Distributed Load-Shedding in the Balancing of Electricity Markets

Claude Crampes, *IDEI and TSE*, and Thomas-Olivier Léautier, *IAE and TSE*

Abstract-- **Thanks to "smart grids", consumers will gradually become active players in electricity markets, especially by voluntarily decreasing their consumption when receiving scarcity messages from the market operator. For a fast and efficient transition to a more dynamic industry, the regulatory and pricing scheme used both for the endowment of consumers with curtailment rights and the exercise of the options must decentralize the socially optimal dispatching. In particular, the options must be acquired at the retail price. This price is to be an income for the suppliers of energy who have defaulted or who have been withdrawn from the initial dispatch. When exercised, the options of load shedding are to be rewarded at the wholesale price paid by defaulting producers. The volume of the options must be allocated to each consumer taking into account his ability to manipulate information on his profile of consumption and his ability to modify the profile.**

Index Terms-- **Energy efficiency, Load management, Industrial economics, Power generation economics, Supply and demand, Innovation management**

I. Introduction

THE need to balance the electric power system in real time to account for the non-storability of electricity is the main explanation for vertical integration in the sector, either structurally or contractually. Non-storability also explains the secondary role traditionally given to demand in the physical balancing of the power system. However, the inclusion of Information and Communication Technologies (ICT) in "smart networks" suggests drastic changes in the near term, providing consumers with a more active role, thus making the whole system more efficient.

Balancing the electric power system has long been a centralized matter, usually achieved by:

- large outages or rolling and selective blackouts, methods still daily experienced in many developing countries;
- the installation of operational reserves called to ensure a given level of security of supply, often defined in terms of blackout duration.

Nevertheless, large consumers are interested in a better control of their energy bills. Since their electricity withdrawal has a significant impact on total demand, producers have progressively proposed contracts including negotiated curtailment clauses. Under this contractual arrangement, the value of electricity signals the time and duration of selective curtailments. When negotiating a contract to supply low price electricity, the electricity producer buys an option on the production of negawatt-hours (NWh)[1] (load shedding) that are cheaper than the production of the additional megawatt-hours (MWh) necessary to balance the system without consumers' participation. For its part, a client that can decrease his consumption pays a lower bill under the condition that he will either stop consuming energy or switch to alternative sources upon request.

The total load-shedding potential is much larger than the capacity offered by large consumers.[2] Every consumer can be disconnected at low damage for dates, durations and quantities varying with his equipment and preferences. The barrier is the cost of implementation. The installation of ICT devices for the remote control of consumption equipment by specialized service providers overcomes this obstacle. It is now technically possible to produce large-scale distributed load-shedding. Additionally, to meet environmental constraints and requirements in energy saving, the active participation of consumers is increasingly seen as politically desirable, especially voluntary load-shedding. For a successful participation of consumers in system balancing, technology is not sufficient. It also takes economic rules allowing to decentralize the efficient dispatch. This is the topic we address in this paper.

In section II we use an elementary discrete model to present the basic problem of how to decentralize efficient demand decreases in the resolution of an energy imbalance. We show that the possibility of exercising an option to discontinue consumption can approximate the optimal production peak, provided that this option is acquired at the retail price and rewarded at the spot price. Interruptible consumers appear as suppliers of NWh, competing against the suppliers of additional MWh. Section III reconsiders the same problem using a more general framework. We assume that the surplus function and the cost function of electricity are continuous. Therefore we can derive and analyze the functions of electricity supply, electricity demand and shedding supply. Again, we show that consumers must pay the retail price of the no-consumption options they exercise and that they must be remunerated at the price of the real-time market. The firms responsible for the necessity to re-dispatch must acquire at the price of the real-time market the electricity they sell at the retail price. In Section V we discuss how to quantify the load-

C. Crampes is Professor of Economics at Toulouse School of Economics, 31000 France (e-mail: ccrampes@cict.fr).

T. O. Léautier is Professor of Management at the University of Toulouse, and researcher at the Toulouse School of Economics, 31000 France (e-mail: thomas.leautier@iae-toulouse.fr).

