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Competition in smart distribution grids☆

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ABSTRACT

Smart grids are often considered a cornerstone of energy transition and market liberalization in electric industries. From a critical reading of the interdisciplinary academic and governmental literature, we draw a new definition of grid smartness that is based on the reduction of the volatility of market prices and flows. Then, relying on a simple industrial-organization model of the electric market, we analyze the impact of smart grids on competition among energy suppliers and on the incentives of distribution system operators to invest in it. We show that the risk-reduction effect of smart grids pushes firms to supply more energy. However, the latter can be compensated by an indirect competition effect of investments in smart grids which prevents the entry of firms into the market, though the aggregate effect on energy supply is always positive. We also find that distribution system operators under-invest in smart grids because they fail to internalize positive externalities on energy consumers and producers.

1. Introduction

The liberalization processes have deeply changed the economic functioning of the electricity sector during the past twenty years in several countries. In the same time span, environmental concerns led governments to pursue energy transition by 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 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 allow for an optimal control of potential system instability – i.e., supply–demand power unbalances on the grid – that are often associated with investments in distributed and renewable energy sources (Zhang et al., 2009; Bell and Simon, 2018). Besides security and efficiency considerations, electric system instability may substantially increase market risk for operators, particularly 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 (Gangale et al., 2017). The introduction of such 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

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to understand the behaviors of market operators. A first contribution of this paper is the introduction of a new, economically meaningful definition of *smartness*. We performed a critical review of interdisciplinary contributions to the issue and of narrative analysis of the most common institutional features of electric industries across the world and, particularly, in the EU countries. After this overview, we identified 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 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 DSO who operates in a framework where output-based regulation cannot be effectively implemented in contrast to perfect regulation. Section 6 discusses the impact of investments in SGs on competition and the role of regulation in this field. Finally, Section 7 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. Fostering investments in the development of the SG is crucial to reduce grid losses and inefficiencies, particularly those that are connected to the use of non-dispatchable energy sources (e.g., solar, wind). 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. Therefore, the Smart Grid is commonly considered a cornerstone of the Energy Transition Process (Moneta, 2018; European Commission, 2016). Given these general objectives, when should a local grid 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 of 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 interests that are often opposite and competing.[2] 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.[3] 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 enhancements of local grids, that support intense and bi-directional information flows, are commonly considered important tools to pursue SGs (Joskow, 2012; Hall and Foxon, 2014; Luthraa et al., 2014). However, more traditional technological concepts seem to be very important to the development of SGs as well: we refer to investments that are useful to provide ancillary services within local grids, such as power storage facilities. 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 (Cambini and Soroush, 2019).

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.[4] 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.[5]

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

[2] Examples of operators with opposite and competing interests are the DSO and the local suppliers of energy and ancillary services. These players would benefit from a certain degree of co-ordination, however information sharing (e.g., about costs, investment perspectives) would also favor competitors in the market game, and provide additional market power to the DSO.

[3] "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" (from the website: https://ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters).

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

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

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 investments and improvement plans of the DSOs are actually increasing the smartness of local grids. Considering these difficulties, a more promising approach is probably output-based regulation (Cambini et al., 2014), provided that we are able to identify a suitable set of measurable indicators of *smart performance* of local grids.[6]

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 (Hossain et al., 2016). 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 (Cambini et al., 2016). 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 system, as well as to provide ancillary services to such activities. Therefore, we suggest an indirect, output-based measure of smart performance of local grids:

Definition 1. Smart grids are identified by 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).

3. The model setup

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 one of the main objectives of governmental strategies, at least in the EU countries, also to stimulate competition and to reward innovation (Erbach, 2017).[7] Second, the demand-response dynamics are particularly relevant to investment decisions of small-scale power plants (Ruester et al., 2014; Bertolini et al., 2018). Another feature that our modeling 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 much of the challenges and adapts its behavior to face the effects of wider reliance on distributed and renewable energy sources (Ruester et al., 2014).

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 suppliers). On the downstream market, the latter directly inflow electricity in the grid in order to sell it to customers.[8]

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: $p(\tilde{Q})$ is the price that consumers connected to the grid are available to pay for electricity; a is the maximum availability to pay; 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 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.[9] For the sake of analytical tractability, we assume that ϵ is a random variable that is distributed as a standard normal $\mathcal{N}(0, \mathrm{Var}(\epsilon))$, with mean 0 and variance $\mathrm{Var}(\epsilon)$. θ^2 is a positive parameter that, depending on its size, amplifies or moderates the impact of the random shocks on price and, according to Definition 1, 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[10] 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[11]; $c > 0$ 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 absolute 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).

