

The Economics of the Smart Grid

Luciano De Castro Joisa Dutra

Abstract—Smart Grid (SG) technologies may bring substantial advantages to society, but the required investments are also sizable. This paper establishes a framework for examining the issues related to the SG, and highlights some of the difficulties in establishing a mechanism for paying SG costs. In particular, we show that generators will lose profits as a direct effect of demand response initiatives, and most of the benefits of SG cannot be easily converted into payments.

I. INTRODUCTION

The electricity industry is about to experience deep reforms, and the adoption of a “smart grid” is one of its main drivers. A Smart Grid (SG) involves the use of sensors, communications, computational ability and control to improve the overall functionality of the electric power delivery system [1]. Its main expected benefits are increased reliability of supply, environmental protection and a potential lowering in production and capacity costs [2].

Even though smart grids are potentially very beneficial, the related costs are substantial. According to [2], the total costs of implementing the Smart Grid in US range between \$338 and \$476 billion over 20 years. An important question is how this cost will be borne and this is the central question of this paper.

In general, it is assumed that the costs of implementing the smart grid should be supported by consumers. According to this view, customers are the ultimate payers, all the other agents being mere “intermediaries”. Even if we accept this reasoning, costs should not need to be uniformly (or proportionately) allocated to customers, since they will not reap benefits in a uniform or proportional manner. If this sort of payment scheme is forced, we envision strong resistance by the consumers. This is indeed already happening [3].

On the other hand, even the notion that the costs should be passed through to consumers is not completely granted. For instance, many technological innovations were acquired and paid for by companies, which were able to recoup their investments by selling better products to their clients. These clients were willing to pay for the offered products because they perceived these new products as advantageous. One can then ask: if the benefits of smart grids are real—as we believe they are—why are they not borne directly by the companies and offered as an option to customers? One of the objectives of this paper is to show the difficulties in finding ways to pay for necessary investments for the SG.

For this, we establish a general economic framework for looking at the main SG issues. After an overview of

these issues in section II, we begin at section III, with a description of SG-interested agents’ utilities. With this, we are able to describe an idealized social planner problem in section IV. The solution of such a problem is out of the scope of this paper, but the discussion is useful to highlight aspects of the problem. With simplifying assumptions, we are able to decompose this problem in two: the distribution problem (section V), and the generation problem (section VI). Section VI shows that all generators are likely to lose with demand response (DR) programs, even those working in the base. This seems to contradict the usual intuition that base generators can earn more by producing more with the “valley filling” expected impact of DR. Section VII concludes.

II. OVERVIEW OF SMART GRID ISSUES

The smart grid is an electricity network that is able to integrate in an intelligent manner all electricity users and providers, while improving economic efficiency and reliability of supply and addressing the growing concerns for the environment. Smart grids include an Automated Metering Infrastructure (AMI), a high level of automation of the grid, distributed generation, storage and an IT infrastructure [4], [5], [6]. SG is expected to lead to sizable benefits, but will also require substantial investments.

Fig. 1 shows EPRI’s estimated annualized value of each benefit of the smart grid [7]. More recently, EPRI [2] updated its estimates to include the benefits of EE and DR, among other factors. The total figure amounts to \$1.3 to \$2 trillion.¹

On the other hand, the most important investments must be done in the distribution (\$ 231 to \$ 339 bi) and transmission (\$82 to \$90 bi) networks [2]. The high required investments may involve public funds. In this spirit the Energy and Independence and Security Act (2007) and the American Reinvestment and Recovery Act (2009) allow for grants that can be allocated to smart grid related investments. Resorting to public funds aims at making smart grid technology available to a broader group of people than the ones who could pay for it. The rationale for this is that a given geographic area may gather people whose change of habits could point to positive net benefits at the same time that some other consumers’ habits could be such that they would not justify the high required investments. But the economic deployment involves making the technology available to all the people located in a given area.

Thus we are dealing with a public goods dilemma and consumers may have incentives to understate their true willingness to pay for the smart grid.

¹We were not able to find independent confirmations of these figures.

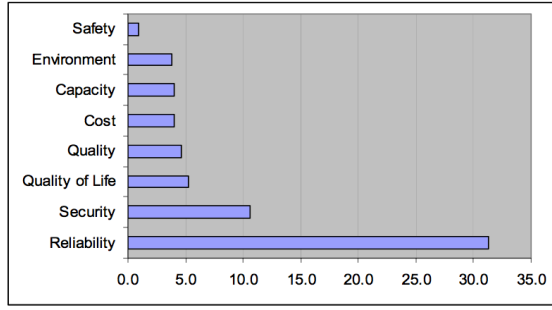


Fig. 1. Estimated Annualized Value (\$ Billions) of each attribute [7].

The energy efficiency level that can be achieved through smart grids also involves a sensible increase in the role of demand response. Consumers may be exposed to pricing mechanisms that are more sophisticated but that may improve economic efficiency. The bulk of residential consumers face flat electricity prices that depart from the underlying cost structure to produce and deliver electricity. The pricing mechanisms that may be implemented in a smart grid environment more closely resemble the ones that have been advocated by economists for decades. Additionally, dynamic pricing schemes coupled with technology may grant considerable peak load reductions deferring investments. This belief is supported by the experimental evidence that has been observed in pilot programs [8]. However, the pervasive use of dynamic pricing is not straightforward. It would depend on some changes at the regulatory level.