[1] Joskow and Marron [4] and [5]

[2] For an overview on how to implement demand response, see Borenstein *et al*. [1]. Torriti *et al*. [7] give details about demand response experiences in some European countries.

shedding capacity. When he signs his electricity contract, the consumer rationally anticipates that he will be able to use some of the purchased energy options not for consumption but for sale to the system operator. With linear price contracts this expectation provokes oversubscription, only limited by the cost of the shedding equipment and the uncertainty on the real-time price.

II. MW *VS.* NW TO CORRECT UNEXPECTED IMBALANCES

Consider a competitive day-ahead market in equilibrium at price *p*. The Market Operator (MO) informs all bidders about their rights and duties at this price:

i) consumers who have bid below *p* and producers who have bid above *p* will not be served and called;

ii) the others will have to withdraw or inject what they have committed to.

Let *u* be the use value of one MWh of electricity and *c* the production cost. Denoting by *n* the last demand bid served and by *m* the last supply bid called at equilibrium, given that the efficient ranking of bids by the MO follows the merit order, we have that $u_n \geq p \geq c_m$, where $u_{n-1} > u_n$ and $c_m < c_{m+1}$.

A. Optimal adjustment

One of the *m* producers supposed to be active at equilibrium informs the MO that he will fail to deliver 1MWh. There are two elementary rebalancing solutions:

- either the MO calls the last non planned producer to supply the missing MWh : it will cost c_{m+1} ,
- or the MO asks the planned consumer with the lowest electricity valuation to reduce its demand by 1MWh ; the cost is the lost gross surplus u_n .

It is clear that the least costly adjustment rule is:

call producer $m+1$ if $c_{m+1} < u_n$

curtail consumer n if $c_{m+1} > u_n$.

B. Decentralized adjustment

Assume that there is no organized market for rebalancing. The defaulting producer is obliged by law to find a solution by himself. If he organizes an auction between available producers to buy the missing quantity, competition will drive the adjustment price to $p_a = c_{m+1}$. With this solution, the defaulting producer is like a supplier without generation assets buying from a wholesale market and selling at price *p* as he had committed. His net loss is $p_a - p = c_{m+1} - p > 0$. The second possibility is to propose a compensation *r* to one of his customers because she will not be served. The producer prefers to buy the missing production if $r > c_{m+1} - p$ and to propose a deal to a consumer otherwise. This decision is in line with the optimal adjustment portrayed in paragraph *A* only if $r = u_n - p$. Therefore, the power-cut deal must be concluded with customer *n*, the one with the lowest willingness-to-pay who holds the right to consume. Moreover *n* must be only compensated for her *net* surplus. Consequently, if customer *n* has already paid the market price *p* to the defaulting producer and if she is called to rebalance the system, the producer must pay her u_n so that she is rewarded $u_n - p$ for no consuming.

In the near future, real-time markets will have candidates to load-shedding competing against reserve producers to solve market imbalances. Big consumers will intervene directly whereas small consumers will delegate decision to aggregators. If we want this pure market adjustment process to decentralize the optimum, candidates to rebalancing must satisfy the following necessary conditions:

- producers shall have the capacity to produce in hand,
- consumers shall own rights on the quantity they intend to renounce, which means they pay to acquire them at the consumption price *p*.

On such a market, competition between consumers who can decrease withdrawals and producers who can increase injections gives the equilibrium price $p_a = \min(u_n, c_{m+1})$.

The basic mechanism we have examined so far can be analyzed more rigorously using standard microeconomic tools. This has been done by Chao (see [2]) who shows how voluntary load-shedding helps to correct the inefficiency of time unvarying electricity prices. Chao emphasizes the necessity to impose that consumers pay the same retail price for the electricity they do consume and the electricity they renounce, contrary to what is done in some countries where put options are not paid.[3] In the next section we go deeper into the study of the rebalancing process when some capacity of production is missing whereas it was announced as available.