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

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

[8] 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).

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

[10] 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).

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

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:

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

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 Section 2 and, particularly, on Definition 1, 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 absolute 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:

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

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 the downstream firms react to the DSO's 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:

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

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 investments 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:

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

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^*:

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

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 market-risk exposure of a firm increases with its supplied energy, that is why less risk-averse firms tend to supply more energy in the downstream market.[12] Given this result, it is easy to see that the less risk-averse firms also have larger utilities.[13] 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.[14]

The simple algebra we used for comparative statics helps us to determine the equilibrium aggregate supply of electricity depending only on parameters[15]:

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

Taking the first order derivatives of Eq. (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, $Var(\epsilon)$, and θ^2. By inspection of the derivatives with respect to the variance of exogenous market shocks $Var(\epsilon)$ 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 or a smaller risk appetite of market operators, 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.*

In our stylized setting, the positive, aggregate impact of investments in SGs described in Corollary 2 is determined by the direct, *risk-reduction effect* of SGs on the energy supply of individual firms. However, a larger aggregate quantity reduces the energy price and the firms' marginal revenues, thus determining also an indirect, *competition*

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

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

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

[13] 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 $j < k$.

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

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

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

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

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

effect. The latter may be sufficiently strong to prevent the entry of new firms or force some incumbent firms out of the market. As we will see with a numerical simulation in Section 6, depending on specific market conditions, the impact of investments in SGs can be positive or negative on the number of firms supplying energy.

5. Investments in Smart Grids

In this section, we analyze the costs and benefits of investments in SGs. As a benchmark, we derive the level of investments that a DSO would implement in absence of an effective regulation (Section 5.1). Then we compare these results with 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 5.2).

5.1. Investments in Smart Grids in the absence of regulation

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). By the maximization of its own utility (7) with respect to I, we obtain the following optimization condition:

$$-NMC = \underbrace{-d\frac{\partial Q^*}{\partial I} - 1}_{mc} + \underbrace{\frac{rd^2Var(\epsilon)}{2(1+I)^2}}_{mb} = 0. \tag{12}$$

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. According to the optimization condition (12), the structural features of downstream markets (i.e., a, c, b, $Var(\epsilon)$ and i) affect the DSO's incentives to invest in SGs[16] and should, in turn, be considered by regulators when setting their policies. We will come back to this issue in the Section 6.

The most important implication of the previous analysis is that, when the smartness of the local grid is not verifiable, the DSO decides a level of I that balances its own marginal costs and benefits, without considering potential positive externalities on the consumers and downstream firms. In the next subsection, we delve into this issue.

5.2. 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, $\sum_{i=1}^{n} \upsilon_i^*$, and of the DSO, V^*:

$$E(W) = \underbrace{\frac{b}{2}Q^{*2}}_{CS} + \underbrace{(a - bQ^* - c)Q^* - nK - \sum_{i=1}^{n} \frac{irb^2Var(\epsilon)}{2(1+I)} q_i^{*2}}_{\sum_{i=1}^{n} \upsilon_i^*}$$
$$+ \underbrace{T - dQ^* - I - \frac{rd^2Var(\epsilon)}{2}\frac{1}{1+I}}_{V^*} \tag{13}$$

where θ^2 is substituted with $\frac{1}{1+I}$. By the maximization of the social welfare function (13) with respect to I, we obtain the following optimization condition:

$$\underbrace{bQ^*\frac{\partial Q^*}{\partial I}}_{MCB} + \underbrace{\frac{a - 2bQ^* - c}{2}\frac{\partial Q^*}{\partial I} + b\sum_{i=1}^{n} q_i^* \frac{\partial q_i^*}{\partial I}}_{MFB} = \underbrace{d\frac{\partial Q^*}{\partial I} + 1 - \frac{rd^2Var(\epsilon)}{2(1+I)^2}}_{NMC} \tag{14}$$

On the left-hand side of the optimization condition (14), we have the net social benefits determined by a marginal increase 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: the risk-reduction effect but also the indirect, competition effect that a safer downstream market unleashes among firms. However, the sum of the two terms on the left-hand side of (14) is positive for reasonable values of parameters.[17] At the first-best optimum, the level of investments in SGs balances the described marginal benefits with the net marginal cost that has to be borne by the DSO – NMC in Eq. (14) – that is given by the sum of direct marginal investment cost and indirect costs associated to larger energy supply $d\frac{\partial Q^*}{\partial I} + 1$, net of the benefit of reduced risk-premium associated to smaller market fluctuations $\frac{rd^2Var(\epsilon)}{2(1+I)}$.