Standard pricing mechanisms such as price caps and rate of return that are the basic methodologies embody a direct link between sales on a unit basis and revenues as well as profitability. This link stands in conflict with the goal of energy efficiency. Hence the extensive use of dynamic pricing depends on the decoupling between sales and revenues, a theme that is sensible from the political point of view.

Another issue is the need to educate consumers on opportunities and risks. So far, a lot of tension has emerged from the lack of consideration for the customer's role. Different choices imply distinct levels of effectiveness and adherence in the consumers' response. The utilities are much more concerned with the savings in operational costs, even though these may not be enough to fund the required investments whereas there are some examples of regulators asking for utilities to make more effort to prove that there are net benefits and how these benefits can be achieved.

In this context non-pricing levers may be as relevant as pricing ones. There is a broad consensus that social and psychological effects do affect consumers' behavior [9]. Behavioral economics now stands as part of the economist's toolkit to create incentives to achieve efficiency gains. Since the bulk of demand side management strategies make use of technologies - such as smart meters - that rely on consumers' reactions, it is extremely relevant that these strategies' net benefits be carefully evaluated before a broad scale deployment. This sort of analysis grant legitimacy to the rolling out

of smart grids even at the regulatory level.

Regulators and policy makers are not willing to allow that all SG costs are charged directly to consumers. This aspect is even more critical due to a higher technological obsolescence of smart grid assets as compared to the physical one.

The above mentioned aspects are only some of the challenges that must be addressed in order to grant a smooth transition to a smart grid framework. This paper is just a first approximation to the subject of the economics of SG.

III. A MODEL OF SG PARTIES' INTERESTS

In this section, we will introduce a model for the SG parties: consumers, distribution companies, generators and society. The last party includes environmental interests not restricted to consumers. In principle, we should also consider transmission companies, which have significant importance for the SG. Because their role in our analysis is very similar to that of distribution companies, we encapsulate both types of firms in the last term. The reader should keep this in mind to avoid confusion.

We consider a general representation of uncertainty: there is an abstract probability space (Ω, Σ, \Pr) . A random outcome $\omega \in \Omega$ determines prices, allocations, etc, but it is not fully observable. In any case, our discussion and treatment of uncertainty will be limited, since it is not central for the aspects that we discuss.

A. Consumers

Let $C = \{1, \dots, N\}$, with $N \gg 2$, denote the set of consumers and T the time set considered: it can be an interval of 24 hours, a week or month, or even something as simple as $\{0, 1\}$, denoting off-peak and peak periods. A function $l_i : T \times \Omega \rightarrow \mathbb{R}$ denotes the (random) consumption of power by consumer i , that is, $l_i(t, \omega)$ is the consumption of individual i when the state of nature is $\omega \in \Omega$. For simplicity, we will omit ω in most of the paper and write just $l_i(t)$, although this yet refers to a specific realization of the demand. We hope no confusion arises. Note that in principle we allow $l_i(t)$ to be negative; in this case, consumer i would be providing power to the grid instead of receiving it. This could be the case if the consumer has production capacities. The possibility that consumers produce energy and inject it in the grid is actually one of the reasons for allowing smart grid technologies. Let \mathcal{D} denote the set of (measurable) functions $l : T \times \Omega \rightarrow \mathbb{R}$.²

The consumer cares about the failures of the electric system, which can occur from two different sources. First, we can have events in which the demand for power is higher than the supply (either because the demand is too high or because some generators have failed). Second, we can have failures in the system for transporting electricity (distribution or transmission). Both kind of failures impact the consumer in the same way, but they are reduced through different

²For some technical applications, it will be convenient to impose more structure in the set \mathcal{D} of functions considered. For instance, we could restrict \mathcal{D} to be equal to the set of L^2 functions in T . This restriction simplifies some technical conditions and does not seem overly restrictive, but it will not play a role in our analysis. In particular, if $T = \{0, 1\}$ as we mentioned above, this restriction is without loss of generality.

actions (investment in capacity or in the grid). Since this paper focuses on the smart grid, we will focus attention only on failures in the grid. Therefore, let $r \in [0, 1]$ be the level of reliability of the service, meaning that the distribution system (transmission plus local distribution) is properly working a fraction r of the time. We assume that r does not depend on the consumption level, to the contrary of usual treatments of reliability [10]. This is reasonable for distribution failures, but it is not completely true: an increase in the demand for energy may increase the probability of failure in the grid.

Let $v_i : \mathcal{D} \times [0, 1] \rightarrow \mathbb{R}$ represent the utility experienced by the consumer depending on its consumption and the level of reliability. Similarly, let $p : \mathcal{D} \rightarrow \mathbb{R}$ denote the total price paid by the consumer.³ Note that this pricing functional is defined on functions (power demanded for each hour). Therefore, this functional is more general than what is usually found in the literature.⁴ This generality helps to convey more clearly the ideas; we are not necessarily advocating for the adoption of more complicated pricing schedules. Note also that the consumer does not pay for the reliability of the service, as it is usually the case. The consumer utility is given by:

$$u_i(l_i, r) - p(l_i). \quad (1)$$

It is useful to describe some examples of the pricing schedules. The last ones are directly related to SG.