III. EFFICIENT RE-DISPATCHING AND FINANCIAL CLEARING

When it comes to solve an unexpected imbalance between supply and demand, the producers able to increase their output and the clients able to consume less than their profile are competing against each other. The source of the problem can be an unexpected large consumption. We instead focus on the role of demand response when a producer who had been registered in the merit order fails to fulfill its commitments. The timing is as follows: *i*) the MO plans the optimal dispatch at the level q^*, *ii*) in real time it appears that the producers who had committed to provide energy in the interval $\left[\underline{q}, \underline{q}+D\right]$ where $\underline{q}+D < q^*$ fail to do so. How does the MO best organize the re-dispatching?

A. Optimal re-dispatching

Let $U(q)$ be the aggregate gross surplus from the consumption of the quantity *q*. It is a continuous and differentiable, increasing and concave function. Let $C(q)$ be the aggregate cost of producing the quantity *q*. It is a continuous and differentiable, increasing and convex function. If the absence of produced energy is the only element to be taken into account, re-dispatching consists in solving

$$\max_{q^c, q^g} U(q^c) - \left[\int_0^{\underline{q}} C'(q)\,dq + \int_{\underline{q}+D}^{q^g} C'(q)\,dq\right] \text{ s.t. } q^c = q^g - D$$

[3] As Ruff [6] says " Normal markets allow consumers to sell what they do not consume as long as they own it, but no rational market pays consumers for not consuming what they do not own, even if they can prove that they would have bought it but didn't. Paying somebody because they might have bought more but didn't is as illogical, unfair, and inefficient as buying the Brooklyn Bridge from somebody who thought about buying it but decided to sell it instead." See also Hogan [3].

where q^c is the quantity consumed and q^g the quantity produced. The optimal quantity consumed is therefore q^{**} such that $U'(q^{**}) = C'(q^{**}+D)$ and $q^{**}+D$ is the quantity produced. The result is illustrated in Fig. 1.

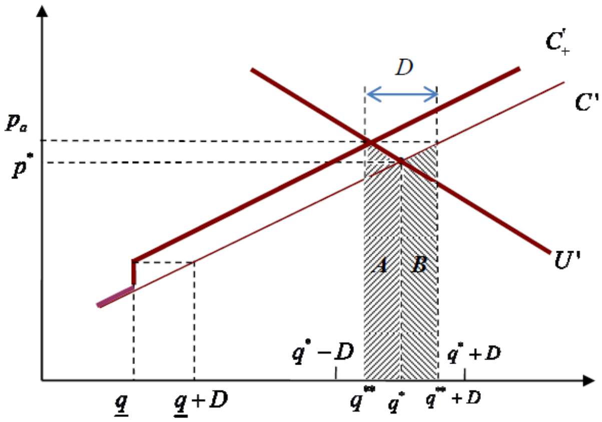

Fig. 1. Optimal redispatching after a production default.

The missing quantity D forces the market operator to consider a merit order of producers "shifted leftwards", entailing a system marginal cost "shifted upwards", from $C'(q)$ to $C'_+(q)$ starting from the quantity $\underline{q}$.

As compared with q^*, redispatching yields a two-fold adjustment :

- consumption is reduced from q^* to q^{**}
- production is increased from q^* to $q^{**}+D$.

These two parts of the adjustment are perfectly symmetric: new producers are called into the merit order starting from the plants with the smallest relative marginal cost and consumers decrease their consumption in the demand merit order starting from electricity with the lowest value. There is a collective loss of efficiency, since the market operator is forced to do without production units that were placed in a good position in the merit order to produce D. In terms of surplus, the social loss is equal to the sum of the gross surplus decrease due to reduced consumption (area A) and the cost increase due to increased production (area B).

B. Constrained redispatching

It may happen that the new dispatch has to comply with some additional constraints, in particular the short term inelasticity of supply and demand. We consider successively the case where consumption cannot be reduced and the case where production cannot be increased.

- If it is mandatory to supply q^* to consumers, the market operator can just call production plants that were formerly out of merit up to reaching the quantity q^*+D. The social loss is more important than in the former case since there is an additional constraint. Geometrically, in Fig. 1 surface A is reduced to 0 and surface B is increased up to the value corresponding to the quantity q^*+D. As marginal cost is increasing and marginal utility is decreasing, the additional cost $\int_{q^{**}+D}^{q^*+D} C'(q)dq$ is larger than the gain in utility $\int_{q^{**}}^{q^*} U'(q)dq$ represented by surface A.