Contrasting this level of investments with what would be the optimal level chosen by the DSO in the absence of regulation — i.e., optimization condition (12), we have:

Proposition 3. *If investments in smart grids are unverifiable, the DSO does not internalize the positive externalities on the consumers and downstream firms and invests less that the first best level.*

6. Discussion

In the analysis of previous sections, we highlighted the controversial role of investments in SGs on the risk-return trade-off that is faced by individual energy suppliers and the DSO. In this section, we first delve into this issue relying on a numerical simulation of our model, then we draw implications for the regulation of investments in SGs.

We numerically simulate our model to understand how the trade-off between the risk-reduction effect and the competition effect is affected when two key parameters that are associated with our definition of grid smartness change. The first parameter is, of course, the underlying volatility of market price $\mathrm{Var}(\epsilon)$, which increases the benefit of

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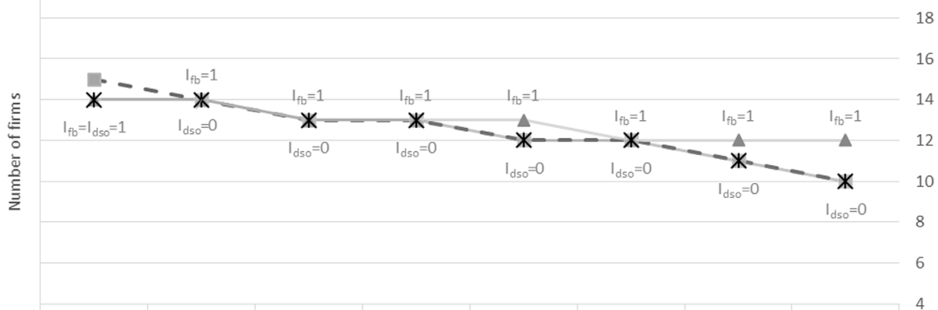
[16] For instance, as the willingness to pay for energy, a, grows or the marginal cost of power supply, c, decreases, the DSO tends to invest less in SGs. The intuition is that when the size of the market is large – for exogenous, structural reasons – market volatility impacts relatively less on the DSO's utility and decisions.

[17] Rearranging the optimization condition (14), we obtain the following condition

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

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



i	1	2	3	4	5	6	7	8
Diff. in Q (FB-B)	11,00	16,32	18,75	20,20	22,22	21,53	22,93	24,17
Diff. in Q (DSO-B)	11,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
■ n. of firms (B)	15	14	13	13	12	12	11	10
▲ n. of firms (FB)	14	14	13	13	13	12	12	12
✱ n. of firms (DSO)	14	14	13	13	12	12	11	10

Fig. 1. Comparative statics on the degree of firms' heterogeneity.

investments in SGs. The second parameter is i, which measures the heterogeneity among energy suppliers in terms of risk aversion and it is likely to have an impact on the strength of the competition effect.[18]

In the benchmark case (B), there is no investment in SGs ($I = 0$). The baseline setting features a potential market of 19 energy suppliers and the following values of the model's parameters: $a = 100$, $b = 0.4$, $c = 5$, $d = 50$, $K = 50$, $r = 0.5$, $i = 1$, and $\mathrm{Var}(\epsilon) = 2$.[19] We solve the model numerically, and we find the equilibrium levels of q_i^*, Q^*, and v_i^*.[20] Only firms with $v_i^* \geq 0$ enter the downstream market. Then we run two comparative statics exercises (see the dotted line with squares in Figs. 1 and 2). First, we increase the heterogeneity of firms i (see Fig. 1), which brings to a reduction in the number of firms that enter the market because of the growth of the risk aversion of the marginal ones. Second, we reduce to 1 and, then, increase beyond 2 the market volatility $Var(\epsilon)$ (see Fig. 2). In this case, larger market volatility brings to a growth of the number of firms that enter the market because of lower supplied energy and higher average price.