- 1) *Fixed Tariff* is the mostly adopted pricing mechanism for residential consumers. It involves high levels of cross subsidies and inefficiency. Since consumers face a flat price there is underconsumption in off peak hours (when prices are lower than costs) and overconsumption in peak hours. In this case, there is fixed tariff $p_e \in \mathbb{R}_+$ that defines the total price of energy. On top of that, the consumer also pays a fee p_d for being connected to the distribution grid, that is,⁵

$$p(l_i) = p_d + p_e \int_T l_i(t) dt. \quad (2)$$

- 2) With *Inclining Block Rates*, the consumer pays a different tariff for each bracket of its consumption. That is, there are points $0 = x_0 < x_1 < \dots < x_k$, tariffs $p_0, p_1, \dots, p_k \in \mathbb{R}_+$ and a piecewise linear function $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ defined recursively by: $f(0) = 0$ and if $x \in [x_j, x_{j+1}]$, $f(x) = p_j(x - x_j) + f(x_j)$, which defines the price functional:

$$p(l_i) = p_d + f\left(\int_T l_i(t) dt\right). \quad (3)$$

³The notation allows, in principle, that the price and utility functionals depend on the random functions $l_i : T \times \Omega \rightarrow \mathbb{R}$. It makes more sense, however, to think that they depend on specific realizations of the load, that is, on the functions $l_i(\cdot, \omega) : T \rightarrow \mathbb{R}$, for a fixed ω . Note also that $p(l_i)$ can be negative. This could correspond make sense if the consumer turns out to be a net provider of energy through its solar panels, for instance.

⁴For instance, [10] describes the prices as a function of the hour and the level of power required. This pricing function could not make a distinction between shapes of consumption, for instance, as the one considered here would allow.

⁵In this and in the subsequent equations, we assume that T is an interval so that the integrals make sense. It is very easy to adapt these expressions for the case in which $T = \{0, 1\}$. For instance, (2) would be just: $p(l_i) = p(e_i^0 + e_i^1)$ for some $p \in \mathbb{R}_+$.

- 3) In *Time of Use (TOU)* tariffs, there are two or more time intervals (peak and off-peak) and a correspondent number of tariffs, $p_0, \dots, p_k \in \mathbb{R}_+$ and time periods, T_0, \dots, T_k such that $\cup_k T_k = T$. These tariffs are set ex ante and may significantly vary from real time prices. Hence TOU rates are not considered dynamic and are considered poorly effective. The price functional (for two time intervals) is:

$$p(l_i) = p_d + p_0 \int_{T_0} l_i(t) dt + p_1 \int_{T_1} l_i(t) dt. \quad (4)$$

- 4) *Seasonal Rates* are pricing schemes that set rates that are different for different times of the year. Consumers face higher charges for usage in peak months and less during non-peak months. It is, therefore, formally identical to TOU mentioned above (sometimes it is considered just as an instance of TOU); the only difference being that the time sets there correspond to periods inside a day, while in Seasonal Rates, the periods are sequences of days.
- 5) In a *Real Time Pricing (RTP)* mechanism consumers' charges are related to the underlying spot prices at the time of consumption. It is used the real-time price $p(t) \in \mathbb{R}_+$ obtained for each $t \in T$ in the spot market. The total price is thus given by:

$$p(l_i) = p_d + \int_T p(t) l_i(t) dt. \quad (5)$$

B. Distribution Company

The distribution company D needs to decide the level of investment in the smart grid, y .⁶ The level of the investment y impacts the potential benefits of SG, which we capture as an impact in the reliability of the grid r and the possibility of implementing demand response, as we will discuss below.

The distribution company has total cost $c_d(y, r)$ of providing the level of reliability r at the level of investment y .⁷ The idea is that with a higher y , the cost of providing r is smaller, that is, the function $c_d(y, r)$ is not necessarily additively separable.

C. Generator

For simplicity, we assume there are two types of technology for producing energy: standard and clean, which will be denoted, respectively, by l_s and l_c . The generators have costs $c_s(l_s)$ and $c_c(l_c)$ of producing energy by these technologies. Naturally, we should have

$$l_s + l_c = \sum_{i \in C} l_i. \quad (6)$$

Note that y enters directly into the cost of reliability, but it does not enter into the cost of producing energy. In this case, how can we accommodate the notion, mentioned above,

⁶As we emphasized earlier, in our analysis "distribution company" includes firms specialized in transmission.

