the reduction of break-down and maintenance costs of local grids. Given these general objectives, when a local grid has to be considered smart (or smarter than another)? The European Commission defined the SGs as *"energy networks that can automatically monitor energy flows and adjust to changes in energy supply and demand accordingly"*.[1] As it is quite common in governmental documents and engineering literature, such a definition points out the importance of technical tools that allow for an automatic, real-time grid balancing. However, as highlighted in the Introduction, a key feature on new electricity markets is the involvement of a large number of operators, thus a major aspect of SGs has to do with information sharing and co-ordination among operators with different – often opposite and competing – interests. This aspect emerges in the second part of the definition provided by the EU, where *smart meters* are referred to as the technology that allows for required information exchanges.[2] Though SGs and smart meters have been traditionally considered as two distinguished targets by EU policy-makers, the metering infrastructure is an enabling technology for the development of the SGs and the participation of all market operators to the management of local grids and to the new electricity markets.

These arguments explain why ICT technological enhancements of local grids, that support intense and bi-directional information flows, are commonly considered important tools to pursue SGs

[1] https://ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters

[2] "With smart meters, consumers can adapt in time and volume - their energy usage to different energy prices throughout the day, saving money on their energy bills by consuming more energy in lower price periods", https://ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters

(Joskow, 2012; Hall and Foxon, 2014; Luthraa et al., 2014). However, more traditional technological concepts, that are useful to provide ancillary services within local grids (e.g., power storage facilities), seem to be very important to the development of SGs as well. In other words, the characterization of SGs on the basis of technological inputs – i.e., the implementation of an *input-based approach* to SGs regulation – is a very hard task and it may also be misleading. Technologies and agents involved in SGs development are both traditional (e.g., batteries, system operators) and innovative (e.g., prosumers, bi-directional metering). On the top of this, the capacity of such technologies and operators to improve the smartness of the local grid is not an intrinsic characteristic, but rather the result of their precise position in the local system. For example, bi-directional metering, despite its innovation level, could be useless in absence of proper tariffs' design depending on grid instantaneous necessities; batteries can be considered as simple traditional investments if they are not set in the system to smooth intermittent productions.

For these reasons, a few attempts to introduce regulatory frameworks fostering investments in SGs in the EU countries started from practical evidences rather than a general policy design. Joskow (2012) suggested to promote a long term strategy side by side with demonstration and pilot projects. Lo Schiavo et al. (2013) observed how the Italian regulator is fostering SGs investments with a case by case, practical approach [3] According to this perspective, Personal et al. (2014) make an effort to measure the effects of SGs projects, drawing lessons to define an assessment scheme, that is made up by different stages, starting from a base level of technical measurements and arriving – through indicators and objectives – to the abstraction of macro-objectives deriving from the purposes of the SGs project. Macro-objectives are the usual targets for the SGs. The evaluation scheme can be applied to different pilot and demonstration projects to test their contribution in reaching SG targets.[4]

The pitfalls of the input-based approach to regulation of SGs and the prevalence of practical approaches over theoretical methods brings us again to the initial question: *what is really smart*? The most important implication of this dilemma is that the regulators are currently unable to observe, let alone to legally *verify*, if the DSOs – who are typically in charge of investments and improvement plans of local grids – are actually investing to increase the smartness of local grids. Considering these difficulties, a more promising approach is probably output-based regulation, provided that we are able to identify a suitable set of measurable indicators of *smart performance* of local grids.[5]

Some of these indicators derive more or less smoothly from the general objectives of SGs – e.g., the number of small, renewable plants that are connected to the local grid. However, a more fundamental index of smartness should try to measure the capacity of SGs investments to reduce the negative externality of growing investments in distributed power generation from renewable sources on all market operators, that is the increased risk of potential system instability and unbalances between demand and supply of energy on local grids. Besides security and production efficiency considerations, instability is likely to increase the volatility of energy prices which may have perverse effects on market operators, particularly on small firms who are less able to diversify risks. Putting it differently, as far as SGs deliver the benefits highlighted by governmental reports and academic literature, we should expect that a smarter local grid generates a safer – i.e., less volatile – environment in which to invest in the capacity to produce and sell energy, to operate the

[3]The ARERA 39/10 Decree on the promotion of SGs pilot projects is a clear evidence of this action.

[4]In the same spirit, Coppo et al. (2015) proposed a similar approach to Italian SGs projects aiming at getting useful measures for future regulation.

