

DEMAND RESPONSE IN EXPERIMENTAL ELECTRICITY MARKETS

GESTIÓN ACTIVA DE LA DEMANDA EN MERCADOS ELÉCTRICOS EXPERIMENTALES

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ABSTRACT

We study consumers' behavior in an experimental electricity market. Subjects make decisions concerning the quantity of electric energy they want to consume in three different pricing environments. In the baseline framework, they decide under a system of fixed prices, invariant to consumption schedule as well as to network restrictions. The other two environments correspond to dynamic pricing systems combined with incentives that aim at cutting energy consumption in a number of selected situations characterized by high network congestion. In such situations, in the first environment subjects get a bonus if they reduce their peak consumption below a certain level, while in the second one, consumers are sanctioned for consuming in peak times. From a social welfare perspective, our experimental data confirm that a dynamic system for prices is more efficient than a fixed one. Moreover, a dynamic scheme with sanctions, although less preferred by consumers, is more effective than the one with bonuses in order to reduce peak consumption. Dynamic pricing with bonuses reaches a good balance between efficiency and consumer acceptance.

KEY WORDS

Dynamic pricing; Electricity demand; Policymaking experiments.

RESUMEN

Estudiamos el comportamiento de los consumidores en un mercado de electricidad diseñado en el laboratorio. Los sujetos experimentales toman decisiones sobre la cantidad de electricidad que desean consumir en tres contextos diferentes. En el tratamiento base, los consumidores deciden bajo un sistema de precios fijos, en el que el precio es invariable tanto a la franja horaria de consumo como a las restricciones de la red. Los otros dos contextos corresponden a sistemas dinámicos de precios combinados con incentivos cuyo objetivo es la reducción del consumo en algunas situaciones seleccionadas caracterizadas por una alta congestión de la red. En estas situaciones, en el primer contexto, se bonifica la reducción del consumo en la hora punta por debajo de cierto nivel, mientras que en el segundo, los consumidores son sancionados por consumir en hora punta. Desde una perspectiva de bienestar social, nuestros datos experimentales confirman que un sistema de precios dinámico es más eficiente que uno fijo. Además, un esquema dinámico con sanciones, incluso si es menos preferido por parte de los consumidores, es más efectivo que uno en el que se bonifica la reducción del consumo en hora punta. Un sistema de precios dinámico con bonificaciones presenta una relación equilibrada entre eficiencia y nivel de aceptación por parte de los consumidores.

PALABRAS CLAVE

Demanda de electricidad; Experimentos de política; Sistemas de precios dinámicos.

INTRODUCTION*

A relevant consequence of the increasing importance of environmental sustainability and the difficulty in modulating energy supply is that solutions are frequently searched from the demand side. In the case of electricity, to consume in a more efficient way implies not only to consume less but also to manage consumption in time. In most electrical systems, consumers do not receive the right signal in order to be able to make a consumption time management. The reason is that, in general, the installed meters do not facilitate measuring and communicating consumption in real time.

Given the evolution of electricity markets and the development of new technologies, demand response programs have recently assumed importance. Brophy Haney, Jamasb and Pollitt (2009) present an assessment of smart metering in liberalized electricity markets by investigating the technology and the international experience. They confirm that there is a widespread consensus that improving the participation of the demand-side should be a central goal for policy in liberalized electricity markets, but the main barriers to greater participation are inelasticity of demand and information asymmetry. As a conclusion, they assess that more innovative forms of metering are necessary for these barriers to be overcome. However, smart metering should not be seen as a goal in itself but rather as a tool in promoting more active demand and innovation in equipment for demand-side management.

Today, it is possible to think of sophisticated demand response systems where intelligent counters could allow consumers to adjust consumption in response to price signals that vary in time, leading to a more efficient electric system.¹ To evaluate the impact of these sophisticated systems on consumers' demand, electricity prices and market efficiency is presently quite difficult given that real micro-data are not available yet, apart from a few isolated pilot samples for which only survey information was collected. In this paper, we try to come close to a real demand response program by studying consumers' behavior in an experimental electricity market. As already noted in detail by Normann and Ricciuti (2009), experiments are well suited to study the effects of policy regime changes. Even if a policy maker is convinced that a new policy is superior to the status

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¹ Conchado and Linares (2010) is an interesting survey of the state of the art in the quantification of demand response program benefits.

quo, experiments are useful in gathering evidence about the duration and properties of the transition period. This is the aim of our experimental analysis.