⁷It may seem more natural to write this cost as $y + c_d(r)$. Our point is that $c_d(r)$ is also a function of y —with a small investment in the smart grid, the distribution company will have to spend more (in personnel, for instance) to achieve the same level of reliability. Therefore, the cost would be $y + c_d^y(r)$, which is just a particular form of $c_d(y, r)$.

that one of the advantages of the SG is the reduction in the production costs? Our point is that this is *not a direct* benefit of the SG. This benefit occurs only through a difference in the costs and the technologies associated to the production of $l = l_s + l_c$. There are two ways in which SG could affect this production. First, it could affect the shape of l by altering the load profile through shaving the consumption at peak through demand response. Even if the total energy is not reduced, we would have a lower cost because cheaper technologies could meet the demand in a higher percentage of the time, reducing the need of high cost technologies.⁸ Second, SG allows consumers to inject electricity in the grid, either through some distributed generation in their premises (*renewable generation*) or through the batteries of their plug in electric vehicles (PEV). In this way, the need for power, especially at peak times, is reduced.

D. Society

The society has an interest in the production of energy by clean technologies. Therefore, it suffers a disutility $-v(l_s)$ for the energy produced by the standard pollutant technologies. Note that we are implicitly assuming that the production technologies that some consumers may have are clean. This comes from the fact that the energy produced by consumers, if it is above their needs, enter as negative sign and, therefore, contributes to reduce $l = \sum_{i \in C} l_i$ and, therefore, l_s .

IV. THE BENEVOLENT SOCIAL PLANNER PROBLEM

It is expected that SG would allow this smoothing of the consumption through different pricing schedules, which are not possible with standard technologies. That is, the pricing function $p: \mathcal{D} \rightarrow \mathbb{R}$ belongs to a set $\mathcal{P}(y)$ of possible pricing functions, which depends on the level y of SG investments. For simplicity, we may assume that the functions in $\mathcal{P}(y)$ are differentiable.

Let us consider first the problem of a market designer or a benevolent social planner, who wants to choose a pricing schedule $p \in \mathcal{P}(y)$ that covers the costs:

$$\sum_{i \in C} p(l_i) \geq c_d(y, r) + c_s(l_s) + c_c(l_c). \quad (7)$$

Given a pricing schedule $p \in \mathcal{P}(y)$, the consumer would choose l_i in order to maximize (1), that is, the utility of the consumer will be given by:

$$U_i(p, r) \equiv \max_{l_i \in \mathcal{D}} u_i(l_i, r) - p(l_i). \quad (8)$$

Note that we did not include a cost for the consumer to choose l_i in face of more complicated $p \in \mathcal{P}(y)$, which is argued by some consumer advocates as relevant.

Given y, r and a price $p \in \mathcal{P}(y)$, the social welfare is:

$$W(y, r, p) \equiv \sum_{i \in C} U_i(p, r) - v(l_s) + \left\{ \sum_{i \in C} p(l_i) - [c_d(y, r) + c_s(l_s) + c_c(l_c)] \right\},$$

⁸This consumption change could also reduce the need of building more generators for reserve, which is also a factor for reducing costs in time.

where the terms in the second line refer to the joint profit of distribution and generators. Given that the determination of the prices need fixed levels of y and r , it is useful to define

$$S(y, r) \equiv \max_{p \in \mathcal{P}(y)} W(y, r, p) \text{ subjected to (6) and (7)}$$

as the social planner's pricing problem. Finally, the actual social planner problem is to choose y and r in order to maximize $S(y, r)$.

The description above is useful for establishing a framework for understanding the questions and problems discussed before. However, at this level of generality, the social planner problem is extremely difficult to solve. Thus, next we impose some simplifying conditions for proceeding with the analysis.

A. Assumptions

Our first set of assumptions allow us to break the social planner problem in several parts, making it more manageable. The first assumption refers to the consumer.

Assumption 1: The utility function of each consumer is additively separable, that is, we have $u_i(l_i, r) = v_i(l_i) + \bar{v}_i(r)$.

Although this assumption may seem restrictive, it will be satisfied by a monotonic (log) transformation if u_i depends on the product of (a function of) r and l_i ; for example if $u_i(l_i, r) = r \int_T l_i(t) dt$.⁹

The next assumption is much more common in practice.

Assumption 2: The pricing functional has to have a clearly specified part for the distribution company and a part for the generation, that is, $p(l_i) = p_d + p_g(l_i)$, so that instead of (7), we have:¹⁰

$$\sum_{i \in C} p_d = N p_d \geq c_d(y, r); \text{ and} \quad (9)$$

$$\sum_{i \in C} p_g(l_i) \geq c_s(l_s) + c_c(l_c). \quad (10)$$

It requires that the tariffs specify different payments for the electricity and for the distribution companies. This is actually the stated policy in Europe and has been adopted by a number of states in US as well.

B. Separation of the problem

Let us define the following function:

$$W_g(y, r, p) \equiv \sum_{i \in C} \left[\max_{l_i} (v_i(p) - p_g(l_i)) \right] - v(l_s) + \left\{ \sum_{i \in C} p_g(l_i) - [c_s(l_s) + c_c(l_c)] \right\}$$

⁹There is a caveat, however. In general, monotonic transformations do not change the optimal allocation, but the consumer problem (8) depends also on the price, in the traditional "partial equilibrium" fashion. Therefore, the optimal choice may not be invariant to monotonic transformations of the utility.

¹⁰The distribution tariff p_d could be different for different classes of customers, but we abstain from making this distinction.

It is now easy to obtain our first result.