[5]This approach should be based on a process of trial, assessment and standardization of the relevant indexes.

system, as well as to provide ancillary services to such activities. Therefore, we suggest to use *the reduction of the volatility of energy prices, returns and power flows, that is not explained by social, economic, and geographical fundamentals (e.g., consumption trends, seasonality), as an indirect, output-based measure of smart performance of local grids.*

In the model we develop and analyze in the remainder of this work, we focus on medium and small electricity producers. This choice is motivated by two reasons. First, the participation of medium and small operators in the electric market is among the main objectives of governmental strategies, at least in the EU countries, also to stimulate competition and to reward innovation (Erbach, 2017).[6] Second, the demand-response dynamics are particularly relevant to investment decisions of small-scale power plants (Ruester et al., 2014). Another feature that our modelling draws from the institutional setting of real-world electric markets, particularly in the EU countries, is the key role of DSOs in managing local grids where small local producers are connected. The DSO plays as a local monopolist on the local distribution grid, but in most cases it is subject to a detailed regulation (de Joode et al., 2009). Anyhow, the DSO bears the majority of challenges and adapts its behavior to face the effects of wider reliance on distributed and renewable energy sources (Ruester et al., 2014).

3 The Model Setup

We consider a simple structure of the electricity sector that focuses on the economic functioning of medium-voltage, local distribution grids. A local grid is represented by two intertwined markets. On the upstream market, a DSO operates, maintains, and enhances the essential facility – that is the local distribution grid – and affords access to it to a number of firms (e.g., power-generation). On the downstream market, firms directly inflow electricity in the grid in order to sell it to customers.[7]

We assume that the generic local distribution grid features an exogenous, inverse electricity demand function equal to:

$$p(\tilde{Q}) = a - b\tilde{Q} \tag{1}$$

where: a is the maximum price that consumers connected to the grid are available to pay for electricity; b is the variation of the price as reaction to a marginal growth in available electricity, and

$$\tilde{Q} = Q + \theta\epsilon \tag{2}$$

is the electricity flow on the local grid, that is determined by two components: The first component, $Q = \sum_{i=1}^{n} q_i$, is the electricity that actually goes to consumers and is sold by n firms that invested

[6] See for example the 2016 Communication of the European Commission "Clean Energy for All Europeans".

[7] In our analysis, we abstract from other important segments and players featuring the electricity sector in several countries all over the world, such as the operator who manages the electricity markets and the operator that warrants long-range energy transmission, connectedness of national grids, and real-time energy balancing on each and every local distribution grid. For sake of simplicity, in our model, we consider a single all-embracing (local) electricity market where the energy price is determined by the interplay between customers' demand and firms' supply over a relatively long period of time (e.g., one year). Therefore, we abstract from the electricity markets microstructure and, particularly, from the real-time dynamics that bring to the determination of prices in the short-run (e.g., one day).

in the downstream market to operate through the local grid; the second component, $\theta\epsilon$, is stochastic and represents possible demand and supply shocks that may affect electricity flow and price.[8] For the sake of analytical tractability, we assume that ϵ is a random variable that is distributed as a standard normal $\mathcal{N}(0,1)$. Therefore, θ^2 is the variance of the random shocks that generates price variability and, according to the discussion of the Section 2, is an inverse measure of the *smartness* of the local distribution grid.

To focus on our main argument, we assume that firms operating on the downstream market share the same cost function[9] but may differ as regards their attitude toward market risk. The generic firm earns a (random) profit equal to:

$$\pi_i = p(\tilde{Q})q_i - cq_i - K \tag{3}$$

where: $q_i \geq 0$ is the electricity provided by the firm i – which can be interpreted as the capacity deployed by firm i to generate power;[10] $c > 0$ is the marginal cost of power supply; and $K > 0$ is the fixed production cost. Profit randomness derives by price variability. As argued, we assume that firms differ in risk attitude. The intuition is that, because of financial market imperfections, larger – i.e., more diversified and capitalized – firms have deeper pockets than smaller firms. For the sake of simplicity, we represent such heterogeneity in the terms of difference in the *risk aversion* of firms. The generic firm i is assumed to maximize the expectation of an utility function, $u_i(.)$, with a constant risk-aversion parameter equal to r_i. Furthermore, we assume that firms can be ranked in terms of risk-aversion, that is: $r_i = ir$, where r is the risk-aversion parameter of the least risk-averse operators (or financial markets).