In the second numerical exercise, we simulate the first best case (FB), in which the benevolent social planner chooses the (possibly positive) level of I that maximizes the social welfare (see the light-gray line with triangles in Figs. 1 and 2).[21] The dynamics of firms' entry is not qualitatively different with respect to the B case, however the optimal investment in SGs is positive in all market configurations we consider and determines a significant impact both on the number of firms that enter the downstream market and, as theoretically predicted, on the total supply of energy. Broadly speaking, for lower values of heterogeneity i and market volatility $Var(\epsilon)$, the optimal investment in SGs tend to reduce the number of firms on the market, while for larger heterogeneity or market volatility I provides an additional incentive to entry.

Our third numerical exercise simulates the case where the DSO decides the level of I to maximize its utility (see the dark-gray line with crosses in Figs. 1 and 2). Again, the fundamental dynamics of firms' entry is qualitatively similar to the B case. However, as theoretically predicted, the DSO tends to have an incentive to under-invest in SGs with respect to the FB case because of the very cost of investment. Under some specific circumstances, this first-order effect is compensated by other effects: when heterogeneity is low (see Fig. 1), many firms enter the market and energy supply is large, then the DSO invests in I to foster the competition effect and restrict market entry; in a similar way, when the market volatility increases (see Fig. 2), the DSO uses the investment in SGs to curb its own risk-premium.

The numerical analysis affords also the characterization of the reaction of firms to investments in SGs. Given market volatility, Fig. 1 shows that the risk-reduction effect of investments in SGs prevails for high values of i, while the competition effect prevails when heterogeneity is low. Looking at Fig. 2, we can observe that, when the variance is low, the competition effect prevails and the investment in SGs reduces the number of firms entering in the downstream market, while the risk-reduction effect prevails for sufficiently high values of $Var(\epsilon)$.

7. Conclusion and policy implications

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. SGs are expected to empower all agents of the electricity markets, open new markets and stimulate the creation of new market agents.

As discussed in 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 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. For example, the intermittencies of renewable energy sources determine a negative externality in terms of grid instability risk. In other words, such technologies reduce the smartness of electricity grids. Investments in energy storage assets and the creation of capacity markets have been proposed in the literature as an appropriate policy to hedge against such a risk (Banshwara et al., 2017; McPherson and Tahseen, 2018). Some efforts to identify the effects of new market structures on local grid functioning are also coming from pilot projects and practical applications.[22] In this

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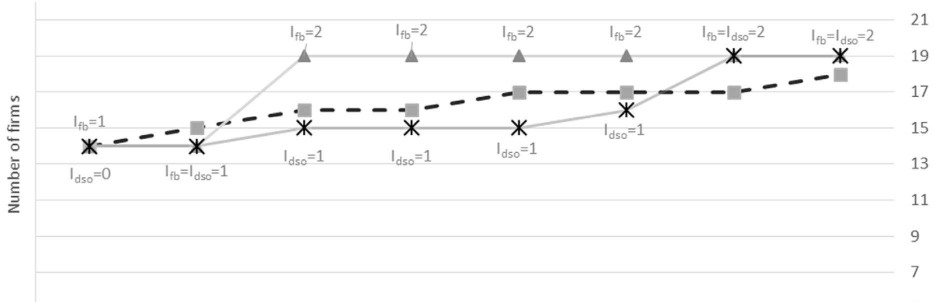
[18] We have also studied the effects of other parameters, but heterogeneity and uncertainty provide the most interesting insights, given the purpose of our work.

[19] Considering these model's parameters, the demand elasticity in the numerical example ranges between −0.78 and −0.17. These values are in line with results of the empirical literature that estimate price elasticities for electricity demand equal to −0.21 in the short term, and −0.61 in the long term, with a range between about −2.00 and −0.004 (Labandeira et al., 2017; Espey and Espey, 2004).

[20] Simulations are obtained by the software Matlab.

[21] Technically, by computing the welfare associated to each level of I, we find the welfare-maximizing I. In our simulation, I can take any discrete integer value. However, we checked that our qualitative results do not significantly change if we consider different discrete steps (e.g., $I \in \{0, 0.2, 0.4, \dots\}$).