Proposition 1: Under assumptions 1 and 2, the social planner problem can be separated in the following problems:

$$S_d(y, r) \equiv \max_r \sum_{i \in C} \bar{v}_i(r) - c_d(y, r) \quad (11)$$

subjected to (9);

$$S_g(y, r) \equiv \max_{p \in \mathcal{P}(y)} W_g(y, r, p) \quad (12)$$

subjected to (6) and (10);

and

$$\max_{y, r} S_d(y, r) + S_g(y, r). \quad (13)$$

Now, we can appreciate some subtle consequences of Assumption 2. Under this assumption, the social planner cannot transfer funds from energy consumption to the payment of the grid. If the available assessments are correct, a substantial part of the benefits of the smart grid are realized through the energy markets and, therefore, are not being properly captured by the above scheme. This may suggest that this separation should not be the preferred route, but we will argue below that even if we try to capture some of the energy market benefits in order to finance the smart grid, we will face substantial difficulties. Before going into this analysis, however, we will examine in more detail the problem (11), which we will call from now on the *distribution problem*.

V. DISTRIBUTION PROBLEM

The distribution problem has a clear and easy solution, as the following proposition establishes.

Proposition 2: Assume that \bar{v}_i and c_d are differentiable and that $r = 0$ cannot be optimal in problem (11). Then, the solution r^* to problem (11) satisfies:

$$\sum_{i \in C} \bar{v}'_i(r^*) = \frac{\partial c_d(y, r^*)}{\partial r}. \quad (14)$$

Proof: This comes directly from the assumptions of differentiability and interiority conditions applied to (11). ■

Note that the choice of r^* to satisfy (14) requires unrealistic knowledge from the social planner. It has to know not only the marginal utilities of all consumers in the society but also the marginal cost of the reliability, given each level of the smart grid investment y . It is natural to ask whether (14) could be implemented through some market mechanism. For instance, assuming y fixed, the social planner could try to fix a price $p_d(r) \equiv \frac{1}{N} c_d(y, r)$ for the level r of reliability and expect that the individuals choose to pay for their optimal share of reliability. Unfortunately, this will not work.

Proposition 3: Assume that \bar{v}_i is differentiable, increasing and concave and that consumers choose a level of reliability using a pricing schedule satisfying (9). Then the level r demanded by the individuals will be sub-optimal.

Proof: In this case, consumer i would maximize $\bar{v}_i(r) - p_d$. Note that a price scheme satisfying (9) does not vary

with r . Therefore, each customer would choose a level of consumption r_i^* satisfying:

$$\bar{v}'_i(r_i^*) \leq 0,$$

with equality if $r_i^* > 0$. Since \bar{v}_i is increasing and $r \in [0, 1]$, this means that $r_i^* = 1$ for every consumer, which does not satisfy (14). ■

In some sense, the result in the above proposition seems artificial, because it comes directly from the fact that the consumers' contributions do not vary with the costs of providing reliability. However, we see this proposition as useful to highlight the importance of charging for reliability. On the other hand, the problems are yet not solved if we introduce a reliability price, as the following proposition considers.

Proposition 4: Assume that \bar{v}_i is differentiable, increasing and concave and $\frac{\partial c_d(\cdot, \cdot)}{\partial r} > 0$. Assume that each customer pays her demanded reliability r_i , but consumes the aggregate reliability $r = \sum_{i \in C} r_i$. The level r demanded by the individuals will be sub-optimal.

Proof: Each consumer's problem will be

$$\max_{r_i} \bar{v}_i \left(r_i + \sum_{j \neq i} \{r_j\} \right) - p_r r_i.$$

Let \bar{r}_i denote the optimal choice of consumer i and $\bar{r} \equiv \sum_{i \in C} \bar{r}_i$. Then, $\bar{v}'_i(\bar{r}) \leq p_r$, with equality if $\bar{r}_i > 0$. From the distribution company perspective, we must have $p_r \leq \frac{\partial c_d(y, \bar{r})}{\partial r}$. If we put $\delta_i = 1$ if $\bar{r}_i > 0$ and $\delta_i = 0$ if $\bar{r}_i = 0$, then $\sum_i \delta_i \left[\bar{v}'_i(\bar{r}) - \frac{\partial c_d(y, \bar{r})}{\partial r} \right] = 0$. If $\bar{r} > 0$, this implies that $\sum_{i \in C} \bar{v}'_i(\bar{r}) > \frac{\partial c_d(y, \bar{r})}{\partial r}$, which shows that (14) is not satisfied and \bar{r} is sub-optimal. ■

By this proposition, we see that there is a “public good” problem in the provision of reliability. Essentially, each consumer “free rides” on the reliability level provided by the others.

In a public goods setting the market failure is related to the fact that economic agents that make decisions based on their willingness to pay for the good end up achieving a provision level that is lower than the choice that would emerge from a social planner's choice. The social planner would provide a level that would amount to a social willingness to pay for the public good.

In a decentralized mechanism consumers have incentives to understate their true willingness to pay because if the good is provided it is not possible to exclude them from consumption and their consumption will not lower other consumers' availability for the good. Once consumers face binding budget constraints, a higher utility can be achieved allocating their income to other private goods.