An interesting aspect that has also influenced us is introduced in Fisher (2008). The author offers a theoretical perspective on the matter and introduces a psychological model to explain why feedback works. She holds that successful feedback has to capture consumer's attention, link specific actions to their effects and activate various motives. One unanimous finding is that households in all countries approve of feedback that is more detailed and more closely linked to consumption actions. Furthermore, there is usually an interest in comparisons with one's own previous consumption.

Generally speaking, the most directly related experimental literature on electricity markets can be classified in two main categories: field experiments and lab experiments. In the first category, Battalio et al. (1979) ran an interesting field experiment designed to determine the effects of various price and non-price policies on electricity consumption. Five different price policies were tested. The results show that price policies work much better than informational policies. Faruqui and Sergich (2009) review the most recent experimental evidence on the effectiveness of residential dynamic pricing programs. Their review of 15 different field experiments on pricing reveals that the demand response impacts from different pilot programs vary from modest to substantial, largely depending on the data used in the experiments and the availability of enabling technologies.

Concerning the second category, the literature provides us with single-sided as well as with two-sided market experiments. Rassenti, Smith and Wilson (2001, 2002, and 2003) are important references on supply-side as well as both-sides active experimental electricity markets. They investigate several features of the California crisis and analyze policy aspects such as market power and the effect of demand-side bidding. For the case of active supply-side, the demand side is represented by a robot bidder who bids non-strategically up to a maximum price, analogously to the must-serve feature of the market. The experiments show that demand-side bidding reduces prices significantly. It also reduces the volatility of prices. The extreme peaks and fluctuations which also characterized the Californian electricity markets were reduced. Prices are generally higher in markets with market power but demand-side bidding can neutralize the effects of market power.

More recently, Adilov et al. (2004) and Adilov et al. (2005) conduct, respectively, experiments on demand-sided and full two-sided electricity markets. The aim of both papers is to test the efficiency of two alternative forms of active demand-side participation. They evaluate different experimental price structures that represent end-use consumers who can substitute part of their usage between day and night: fixed price, a demand response program with fixed price and credit for reduced purchase, and a real time pricing system where prices are forecasted for the upcoming day/night. Their main conclusion is that the real time program results in the greatest market efficiency.

We present here a lab experiment that analyses the demand side of the market. Inspired by the design of Adilov et al. (2004), we consider an electricity market in which consumers of different types decide the quantity they want to buy under different pricing systems, while the “hockey-stick”-shaped supply is exogenously given. In their experiment, consumption generates the same level of utility independently of the quantity consumed,² while our multi-step demand function reflects a (more realistic) decreasing marginal utility of consumption. Another differentiating feature of our design is that we allow for sanctions due to overconsumption and not only for bonuses when energy saving occurs. Our buyers decide in two frameworks, one with fixed and another with dynamic pricing. Fixed pricing constitutes our benchmark T0 treatment. Within the dynamic pricing setup, as commented above, we specifically test for the role of bonuses as well as sanctions as demand response systems in our experimental treatments T1 and T2 respectively. In Treatment 1, in certain selected periods of network congestion, subjects receive a bonus if they reduce their peak consumption below a certain level. In Treatment 2, in the corresponding periods, consumers are sanctioned for consuming in peak times. These two systems are designed in such a way as to allow for a neat comparison between them, given that they are aimed at motivating the same level of energy savings.

In line with the conclusions in Faruqui and George (2002) and in Adilov et al. (2004), our data show that dynamic pricing can provide substantial net benefits to mass market consumers and electric utility shareholders. In particular, from a social welfare perspective, our experimental data confirm that a dynamic system of prices is more efficient than a fixed one. Furthermore, a dynamic pricing system combined with sanctions is more effective than one with bonuses in order to reduce peak consumption. However, when bonuses or sanctions are applied, the dynamic pricing system loses efficiency, particularly in the case of sanctions.