Based on the assumption of constant absolute risk aversion and normal distribution of shocks, the objective function of the generic firm can be written in monetary terms as the certainty-equivalent of the expected utility v_i – where $E(u_i(\pi_i)) = u_i(v_i)$ – that is given by the expected profit $E(\pi_i)$, net of the risk premium ρ_i:

$$v_i = \underbrace{(a - bQ - c)q_i - K}_{E(\pi_i)} - \underbrace{\frac{irb^2\theta^2}{2}q_i^2}_{\rho_i} \tag{4}$$

Considering the functioning of the electric markets in the real world, we assume that the main investments in SGs are carried out by the DSO who is responsible for system operations of the local grid. We also abstract from access regulation issues and assume that DSO revenues are exogenous and fixed by the regulator. Thus, the profit of the DSO is:

$$\Pi = T - d\tilde{Q} - I \tag{5}$$

where: T are the exogenous revenues; $d\tilde{Q}$ are distribution-system operating costs with $d > 0$; and $I \geq 0$ is the investment in smart grid. As in the case of downstream firms, also the DSO faces the market risk, given that actual energy flows affect its operating costs. Based on the discussion of

[8]These shocks include exogenous variations of available electricity that are determined by the national transmission operator to fulfil the balancing of demand and supply on all local distribution grids.

[9]By this assumption, we are particularly abstracting from issues that are related to the order of entry in the market of plants exploiting different power-generation technologies (e.g., nuclear, hydrocarbon, photovoltaic, wind).

[10]For example, in the case of photovoltaic plants, this is equivalent to the power-generation capacity that is deployed.

Section 2 and, particularly, on our definition of investments in SGs, we assume that:

$$\theta^2 = \frac{1}{1+I} \in (0,1], \tag{6}$$

more investments in SGs by the DSO, I, dampen the volatility of prices and quantities on the electricity market, θ^2. Following the same argument we made for downstream firms, we assume that also the DSO is risk-averse and maximizes an utility function, $U(.)$, with a constant risk-aversion parameter. Given that the DSO tends to be a large operator in the electricity market, we assume that it has the lowest possible risk aversion r. Thus, the objective function of the DSO can be written in monetary terms as the certainty-equivalent of the expected utility V – where $E(U(\Pi)) = U(V)$ – that depends on the expected profit $E(\Pi)$, net of the risk premium ρ:

$$V = \underbrace{T - dQ - I}_{E(\Pi)} - \underbrace{\frac{rd^2}{2}\frac{1}{1+I}}_{\rho} \tag{7}$$

Finally, given the considered technological and economic structure of the electric sector as described in Section 2, it is appropriate to model it as a Stackelberg leader-follower oligopoly, where the DSO moves first and determines the level of investments in SGs; then downstream firms react to DSO move and choose whether to entry – i.e., to provide electricity through the local grid – and, if they do, they compete *à la* Cournot by setting the quantity of electricity to sell – that is, the power-supply capacity. The generic firm i enters the market if and if only it expects a sufficiently high utility level. Without loss of generality, we assume that this is the case when $v_i \geq 0$. The *marginal firm* that enters the market, n, is such that, at the equilibrium:

$$v_n \geq 0 \quad and \quad v_{n+1} < 0 \tag{8}$$

As usual in Stackelberg games, we determine equilibria by backward induction.

4 Downstream Competition with Fixed Investments in Smart Grids

As a benchmark, first we consider the case where investment in SGs – hence, market volatility – is given. In this case, the DSO plays no active role in the analysis since I (i.e., θ^2) is exogenously given. Therefore we focus on the analysis of the downstream market. Let us consider a generic firm that entered the market. The first order condition with respect to q_i, deriving from the maximization of the objective function (4), is:

$$\frac{\partial v_i}{\partial q_i} = a - bQ - c - b(1 + irb\theta^2)q_i = 0. \tag{9}$$