In a smart grid setting the increase in reliability that can be provided does not straightforwardly allow exclusion. This is due to the fact that there are economies of scale to a certain level in the sense that costs to grant reliability of supply in a given area can be lower for an additional consumer. Hence

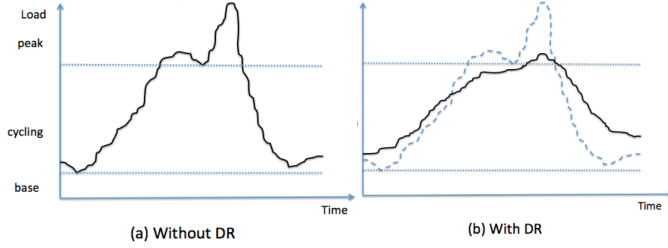


Fig. 2. Change in the load shape with DR

from the political point of view it may not be feasible to shut down consumers.

There are well known economic solutions to the problem of public goods, such as Lindahl prices and taxes [11].

Lindahl prices require that each level of reliability be treated as an exclusive good, that could be rejected from the individual. In our situation, this means that if an individual chooses a reliability $r_i < r_i^*$, the distribution company would have to shut off that consumer deliberately, so that he or she would consume indeed r_i . This seems unlikely to be implemented.

Another solution is to try to set a tax that will charge consumers so that the public good will be funded through the collected revenue. In this setting every consumer would be taxed by the social planner in terms of his consumption of reliability. The desired amount would be such that the marginal rate of substitution would equal the marginal cost of providing reliability. The optimality condition would demand that the state chose taxes $t_i(r_i) = p_i^*(r_i)$ where p_i^* would be the Lindahl prices. This would amount to an unrealistic requirement of information from the state's point of view.

VI. GENERATION PROBLEM

We call problem (12) the generation problem. As we have observed before, the smart grid investments enter into this problem only through the change of energy demanded (demand response or DR) and the flexibility of incorporating renewable energies into the grid.

The first effect is depicted in Fig. 2. What one hopes with DR is that the peak generators will be less active, while the cycling and base generators will be more active. Since the latter generators produce at a lower cost than the former, the result is a reduction of overall costs of electricity production.

However, it is less clear what is happening with the revenue for each kind of generators. For instance, it seems that a generator that operates in the base will have the opportunity to produce for longer periods. This indeed is likely to occur because some of the energy consumed in the peak, during which the base generator is already at full capacity and could not provide that energy, could now be provided by those generators. Since these generators will work for longer periods, it seems reasonable to infer that they will have higher profits and revenues. Moreover, the peak generators would certainly lose. These are, indeed, the standard intuitions. As we are going to see, they may be

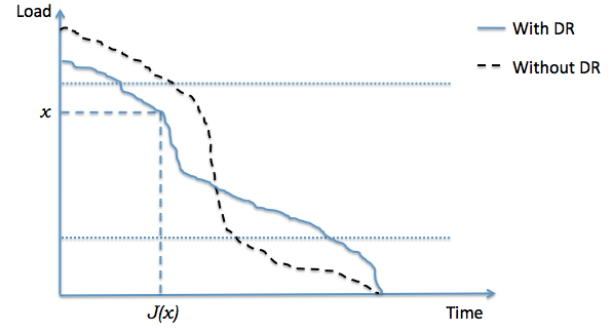


Fig. 3. Load-duration curves with and without DR

wrong. For clarifying this issue, we need to formalize the generators' costs, the spot price, and the DR consequences on the load function.

A. The generators' costs and the spot price

We assume that the spot price is determined by the marginal cost of the highest cost technology used to meet the total load (demand) $l(t)$. The cost for attending the load x is $c(x)$, where c is assumed twice differentiable, increasing and convex. Therefore, the total cost introduced before is:

$$c_s(l_s) = \int_T c(l_s(t)) dt.$$

Our results in this section can also be easily adapted to the case of a finite number of different generators. That is, we could have assumed that there were m generators, and generator $j = 1, \dots, m$ has costs c_j , satisfying $0 < c_1 < c_2 < \dots < c_m$, and capacity k_j , so that whenever the load is between $L_j \equiv \sum_{i=1}^j k_i$ and L_{j-1} , the price is determined by the marginal generator j , that is, it is equal to c_j .

B. DR impact on the load function

The expected effect of the introduction of DR programs is to shift consumption from the costly periods (e.g. peak), to the less costly (e.g. base). This implies that the shape of the load is made "smoother": the valleys are filled, while the peaks are shaved. This is sometimes called the "ironing" of the load function. We were not able to find a formal definition of this expected change, so we will propose one. To understand our motivation, it will be useful to depict the loads shown in Fig. 2 in terms of the load-duration curve (Fig. 3). A load-duration curve specifies, for each level of load x , the number of hours $J(x)$ that the customers' load exceed x .

Now, although the demand in each load level may reduce or increase, DR is expected to reduce the load in the high cost (high demand) periods and perhaps increase it in low cost (low demand) periods. The following definition captures this effect.