[22] For example, the SmartNet Project – financed by the EU program Horizon 2020 – analyzed new practical solutions to integrate local renewable energy



Var(ε)	1	2	3	4	5	6	7	8
Diff. in Q (FB-B)	7,36	11,00	24,37	28,96	31,82	35,23	38,21	1,00
Diff. in Q (DSO-B)	0,00	11,00	14,72	17,78	19,28	22,58	38,21	39,78
■ n. of firms (B)	14	15	16	16	17	17	17	18
▲ n. of firms (FB)	14	14	19	19	19	19	19	19
✱ n. of firms (DSO)	14	14	15	15	15	16	19	19

Fig. 2. Comparative statics on the degree of demand uncertainty.

perspective, the key to perform an effective regulation, aiming at the optimal grid management, is not only to understand the effects of technologies and market services, but also the capacity to measure such effects in order to balance possible trade-offs and design appropriate subsidies or alternative incentive schemes.

In order to fill such a gap, our main contribution is to derive a new definition of grid smartness that can be operationalized as a measure for the assessment of alternative investments and market structures and, thus, to implement an effective regulation. Building on a critical review of the literature, we proposed to identify SGs *by 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)*. Relying on a standard industrial-organization model that is based on institutional features of real-world electric markets, we showed how such a definition can be used 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 that is motivated by the reduction of market risk, which is relevant for operators that are risk-averse. We found that the risk-reduction effect is sufficiently strong to determine the growth of aggregate power-generation capacity. However, such risk-reduction effect is partly counterbalanced by the competition effect, that – by cutting average price and firms' profits – may prevent market entry of small and more risk-averse firms. By means of numerical simulations, we found that the risk-reduction effect prevails when either the demand uncertainty or the degree of heterogeneity among firms are large. Moreover, our theoretical and numerical analyses show that, because of positive externalities of SGs, the DSO does not have sufficient incentives to optimally invest in it.

Admittedly, our contribution and findings are theoretical, but they have clear policy implications. First, we introduced a definition of SGs that can be operationalized by indicators of volatility of electricity prices and flows. Compared to our simple model, such an exercise is to a large extent the subject of future research. Moreover, the translation of our definition into a measurable indicator of smartness is likely to be rather technical and sensitive to the technological and institutional settings of electric markets of different countries. However, constructing such indicators will afford researchers and policy-makers with the possibility to assess regulatory frameworks and policies to foster investments in SGs, as well as to calculate what we can call the "smartness footprint" of single investments, alternative market frameworks, and so on. For example, such indicators would allow to calculate the negative externality cost of intermittencies determined by a specific photovoltaic plant or the positive externality benefit of a new capacity facility.

Our model provides an idea of how such a smartness indicator could be used by regulators. In the paper, we discussed the limitations of (current) input-based regulations on SGs and we argued that better definitions of the performance of SGs could pave the way to effective, output-based regulations. For example, by designing an incentive scheme for DSOs that rewards *smarter* grids (i.e., the reduction in volatility of electricity prices and flows), the regulator may implement a policy that foster research and innovation in SGs. Also, the introduction of reliable indicators of smartness, by removing the current, pervasive non-verifiability of grid smartness, paves the way to new regulatory solutions, such as Public–Private Partnerships (PPPs) for SGs. PPPs are commonly used in the energy, agricultural and forestry sectors to enhance innovation in contexts where regulations based on verifiable outcomes are not feasible due to the high level of uncertainty (Iossa and Martimort, 2015; Buso and Stenger, 2018). In particular, in the energy sector, PPPs usually take the form of Energy Performance Contracts (EPCs) whereby governments are able to enhance energy efficiency of public buildings or cities. The introduction of an indicator of smartness would allow to extend the use of EPCs to the implementation of investments in SGs involving different players, such as the DSOs (and TSOs), the local energy suppliers, and prosumers.

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 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 DSOs, given that alternative conduct rules of the DSOs are likely to perform differently under vertical integration or separation 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). Finally, with this study we show how SGs regulation should consider features of downstream markets. The future research should focus more on the link between technologies, economic behaviors, and grid smartness and identify the regulatory frameworks that are conducive to optimal investments in SGs.

CRediT authorship contribution statement

Marina Bertolini: Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing. **Marco Buso:**

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sources, reshaping markets and the relationship between the Transmission System Operator (TSO) and the DSOs (see http://smartnet-project.eu/, last accessed February 14th, 2020).

Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing. **Luciano Greco:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, 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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