After each treatment, we conducted a questionnaire in order to test whether preferences change with experience.³ Interestingly, when asked about their preferences, subjects declare to prefer the dynamic pricing system with bonus over the other systems, despite the fact that their gains were higher under fixed prices.

The structure of the paper is as follows. In section 2 we describe the general framework in which our electricity market is defined. All details concerning the experimental design are explained in section 3, and section 4 summarizes the main results. Section 5 concludes. An appendix at the end includes the instructions to experimental subjects.

² Their valuation is different depending on the type of energy and the time of consumption, but not on quantity consumed.

³ Adilov et al. (2004) also conducted a preference poll similar to ours.

FRAMEWORK

In this section, we introduce all common elements characterizing the electricity market, and then describe each of the three market environments that correspond to our experimental treatments.

The Electricity Market

The sale of electricity occurs in a competitive market over a number of periods, each composed of two sub-periods: Peak and Valley, to represent peak and off-peak usage respectively.⁴ The energy consumed can be either transferable or non-transferable. The latter must be consumed in a certain sub-period and in that only, and is meant to capture energy with a relatively inelastic demand with respect to time (heating, lighting, etc.). Thus, non-transferable Peak (Valley) energy must be consumed in the Peak (Valley) sub-period only. On the other hand, transferable energy (TE) can be used either during the Peak or during the Valley of a same period in a substitutable manner. In this way, buyers can choose the quantity of TE to consume in each sub-period, much as each household can decide to run their dishwasher or washing machine in different times of the day.

Every period, consumers must decide the quantity of transferable and non-transferable energy to buy for both the Peak and the Valley in order to maximize their net gains, calculated as the difference between their valuation of the electricity consumed and the money spent to buy this electricity. As common in laboratory experiments, the valuation of purchases is pre-assigned to buyers through an Induced Utility Function (IUF), which determines the maximum price the consumer is willing to pay for each unit of electric energy. The utility provided by the use of electricity depends on the quantity consumed according to a discrete steps function, and is always higher for the Peak than the Valley. Moreover, each consumer's valuation of transferable energy purchases is always equal or lower than their valuation of non-transferable electricity.⁵

There are two types of consumers in the market, one who depends more on electricity than the other, i.e. willing to pay a higher price for energy of any kind at every sub-period.⁶ The utility function is parameterized using actual data on the electricity consumption of Spanish households.⁷ These data detail the quantity of energy consumed by different

⁴ Peak and Valley closely approximate the day/night notation used in the literature. Specifically, Peak corresponds to the time interval 12:00-22:00.

⁵ Individuals' demand in Adilov et al. (2004) is represented by a two-step value function with separate valuations for day and for night usage and for transferable and non-transferable electricity.

⁶ Except for the first step of the utility function in which the willingness to pay for the two types of consumers coincides. This first step reflects first necessity consumption.

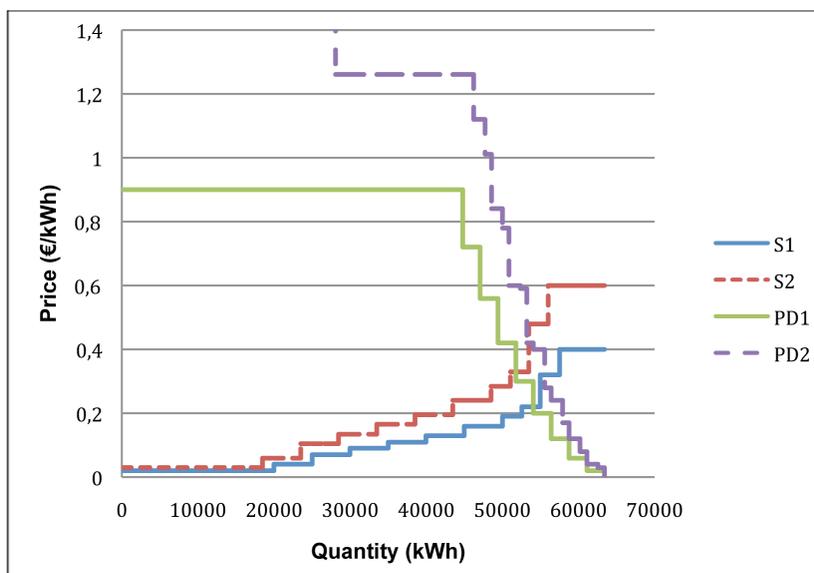
⁷ The data were collected in the context of a project on the development of technological solutions for the Spanish electricity network.

types of electric appliances or uses (washing machine, heating, television, etc.) for every hour in the day. Each type of usage was classified as belonging to the non-transferable or transferable energy categories and data were aggregated to obtain total quantities which were then assigned utility values compatible with realistic equilibrium market prices.