Assumption 3: With DR, the energy demanded from higher cost generators is lower. That is, for every $L > 0$,¹¹

$$\int_L^\infty \Pr(l^0(t) > u) du \geq \int_L^\infty \Pr(l^1(t) > u) du. \quad (15)$$

Notice that we have not required that the total energy consumption remains the same. As they reader may have noticed, if we add the extra assumption that the total consumption (integral of the load) does not change, this is just Second Order Stochastic Dominance.

C. Effects of DR on generators' revenues and profits

The following proposition shows that the intuition cited at the beginning of this section is not correct.

Proposition 5: Under assumption 3, the revenue and the profit of all generators decrease with DR.

Proof: The revenue of generator x , which operates if $l(t) > x$, is:¹²

$$\begin{aligned} \int_x^\infty c(u) dF^0(u) &= -[c(u)(1 - F^0(u))]_x^\infty \\ &\quad + \int_x^\infty c'(u)(1 - F^0(u)) du, \end{aligned}$$

Since $1 - F^0(\infty) = 0$, the revenue from energy is equal to:

$$c(x)(1 - F^0(x)) + \int_x^\infty c'(u)(1 - F^0(u)) du,$$

where the first term is the cost of generator x , while the second is its profit. Now, define $H^0(x) \equiv \int_x^\infty (1 - F^0(u)) du$. Then, generator x 's profit is:

$$-[c'(u)H^0(u)]_x^\infty + \int_x^\infty c''(u)H^0(u) du.$$

Since $H^0(\infty) = 0$, this simplifies to:

$$c'(x)H^0(x) + \int_x^\infty c''(u)H^0(u) du.$$

A similar expression holds for the case with DR. Since (15) is just the assumption that $H^0(u) \geq H^1(u)$ for all u , then we have the conclusion. ■

Proposition 5 contradicts the usual intuition that base operators, that may have the opportunity of produce more under DR, will gain from the consumption shifts. For this, we have assumed that the total demand does not increase with DR (this is implicit in assumption 3). It may be the case that the total demand increases with DR, because consumers have access to cheaper energy. It is not clear if this can indeed be an effect of DR, but in any case, Proposition 5 shows that this could be the only way generators could benefit with DR.

In the above analysis, we have not taken in consideration the ancillary service revenues that a generator may provide. For a peak generator, these services can be a substantial part of its revenues and profits. If the introduction of DR increases

the need of ancillary services—because of an increase in the volatility of the load, for instance, which is likely to occur [12]—then the direct beneficiaries from DR will be exactly peak, not base generators.

This analysis focused on a fixed configuration of the industry, that is, it abstracted from the introduction of new generators. If the argument in the previous paragraph is indeed valid, then it may well be the case that we can have more peak generator construction than the current understanding of DR leads to expect.

Another implication of the analysis in this section is that it does not seem reasonable to expect that generators will be called to bear some of the costs of smart grid implementation. Since DR is an important part of the effects of the smart grid and it has a negative impact on them, they will probably resist any attempt at sharing its costs.

D. The Reduction in the Required Investments

Estimates of the benefits of DR and Energy Efficiency (EE) are between \$192 and \$242 bi according to [13].¹³ It should be noted, however, that these figures refer to the difference between the investments needed in capacity expansion in a baseline scenario without SG and a scenario where SG would allow for less capacity.

In principle, these gains could be used to calculate payment by consumers, but there is a problem. No matter the path is chosen, it will be just one path; the other one will be counterfactual. Therefore, we will never have a *factual* number that could be used to define payments. It would be almost impossible to know what each consumer *would have paid* if the SG were not implemented. Also, with the provision that the consumer has to benefit from DR—as in the cases in which the consumer has the option to choose between a fixed tariff and real time pricing—the appropriation of these gains are harder, as we clarify next.

E. The problem of consumer's freedom of tariff choice

In environments with consumer choice over tariffs, the new pricing rules have to give benefits to the consumers, otherwise they will not be chosen. A consequence of this freedom is that a number of customers will prefer to maintain the fixed tariff, perhaps undermining the benefits of the SG. To see that, consider the following:

Definition 1: A consumer is called “representative” or “typical” if its demanded load l_i has the same shape as the total load, that is, $l_i(t) = \alpha l(t)$, for some $\alpha > 0$. In the case of discrete generators, the definition is a little bit more permissive: a consumer i is typical if for every $j = 1, \dots, m$,

$$\begin{aligned} h_{ij} &\equiv \Pr([L_{j-1} < l_i(t) \leq L_j]) \\ &= h_j \equiv \Pr([L_{j-1} < l(t) \leq L_j]), \end{aligned}$$

where L_j denotes the sum of capacities of all generators from 1 to j .

¹¹Hereafter, we will use superscripts 1 and 0 to represent the situation with and without DR, respectively.

¹² $F^0(x)(F^1(x))$ denotes the probability that $l^0(t)$ ($l^1(t)$) is below x .

¹³These numbers were used in [2] to obtain the estimates mentioned in the introduction.