- If there is no way to increase production after the announcement that D is missing, the only solution consists in reducing consumption from q^* to q^*-D. The social loss is then exclusively represented by the absent utility $\int_{q^*-D}^{q^*} U'(q)dq$, that is surface A stretched leftwards to q^*-D.

When feasible, the solution that consists in combining consumption reduction and production increase is generically more efficient than those based on one single side of the market. Nevertheless, we see from Fig. 1 that the good dose for the two adjustments depends on the slopes of the curves U' and C'. Thus, if in the neighborhood of q^* the curve U' is very steep and/or if the curve C' is nearly horizontal, it is optimal not to reduce consumption and to exclusively rely on production reserve. Conversely, if in the neighborhood of q^* the marginal cost is strongly increasing and/or U' is almost horizontal, the optimal solution essentially requires reduced consumption.

C. Implementation by market mechanisms

Decentralizing the optimal mechanism described above requires a market for adjustment on top of the spot market. The production failure D occurs after q^* is planned. Therefore transactions settled initially are to be cleared at the spot price $p^* = U'(q^*) = C'(q^*)$ and only quantity D is to be paid at the real-time price.[4]

The producers participating in this market are those with a marginal cost above $C'(q^*)$. We assume that they cannot influence the real-time price p_a. Their supply is the solution to the problem $\max_q p_a q - \int_{q^*}^{q^*+q} C'(q)\,dq$. From the first order condition, we can write the supply of adjustment by generators as $q_g(p_a) = C'^{-1}(p_a) - q^*$, which is an increasing function of p_a since marginal cost is increasing given the merit order implemented by the market operator.

The consumers participating in this market are those with a marginal surplus above $U'(q^*)$. They also are price takers. Their adjustment supply is the solution to the problem

$$\max_q U(q^*) - p^* q^* + p_a q - \int_{q^*-q}^{q^*} U'(q)\,dq \qquad (1)$$

since their cost is the loss of utility for the units not consumed between q^*-q and q^*. From the first order condition, we can write the supply of adjustment by consumers as $q_c(p_a) = q^* - U'^{-1}(p_a)$, which is an increasing function of p_a since marginal utility is a decreasing function of consumption and the candidates to shedding are called by the market operator according to the merit order.

[4] When the failure D is known *ex ante* as in Chao [2], the equilibrium of the electricity market is reached at the spot price paid by all consumers and received by all active producers. Defaulting producers are simply removed from the merit order without further consequence.

The equilibrium price is the solution p_a^* of the equality between the demand for adjustment D and the supply by both types of agents $q_g\left(p_a\right)+q_c\left(p_a\right)=D$. That is

$$C'^{-1}\left(p_a^*\right)-U'^{-1}\left(p_a^*\right)=D.$$

At this price, from Fig. 1 it is clear that $q_c\left(p_a^*\right)=q^*-q^{**}$ and $q_g\left(p_a^*\right)=q^{**}+D-q^*$.

D. Financial clearing

Let us now examine the financial accounts of the agents in the day-ahead and adjustment markets. To get a clear view of the expenditures and revenues, we assume in Table 1 that financial flows transit through the accounts of the MO and the MO does not retain any profit from these adjustments.

The accounts of the non-defaulting planned producers are easily understandable: they produce what they agreed to sell q^*-D at the price of the initial program p^*. The planned consumers are allowed to consume q^* paid at the unit price p^*, but they only consume q^{**}. The producers initially located between q^* and $q^{**}+D$ are called to replace (partially) the defaulting producers who were located between $\underline{q}$ and $\underline{q}+D$. They are paid the adjustment price p_a^* for every unit they produce.

Consumers diminish their consumption by the quantity q^*-q^{**}, which gives them the revenue $p_a^*\left(q^*-q^{**}\right)$. The cost incurred to obtain this gain can be presented in two ways:

* globally the curtailed consumers lose the utility they could benefit from their consumption, $U\left(q^*\right)-U\left(q^{**}\right)$ (area *A* in Fig. 1).