Considering that all firms decide on the basis of first order conditions similar to (9) and after some algebra, we can write the value function of the firm i's at the optimum, depending on the equilibrium quantity q_i^*:

$$v_i^* = b\left(1 + \frac{irb\theta^2}{2}\right)q_i^{*2} - K. \tag{10}$$

A few results of comparative statics are useful to characterize the behavior of firms and of the equilibrium in the downstream market. As first, we observe that the more energy is supplied by a firm the larger is its market-risk exposure, that is why less risk-averse firms tend to supply more energy in the downstream market.[11] Given this result, it is easy to see that the less risk-averse firms also have larger utilities.[12] Therefore, the marginal firm n is the most risk-averse among firms operating in the downstream market. However, because of the fixed cost, also the marginal firm has to provide a strictly positive quantity of energy.[13]

The simple algebra we used for comparative statics helps us to determine the equilibrium aggregate supply of electricity depending only on parameters:[14]

$$Q^* = \frac{a-c}{b} \frac{\sum_{i=1}^{n} \frac{1}{1+irb\theta^2}}{1+\sum_{i=1}^{n} \frac{1}{1+irb\theta^2}}. \tag{11}$$

Taking the first order derivatives of the equation (11) with respect to all parameters, we easily see that Q^* increases with the maximum willingness to pay of consumers a and decreases in all other parameters – i.e., b, c, i, r ,and θ^2. By inspection of the derivatives with respect to the variance of exogenous market shocks θ^2 and to the basic risk-aversion of market operators r, we have the following result:

Proposition 1 *Given the number of firms that operate in the downstream market, the aggregate equilibrium supply of electricity decreases in the variance of exogenous shocks and in the basic risk-aversion of market operators.*

This result is interesting to understand that a larger market risk (θ^2) or a smaller risk appetite of market operators (larger r), on average, dampens investments in distributed energy generation capacity, since market operators are willing to hedge against market risks. In particular, considering the assumption that $\theta^2 = \frac{1}{1+I}$, we have

Corollary 2 *Investments in smart grids increase the aggregate quantity of energy and reduce, on average, the price at the market equilibrium.*

[11]To see this result, let us consider two firms such that $j < k$. By the respective first order conditions, we have that:

$$b(1+krb\theta^2)q_k^* = a - bQ^* - c = b(1+jrb\theta^2)q_j^*;$$

hence, $q_k^* < q_j^*$.

[12]Substituting the first order condition (9) in the value function (10) and considering that the less risk-averse firms supply more energy, we easily check that $v_k^* < v_j^*$ for any $j < k$.

[13]Substituting the value function (10) in the first condition (8), we obtain:

$$q_n^* \geq \sqrt{\frac{2K}{b(2+nrb\theta^2)}} > 0.$$

[14]Based on the first order condition (9), we have that:

$$q_i^* = \frac{a - bQ^* - c}{b(1+irb\theta^2)}.$$

Then, summing over all i, we obtain the equation (11).

In our stylized setting, the positive effect of investments in SGs described in Corollary 2 may also have an indirect, negative impact on competition in the downstream markets. A larger aggregate quantity (i.e., stronger competition among firms) reduces the energy price and the firms' marginal revenues, on average; as far as the latter effect is strong enough it may counterbalance the reduction in risk-premium and force the marginal firm out of the market.

5 Investments in Smart Grids

In this section, we analyze the costs and benefits of investments in SGs. As a benchmark, we consider the case of an all-mighty, welfare-maximizing regulator who perfectly controls investments in SGs implemented by the DSO in order to characterize the first-best level of such investments (Section 5.1). Then we compare these results with the level of investments that a DSO would implement in absence of an effective regulation (Section 5.2).

5.1 A Perfect Regulation of Investments in Smart Grids

In this section, we derive the optimal investment in SGs that a benevolent regulator would choose to maximize the social welfare, provided that it faces no implementability constraint. As usual, the social welfare is given by the expected value of the sum of the consumer surplus $CS = \frac{E((a-p(\tilde{Q}))Q)}{2}$ and the monetary values of utilities of the downstream firms, $\sum_{i=1}^{n} v_i^*$, and of the DSO, V^*:

$$E(W) = \underbrace{\frac{b}{2}Q^{*2}}_{CS} + \underbrace{(a - bQ^* - c)Q^* - nK - \sum_{i=1}^{n} \frac{irb^2}{2(1+I)} q_i^{*2}}_{\sum_{i=1}^{n} v_i^*} + \underbrace{T - dQ^* - I - \frac{rd^2}{2}\frac{1}{1+I}}_{V^*} \tag{12}$$

where θ^2 is substituted with $\frac{1}{1+I}$. By the maximization of the social welfare function (12) with respect to I, we obtain the following optimization condition:

$$\underbrace{bQ^* \frac{\partial Q^*}{\partial I}}_{MCB} + \underbrace{\frac{a - 2bQ^* - c}{2}\frac{\partial Q^*}{\partial I} + b\sum_{i=1}^{n} q_i^* \frac{\partial q_i^*}{\partial I}}_{MFB} = \underbrace{d\frac{\partial Q^*}{\partial I} + 1 - \frac{rd^2}{2(1+I)^2}}_{NMC} \tag{13}$$