Finally, the induced utility of energy is substantially increased in correspondence with pre-determined “high demand periods”, when unfavorable weather conditions (such as a heat-wave) make everyone value electricity more, thus shifting the demand function to the right. More precisely, in a high demand period the utility of the consumer who is very dependent on electricity doubles, while that of the less dependent consumer increases by 40%.

As an illustrative example, Figure 1 shows the aggregate demand functions in the Peak both for a normal (PD1) and for a high demand (PD2) period assuming that every consumer buys all transferable energy in the Peak sub-period. The supply side of the market is pre-determined (S1), varying with the network status. In every treatment, certain pre-specified periods are subject to a reduction in supply (S2), for instance due to a power outage, leading to higher offered prices. We call these “periods with supply restrictions”.

Figure 1.
Demand and supply curves in the peak sub-period



S1: Supply curve in a normal period; S2: Supply curve in a period with restrictions; PD1: Benchmark aggregate demand curve in the Peak assuming that all transferable energy is consumed in this sub-period; PD2: Peak aggregate demand curve in a “high demand” period, assuming that all transferable energy is consumed in the Peak.

The three treatments

In the benchmark environment (Treatment 0), we take as a reference the residential electricity market in Spain, characterized by a fixed price structure, whereby consumers face the same pre-determined energy price independently of the time of the day in which consumption takes place and of the state of the electric network.

In the other two treatments, however, we introduce a dynamic pricing scheme, where prices are determined in real time as the actual market-clearing prices. In such a scheme, therefore, prices are necessarily unknown at the beginning of the period, when buyers observe their energy valuation and the supply shock. Rather, in this case consumers are presented with a forecast of the range of expected prices in the Peak and Valley sub-periods. More precisely, this forecast for each sub-period consists of the interval in which the market-clearing price will fall in that sub-period if all consumers act rationally⁸. The final actual price will be closer to the lower or the upper bound of the interval depending on the consumers' expectations which translate into their consumption of transferable and non transferable energy. In fact, buyers are made aware that if all of them choose to consume their stock of TE during the Peak (Valley), the market-clearing price of electricity for the Peak will be the upper (lower) bound of the price interval corresponding to Peak, and simultaneously the price for the energy bought in the Valley sub-period will be the lower (upper) bound of the price interval given for the Valley.

Knowing the price forecasts (detailed in Table 1), buyers select their quantity purchases, for which they will be charged the price that clears the market. In the market, the

Table 1.
Price Intervals Forecasts

Forecasts	Lower Bound, Peak	Upper Bound, Peak	Lower Bound, Valley	Upper Bound, Valley
N	0.16	0.22	0.07	0.11
HD	0.16	0.32	0.07	0.11
SR	0.24	0.33	0.11	0.17
SR + HD	0.24	0.42	0.11	0.17

N: Normal Period - period with no supply restrictions and no demand shock; HD: High Demand Period - period with an increase in demand; SR: Period with Supply Restrictions - period with a decrease in supply; SR + HD: High Demand Period with Supply Restrictions - period with a decrease in supply and an increase in demand.