* analytically this cost can be split into two parts: *i*) the loss of net utility $\int_{q^{**}}^{q^*}U'(q)dq-p^*\left(q^*-q^{**}\right)$ which is what the consumers would have received absent any consumption drop and *ii*), the settlement of the invoice $p^*\left(q^*-q^{**}\right)$ needed to acquire the option to do so.

On top of the importance of a price signal reflecting the value of energy to pilot the consumer's choice, the economic rationality of the payment $p^*\left(q^*-q^{**}\right)$ is common with all market transactions: an economic agent can sell only what he or she owns or what he or she can produce. Production facilities called up to $q^{**}+D-q^*$ must be paid $p_a^*\left(q^{**}+D-q^*\right)$ because they own the technology to produce this volume and they bear the related cost. Consumers do not own production facilities. They are entitled to the receipt of $p_a^*\left(q^*-q^{**}\right)$ only if they hold property rights on the quantity q^*-q^{**}, either by paying the bill $p^*\left(q^*-q^{**}\right)$ when they registered for their consumption profile, or because they commit to pay in the future.

This interpretation in terms of property law is highlighted by Chao (see [2]). We can reach the same conclusion thinking in terms of the commitments made at the initial dispatching program:

- planned producers commit to provide energy (and expect to receive the corresponding gain);
- planned consumers commit to withdraw energy (and pay the corresponding bill, at that time or in the future);
- any discrepancy with respect to the initial plan must be corrected by the MO and the financial consequences must be cleared accordingly.

TABLE I

REVENUE AND EXPENDITURE FLOWS

Non-failing planned producers

Expenditures	Reward
$\int_0^{\underline{q}}C'(q)dq$	$p^*(q^*-D)$
$\int_{\underline{q}+D}^{q^*}C'(q)dq$	

Failing planned producers

Expenditures	Reward
p_a^*D	p^*D

Non-planned producers

Expenditures	Reward
$\int_{q^*}^{q^{**}+D}C'(q)dq$	$p_a^*(q^{**}+D-q^*)$

Non-curtailed consumers

Expenditures	Reward
p^*q^{**}	$U\left(q^{**}\right)$

Curtailed consumers

Expenditures	Reward
$p^*(q^*-q^{**})$	$p_a^*(q^*-q^{**})$

Market operator

Expenditures	Reward
$p^*(q^*-D)$	p_a^*D
$p_a^*(q^{**}+D-q^*)$	p^*q^{**}
$p_a^*(q^*-q^{**})$	$p^*(q^*-q^{**})$
p^*D	

Firms that have committed to provide the quantity of energy q^* do so, either by producing or by paying the unit price p_a^* to acquire the energy D they are short of. Consumers who have committed to take q^* paid at price p^* consume q^{**} and exercise their put option on the quantity q^*-q^{**} sold at price p_a^*.

Table 1 shows that given the different financial inflows and outflows listed in the account of the market operator, it remains a positive balance equal to p^*D. To balance the MO's books, p^*D must be transferred to the defaulting producers (see the arrow in Fig. 1). Indeed, they have committed to produce D in the initial dispatch, so they are entitled to pocket p^*D. The difference with the other producers is that they fulfill their obligation not with their own energy but with energy produced by others $q^{**}+D-q^*$ and non consumed energy q^*-q^{**}, both paid at price p_a^*. They are in the same position as a supplier without generation assets, obliged to buy from an external source.

By aggregating the two accounts of the consumers, we find that their net utility is $U(q^{**})+p_a^*(q^*-q^{**})-p^*q^*$. On the other side of the markets, by aggregating the three accounts of the firms, we obtain their net profit

$$p^*q^*-p_a^*(q^*-q^{**})-\left[C(q^{**}+D)-\left(C(\underline{q}+D)-C(\underline{q})\right)\right]$$

Doing so brings up compactly the settlement of the bills of the subscribed electricity p^*q^* and the payment of the curtailment bill $p_a^*(q^*-q^{**})$.

To conclude this section, it is useful to revisit the pivotal role of the price paid to acquire put options on NWh. If this price was only the knife used to share the rent between consumers and producers, its value would be irrelevant from an efficiency point of view. However, it affects the decisions of the agents, like any purchase or sale price. As was already noticed in the discrete model of section II, market implementation of the first best requires consumers to pay for the right to resell their consumption.