Assumption 4: Two pricing schedules are available to the consumers: fixed tariff and real time pricing. The fixed tariff p_e is calculated so that the total energy consumed equals the cost of producing it, that is,

$$p_e \int_T l(t) dt = \int_T p(t) l(t) dt. \quad (16)$$

Note that this assumption is not necessarily realistic. The establishment of fixed tariffs may require considerations much more complex than the simple equation (16) suggests. In any case, the assumption should be considered in relation to the definition of representative consumer. Together, they yield the following:

Proposition 6: If a typical consumer has a cost $\varepsilon > 0$ of watching real time prices and controlling his or her consumption accordingly, he or she will strictly prefer the fixed tariff.

Proof: By the definition of typical consumer and (16), we have

$$p_e \int_T l_i(t) dt = \int_T p(t) l_i(t) dt.$$

Therefore, the typical consumer is indifferent between the fixed tariff and the real time pricing, from the point of view of pure costs (without considering the costs of monitoring prices and consumption). Under the assumption, this consumer would strictly prefer the fixed tariff. ■

This result suggests that many consumers would prefer the fixed tariff. This can be detrimental for the expected benefits of the DR, because some consumers will naturally opt out of its impacts. Besides reducing the intended benefits of DR, this can also reduce the “pool” of consumers that could be charged (in an incentive compatible way) for the SG. Indeed, as we mentioned before, one could try to use the benefits with a lower energy tariff to compensate for the SG investments. The above proposition suggests that the number of consumers for which this compensation would be “incentive compatible” is limited.

Of course, some of these problems could be solved by eliminating the “freedom of choice,” and imposing unique pricing schemes. While this may indeed be done—and it seems likely to occur—, a significant part of the consumers may be made worse off with DR. In fact, this has already been observed in pilot projects [14]. If those consumers rationally anticipate this, they may try to block such initiatives through political activism, leading to a less than efficient penetration of SG.

F. The environmental problem

So far, we have not analyzed the environmental part of the problem. As we have described the incentives, this enters in the social planner problem as just an externality for the society. Therefore, it suffers all the problems of public goods, already discussed in section V. In sum, even representing a substantial benefit, the environmental gains cannot be used to pay for SG investments.

VII. CONCLUSION

This paper aims to shed some light on the ongoing discussion regarding the deployment of smart grid technologies. We truly believe that this may represent a deep technological innovation in the electricity industry. Even though estimated net benefits are considerably high, the underlying costs are quite expressive. However, the idea that net benefits should be the reference may be misleading, for two reasons.

First, it shades the fact that, while the overall benefit for the society may be positive, some parties may lose with the innovations associated with SG. For instance, we have shown that all existing generators and some consumers are likely to lose with DR. Those parties may try to block the deployment of these technologies and this may create problems for a successful implementation of the SG.

Second, some of these benefits have the characteristics of “public goods,” which are known to be hardly provided through markets at an efficient level. Given the trend for deregulation and reliance on market-oriented measures, the public-good characteristic of SG will likely create problems for its desirable level of implementation.

All these problems require serious efforts of finding solutions. By describing the nature of these problems and offering an economic framework for analyzing them, we hope this paper contributes to attract a broader audience’s attention to these issues and to the choices involved for achieving a welfare improving allocation.

REFERENCES

- [1] C. Gellings, *The smart grid: enabling energy efficiency and demand response*. CRC, 2009.
- [2] EPRI, “Estimating the costs and benefits of the smart grid,” Electric Power Research Institute, Tech. Rep., 2011.
- [3] L. Madigan, “An experiment too expensive for consumers,” *Chicago Tribune*, June 21, 2011.
- [4] S. Massoud Amin and B. Wollenberg, “Toward a smart grid: power delivery for the 21st century,” *Power and Energy Magazine, IEEE*, vol. 3, no. 5, pp. 34–41, 2005.
- [5] P. Fox-Penner, *Smart Power: Climate Change, the Smart Grid, and the Future of Electric Utilities*. Island Pr, 2010.
- [6] M. Negrete-Pincetic and S. Meyn, “Intelligence by design for the entropic grid,” in *IEEE PES 11: Power Energy Society General Meeting*, 2011.
- [7] EPRI, “Power delivery system of the future—a preliminary estimate of costs and benefits,” Electric Power Research Institute, Tech. Rep., 2004.
- [8] A. Faruqui and S. Sergici, “Household response to dynamic pricing of electricity: a survey of 15 experiments,” *Journal of Regulatory Economics*, pp. 1–33, 2010.
- [9] H. Allcott and S. Mullainathan, “Behavior and energy policy,” *Science*, vol. 327, no. 5970, p. 1204, 2010.
- [10] R. Wilson, *Nonlinear pricing*. Oxford University Press, USA, 1993.
- [11] A. Mas-Colell, M. Whinston, and J. Green, *Microeconomic theory*. Oxford University Press New York, 1995.
- [12] M. Roozbehani, M. Dahleh, and S. Mitter, “Volatility of power grids under real-time pricing,” *Arxiv preprint arXiv:1106.1401*, 2011.
- [13] M. Chupka, R. Earle, P. Fox-Penner, and R. Hledik, “Transforming america’s power industry: The investment challenge 2010-2030,” *The Brattle Group*, 2008.
- [14] A. Faruqui and J. Palmer, “Dynamic pricing and its discontents,” *Regulation, Fall*, 2011.