On the left-hand side of the optimization condition (13), we have the net social benefits determined by a marginal growth of investments in SGs that are given by the growth of the consumer surplus, MCB, and by the variation of the sum of utilities of downstream market firms, MFB. As discussed in Section 4, the latter term is not necessarily positive, given that investments in SGs have two opposite effects on operators' utilities – a positive effect driven by a reduction of the cost of risk-taking but also a negative effect linked to the stronger competition that a safer downstream market unleashes among firms (as it is shown by the growth of aggregate energy supply). However, the sum of the two terms on the left-hand side of (13) is positive for reasonable values of parameters.[15]

[15] Rearranging the optimization condition (13), we obtain the following condition

$$MCB + MFB = \left(\frac{a-c}{2} - b\sum_{i=1}^{n} \frac{(1+I)}{1+I+irb} q_i^*\right)\frac{\partial Q^*}{\partial I} + \frac{b}{1+I}\sum_{i=1}^{n} \frac{irb}{1+I+irb} q_i^{*2},$$

that is positive for a size of the energy market – i.e., $a - c$ – that is not too small.

At the first-best optimum, such a perfect regulator would choose the level of investments in SGs that balances the described marginal benefits with the net marginal cost that has to be borne by the DSO – NMC in equation (13) – that is given by the sum of direct marginal investment cost and indirect costs associated to larger energy supply $d\frac{\partial Q^*}{\partial I}$, net of the benefit of reduced risk-premium associated to smaller market fluctuations $\frac{rd^2}{2(1+I)}$.

5.2 Unverifiable Smartness of Local Distribution Grids

As discussed in Section 2, the regulation of SGs investments is to a large extent an open issue. Input-based regulation of SGs is difficult to implement and, possibly, misleading, while output-based regulation largely lacks of any reliable measure of *smart performance* which could be observed and verified by the regulator. Therefore, in this section, we assume that the regulator is unable to effectively regulate investments in SGs because of *the impossibility to verify the smartness of the local distribution grid*.

In absence of any effective mandate from the regulator, the DSO decides the level of investments, I, anticipating downstream firms' decision of power supply. In Section 4, we analyzed the behavior of firms in the downstream market, taking I as given, and we studied the reaction of firms and downstream market equilibrium to changes in the volatility of energy price and, thus, in SGs investments (see Proposition 1 and Corollary 2). Based on the first order condition with respect to I, it is easy to see that the DSO maximizes the expectation of its own utility (7) by putting the right-hand side of equation (13) equal to zero:

$$-NMC = -\underbrace{d\frac{\partial Q^*}{\partial I} - 1}_{mc} + \underbrace{\frac{rd^2}{2(1+I)^2}}_{mb} = 0. \tag{14}$$

As we observed in the discussion of the optimization condition (13) in Section 5.1, a marginal increase of investments in SGs involves direct and indirect monetary costs for the DSO, mc, but also a reward in terms of reduced risk-premium associated to the variability of energy flows on the local grid, mb. When the quality of investments in SGs is not verifiable, the DSO decides a level of I that balances its own marginal costs and benefits, without considering the positive externalities on the consumers and downstream firms – i.e., the sum of $MCB + MFB > 0$. Contrasting this level of investments with what would be the optimal level under perfect regulation – i.e., optimization condition 13, we have:

Proposition 3 *If investments in smart grids are unverifiable, the DSO invests less than the first best level.*

Comparative statics helps us to work out some theoretical predictions that could be checked by empirical analyses (see Appendix). We can, particularly, work out clear-cut predictions as regards the the market size – that is the difference between a and c – and the marginal cost of energy flows for the DSO – i.e., d. When the willingness to pay for energy, a, grows or the marginal cost of power supply, c, decreases the DSO tend to invest less in SGs. The intuition underlying this prediction is that when the size of the market is large – for exogenous, structural reasons – market volatility impact relatively less on the DSO's utility and decisions. Another prediction that we are able to work out is that when the marginal cost of larger energy flows for the DSO, d, is larger, then the DSO would try to hedge against market volatility by investing more on SGs technologies.[16]