To confirm that, suppose consumers pay only the day-ahead price for their actual consumption, instead of problem (1) they solve

$$\max_q U(q^*)-p^*(q^*-q)+p_aq-\int_{q^*-q}^{q^*}U'(q)dq .$$

The first order condition is $U'(q^*-q)=(p_a+p^*)$, as if no-consumption were rewarded twice. This yields an excess supply of adjustment by consumers as compared with the first best. Therefore, the put options on NWh must not be given for free to electricity consumers.

In the next section, we show that even though the pricing rule is correct, load-shedding creates a moral hazard problem.

IV. Strategic Behavior of Consumers in Demand Response Programs

Consider a consumer that chooses the quantity of electricity purchased q and the fraction consumed q^c. The problem can be solved in two different ways. The naïve solution assumes that the consumer does not behave strategically: he simply chooses a consumption profile given the offer price, and later adapts his consumption level if a profitable curtailment opportunity occurs. By contrast, the opportunistic solution incorporates the value of the acquired curtailment rights in the consumer's choice. These two solutions are presented successively below.

A. Non-strategic consumer

If the consumer is myopic, he solves the following sequence:

i) he first chooses the planned level of consumption given the MWh price p: $\max_q \; U(q)-pq$, which determines the demand for energy $q(p)$;

ii) upon observing the reward for consumption reduction p_a, he then allocates his purchase $q(p)$ between the consumption of MWh and the sale of NWh by solving

$$\max_{q^c} \; U(q^c)+p_a(q(p)-q^c) .$$

In this case, the consumer's demand response is well in line with the decentralization of both the optimal dispatch $U'(q)=p$ and the optimal redispatch $U'(q^c)=p_a$. In reality, consumers are strategic, or more simply, they are not totally myopic. They take their decisions anticipating the opportunity of rewarded curtailment, which produces a different outcome.

B. Strategic consumers facing certain adjustment prices

Assume that the consumer can perfectly forecast the adjustment price p_a at the time he orders the quantity *q*. He thus solves

$$\max_{q,q^c} \; U(q^c)+p_a(q-q^c)-pq \quad \text{s.t.} \quad q^c \le q$$

The solution proceeds backwards: first the consumer chooses q^c given the quantity of electricity subscribed *q*, then he chooses *q*.

i) For every value *q* chosen at the subscription time, the quantity actually consumed is the solution to

$$\max_{q^c} \; U(q^c)+p_a(q-q^c) \quad \text{s.t.} \quad q^c \le q$$

Consumption is therefore $q^c(p_a,q)$ such that

$$q^c(p_a,q)=0 \quad \text{if } p_a>U'(0)$$
$$q^c(p_a,q)=U'^{-1}(p_a) \quad \text{if } U'(0)>p_a>U'(q)$$
$$q^c(p_a,q)=q \quad \text{if } U'(q)>p_a .$$

This function is represented in the left panel of Fig. 2. The right panel shows the load reduction, that is the supply of NWh, obtained by subtracting consumption $q^c(p_a,q)$ from the energy purchased *q*. The two curves are obviously dependent on the quantity subscribed *q*.

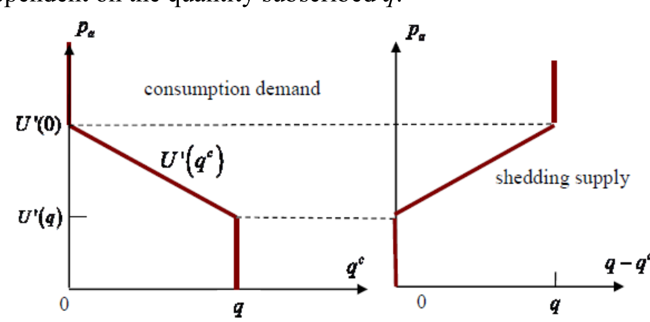

Fig. 2 Demand for electricity consumption, and supply of electricity curtailment

ii) Consider now the *ex ante* problem. At the moment where the consumer decides on the subscribed quantity of electricity *q,* he must solve:

$$\max_q \; U(q^c(p_a,q))+p_a(q-q^c(p_a,q))-pq$$

Knowing the first order condition that will prevail *ex post*, we have from paragraph *i*) above that $(U'(q^c)-p_a)\dfrac{dq^c}{dq}\equiv 0$ for all $p_a>U'(q)$. Consequently the derivative of the consumer's objective function with respect to *q* is just equal to $(p_a-p)\ge 0$. It means that the consumer facing a potential arbitrage between consuming at price *p* and the adjustment market at price p_a is encouraged to bid for a very high demand of energy with the objective to resell a lot of NWh on the adjustment market.

Several safeguards will actually limit this disproportionate demand of energy, including the dimension of the electric equipment that makes too high consumption claims non-credible. Hereafter, we consider another limit, the uncertainty on the price of the adjustment market.

C. *Strategic consumers facing uncertain adjustment prices*

Suppose that, when the consumer chooses the subscribed quantity *q* at price *p*, the adjustment price p_a is uncertain. Nevertheless, it will be known when choosing the quantity consumed q^c. The problem is

$$\max_q \int_0^\infty \left\{ \max_{q^c} U(q^c) + p_a(q-q^c) \;\; s.t. \;\; q^c \le q \right\} dF(p_a) - pq$$

where $F(p_a)$ is the distribution of probability of the price on the adjustment market. Since the consumer knows p_a at the time to fix the supply of NWh, the demand of electricity consumption remains the function $q^c\left(p_a, q\right)$ constructed previously.

Then the *ex ante* problem is

$$\max_q -pq + \int_0^{U'(q)} U(q)dF(p_a)$$
$$+\int_{U'(q)}^{U'(0)} \left[U(q^c(p_a,q)) + p_a\left(q - q^c(p_a,q)\right) \right] dF(p_a)$$

Contrary to the case of paragraph *B* above, we can now obtain an interior positive solution $\tilde{q}$ to this problem. It is determined by the first order condition

$$U'(\tilde{q})F(U'(\tilde{q})) + \int_{U'(\tilde{q})}^{\infty} p_a dF(p_a) = p$$

In effect, the last unit bought is paid *p* and it will be used either for consumption (if the price p_a is too low) or for resale, which will generate p_a in the states of nature where the put option is exercised, that is when $p_a \ge U'(\tilde{q})$.

When there is a positive probability that the put will not be exercised, uncertainty limits the purchase of electricity options devoted to curtailment. Nevertheless, purchases remain larger than for non-strategic consumers since the quantity subscribed $\tilde{q}$ is not only determined by $U'(.)$ and *p*, but also by the distribution of probabilities of p_a. This excess purchase can be easily proven by rewriting the above first order condition as

$$U'(\tilde{q}) + \int_{U'(\tilde{q})}^{\infty} \left[p_a - U'(\tilde{q}) \right] dF(p_a) - p = 0$$

Consequently $U'(\tilde{q}) - p < 0$, instead of $U'\left(q^*\right) - p = 0$ at first best. Therefore, $U'\left(\tilde{q}\right) < U'\left(q^*\right)$ and, since $U(.)$ is concave, $\tilde{q} > q^*$.

For each possible level of the energy price, in particular the price p^* that implements first best, the consumer buys more than he plans to consume. This incentive to order an excessive quantity of electricity depresses *ex post* the price of the adjustment market as can be seen from the right panel of Fig. 2: the vertical segment of the supply of NWhs is shifted rightwards (from q^* to $\tilde{q}$), the intercept with the vertical axis decreases (from $U'\left(q^*\right)$ to $U'\left(\tilde{q}\right)$) and the increasing part of the function moves accordingly downwards and rightwards. Then, for any demand function of adjustment by the market operator to the consumers holding put options, the equilibrium price on the adjustment market $\tilde{p}_a$ will be lower than the efficient one p_a^*.

The strategic behavior of consumers has two adverse effects:

- a disruption in the merit order, since some candidates to load-shedding will be inserted into the queue before production plants whose cost is lower than the lost utility;
- an equilibrium price too low in the adjustment market, which distorts the incentives to invest.

To avoid this opportunistic bias, the decisions of the consumers must be considered within a dynamic process taking into account the incentives to hide information and to change the unobservable consumption decisions. To reduce strategic behavior (adverse selection and moral hazard) the retail electricity suppliers should offer contracts with nonlinear prices for packets of energy, each packet containing a pair of variable price and guarantee of supply that plays the same role as an index of quality. Consumers could thus self-select within this menu, revealing their private information about the true intensity of their need for electricity. From contract theory, we know that first best cannot be reached with the result that consumers will keep information rents. Nevertheless, a menu of subscriptions with pairs of variable prices and delivery guarantees would largely outperform uniform linear prices.

V. CONCLUSION

Increasing the flexibility of the demand for electricity should be a priority. The ever rising cost of fossil fuels and the growing importance of environmental externalities prohibit the business as usual approach: simply keep investing in production facilities to meet a price insensitive demand.

The Information and Communication Technologies applied to electrical networks allow us to expect significant changes in demand response in the near future. As consumers become more concerned with their energy bill and are increasingly able to delegate the control of their consumption to service providers, we will gradually reach a state of the industry where demand plays a fully active role in the balancing process. We must therefore encourage R&D leading to the installation of electronic tools allowing consumers to control their demand efficiently.

The solution is not just technical. It also requires a regulatory environment that respects the principles of an efficient allocation of resources, which means, in a market economy, a system of rights and fees that can decentralize optimal dispatch and re-dispatch. When consumers are allowed to freely choose either to consume or to be paid for not consuming, the quantity of put options they acquire, the price they pay to acquire them and the price they receive when they exercise them must be objective and verifiable to be included in detailed subscription contracts. The legal framework for firms that will develop the service of distributed load-shedding must also be clearly defined since they will progressively acquire a lot of information on the behavior of consumers and they will intervene at critical periods under the supervision of the market operator.

VI. References

[1] S. Borenstein, M. Jaske and A. Rosenfeld, "Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets", *Center for the Study of Energy Markets*, WP 105, University of California, October 2002.

[2] H. P. Chao, "Price-responsive demand management for a smart grid world", *The Electricity Journal*, vol. 23, Issue 1, pp. 7-20, Jan/Feb. 2010.

[3] W. Hogan, "Providing Incentives for Efficient Demand Response", *Electric Power Supply Association, Comments on PJM Demand Response Proposals*, Federal Energy Regulatory Commission, Docket No. EL09-68-000, Oct. 2009.

[4] P. L. Joskow and D.B. Marron, "What Does a Negawatt Really Cost? Evidence from Utility Conservation Programs", *Energy Journal*, Vol. 13 Issue 4, pp. 41-74, 1992.

[5] P. L. Joskow and D.B. Marron, "What Does a Negawatt Really Cost? Further Thoughts and Evidence", *The Electricity Journal*, pp. 14-26, Jul. 1993.

[6] L. Ruff, "Economic principles of demand response in electricity", *Edison Electric Institute*, Washington DC, Oct. 2002.

[7] J. Torriti, M. G. Hassan and M. Leach, "Demand response experience in Europe: Policies, programmes and implementation", *Energy*, Volume 35, Issue 4, pp. 1575-1583, Apr. 2010.

VII. Biographies

Pr. Crampes was born in France in 1948. He received the Ph.D. degree from Toulouse University in 1975. He is currently professor at Toulouse School of Economics (TSE) and senior researcher at Institut D'Economie Industrielle (IDEI). He has been a member of the economic council of the French regulation body for electricity. He currently acts as an advisor for EDF, the main electricity producer and supplier in France. His areas of research interest are the economics of networks, industrial organization and the economics of intellectual property.

Pr. Léautier was born in France in 1967. He received a MS in applied Mathematics from Ecole Polytechnique, a MS from Ecole Nationale des Ponts et Chaussées, a MS in Transportation and a PhD in Economics from the Massachusetts Institute of Technology. He is a professor of management at the University of Toulouse's Institut d'Administration des Entreprises, and a member of the Toulouse School of Economics. The microeconomics of electric power markets constitute his primary research interests.