6 Discussion

The development of SGs is crucial to face the new challenges of electric industries across the world as determined by the long-run strategic tasks of energy transition and market liberalization. As discussed in the Section 2, the understanding of what is the smart performance of (local) grids is important to assess the real impact of such innovations on the functioning of (new) electric markets and, based on such assessment effort, to shape the regulatory frameworks that may speed up the pace of innovations toward SGs, controlling for possible unintended consequences. In this paper, we introduced a new definition of grid smartness based on the volatility of energy prices and flows. Such a definition, with the help of a very standard industrial-organization model that is based on institutional features of real-world electric markets, allowed us to analyze the impact of investments in SGs on competition among power-suppliers and the incentives of the DSOs to actually undertake such investments.

We confirmed the intuition that investments in SGs have a pro-competitive effect (Bertolini et al., 2018) that is motivated by the reduction of market risk , which is relevant for operators that are risk-averse. We found that such pro-competitive effect is sufficiently strong to determine the growth of aggregate investments in power-generation capacity that are decided by the firms operating in the market. However, such pro-competitive effect is partly counterbalanced by the strategic impact of stronger competition that, by curbing average price and firms' profits, may prevent small and more risk-averse firms to enter the energy market. Building on our simple modelling, future research may theoretically and empirically characterize the size of these two counterbalancing effects for individual firms, particularly for marginal firms, and try to identify under which condition investments in SGs are actually pro-competitive – in the sense that they increase the number of market players – and, conversely, in which cases the growth in aggregate investments in power-generation capacity is linked to market concentration (i.e., to the growth of the market share of larger firms).

The critical discussion of the definition of SGs and our model allowed us to focus on the issue of SGs regulation. While output-based incentive schemes are likely to be more effective than input-based ones in the electric sector (Cambini et al., 2014), these are quite difficult to implement as regards SGs, because of the lack of reliable indicators of smartness which implies that the regulator faces a pervasive output unverifiability. In similar cases, public-private partnerships – i.e., the bundling of different tasks by means of possibly complex institutional agreements – may be a solution (Iossa and Martimort, 2015; Buso and Stenger, 2018). Our contribution opens the avenue to the investigation of a number of further issues regarding the link between competition and regulation in the electric markets. As first, further research should analyze the potential complementarity or substitutability of investments in SGs implemented by the DSO and by other market players (e.g., firms providing energy storage services). Another important issue is the role of structural regulation and its relationship to conduct regulation of the DSO, given that alternative conduct rules of the DSO are likely to perform differently under vertical integration or separation

[16] The impact of changes of other parameters is not clear-cut, unless further specifications are introduced in the model, because of counterbalancing effects.

between the tasks to operate the grid upstream and to use it downstream competing with other firms (Ropenus and Jensen, 2009; Von de Fer and Ropenus, 2017).

Appendix

In this Appendix we carry out comparative statics results regarding the Section 5.2. As first, let us remark that the first order condition of the problem of the DSO (14) is equivalent to:

$$FOC_{DSO} = -\frac{\partial Q^*}{\partial I} - 1 + \frac{rd}{2(1+I)^2} = 0$$

Given the second order condition

$$SOC_{DSO} = -\frac{\partial^2 Q^*}{\partial I^2} - \frac{rd}{(1+I)^3} < 0,$$

the impact of a marginal change of the market size indicator $a - c$ on the optimal I is given by

$$\frac{dI^*}{d(a-c)} = -\frac{\frac{\partial FOC}{\partial(a-c)}}{SOC_{DSO}},$$

and its sign depends on the sign of $\frac{\partial FOC}{\partial(a-c)}$. By

$$\frac{\partial FOC_{DSO}}{\partial(a-c)} = -\frac{\sum_{i=1}^{n} \frac{irb}{(1+I+irb)^2}}{b\left(1+\sum_{i=1}^{n} \frac{1+I}{1+I+irb}\right)^2} < 0$$

we obtain that $\frac{dI^*}{d(a-c)} > 0$. In the same way, by

$$\frac{\partial FOC_{DSO}}{\partial d} = \frac{r}{(1+I)^2} > 0$$

we find $\frac{dI^*}{dd} < 0$.

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