⁸ In the sense of choosing quantities consistent with the information about the prices provided.

supply is simulated by software which associates a price per kWh to each level of the electricity aggregate demand, in every period. More precisely, we adopt a “hockey-stick” shaped supply function similar to the ones used in previous experiments (Mount et al., 2001; Adilov et al. 2004). As can be seen in Figure 1, in this supply function the price increases very slowly up to a certain quantity of electricity offered, past which there is a substantial jump to higher prices (leading to the function assuming a shape of a hockey stick). This functional form intends to represent the fact that in order to increase electric energy above a certain level it is necessary to operate new marginal power stations characterized by higher operative costs. The parameterization of this supply function is based on the average market price of electricity per hour over 2009 up to February 2010, provided by the Spanish Electricity Market Operator. We assume a margin of 200% for the operator, and fix a cap of 0.4€ for the price in our calibration.⁹ To appropriately capture market behavior in situations of restricted supply, the function shifts to the left in the periods with restrictions, leading to an increase in prices for any production level. More precisely, in these periods the quantity offered at any price diminishes by 1,500 kWh and the supply price rises by 50% at any quantity. In this case, the price cap is fixed at 0.6€. In Treatment 1, the dynamic pricing scheme is combined with a Peak Time Rebate, whereby in some of the congested periods (not normal), buyers receive a bonus for each kWh they save with respect to a certain individual reference level of consumption. This reference consumption level is calculated as the individual mean consumption in the previous Peak sub-periods characterized by the same network status, but where no Peak Time Rebate system was activated.

On the other hand, in Treatment 2 dynamic pricing is combined with Critical Peak Pricing. In this case, in some of the periods in which a congestion problem arises due to a technical restriction in supply or an increased pressure in demand, or both, a one-off measure is taken consisting in a drastic rise in the price of energy. More precisely, all electricity consumed in the Peak of that period is charged a fixed extra amount above the corresponding market clearing price.

The implementation of these pricing mechanisms in Treatments 1 and 2 is designed in such a way as to allow for a comparison between them. In the Peak Time Rebate, the reference level is chosen such that, at the optimum, individuals choose to consume the same quantity of electricity as in the Critical Peak Pricing. In other words, both schemes are aimed at reducing consumption by the same amount. In practice this translates into paying consumers a bonus equal to the extra amount charged in Treatment 2 as a sanction to consumption per kWh of Peak energy saved with respect to their reference consumption.

⁹ This price cap could for instance represent an external option to buy extra amounts of energy from foreign countries.

Experimental Design

Subjects participating in the experiment were undergraduate students in Business Administration at the University Jaume I of Castellón (Spain). In order to allow for a within subjects analysis, the same set of 40 participants was engaged in all three treatments over one morning. The experiment was programmed in z-Tree software (Fishbacher, 2007) and was carried out in the Laboratory for Experimental Economics (LEE) of the University Jaume I.

Four groups were randomly and anonymously formed with 10 buyers each, participating in the same energy market for the whole duration of the experimental session. As mentioned before, the energy supply was simulated by computer. In the benchmark experiment we fix the price of electricity for both Peak and Valley to be 12 EXCUs per kWh, being the EXCU the EXperimental Currency Unit used in our experimental lab.

First, the benchmark treatment with fixed prices was repeated for 8 consecutive periods, followed by Treatments 1 and 2, played for 22 consecutive periods each. To summarize, each period could be one of four possible types: a normal period (without any shocks to demand or supply), a high demand period (in which the valuation of energy is increased for all consumers and for all kinds of electricity), a period with supply restrictions (in which the energy supply price rises at any quantity), and a high demand period with supply restrictions (that combines the characteristics of the two latter cases). Sanctions or bonuses in Treatments 1 and 2 were applied in a total of six periods, two of each type, but never in a normal period. In Treatment 2, the sanction consisted in charging Peak energy an extra 50 EXCUs above the market clearing price. In Treatment 1, consumers were paid a bonus of 50 EXCUs per kWh of Peak energy saved with respect to their weighted mean consumption of Peak energy in the previous non-incentivized periods characterized by the same network status.

The same sequence of events (shocks to demand and/or to supply) was used in the three treatments (see details in Table 2, while Table 3 offers a summary of the experimental treatments). Before the beginning of the experimental session, subjects were randomly assigned the role of consumers highly dependent or less dependent on electricity (in a proportion of 50-50 in each market), and received a series of instructions describing the general features of the experiment and the characteristics of the benchmark environment played first. They were asked not to communicate with the other players, given that their gains were also related to the others' behavior. They had about 30 minutes to read the instructions (which can be found in the Appendix), and had the opportunity to ask any questions they had. Specific instructions on the Peak Time Rebate and the Critical Peak Pricing were handed out just before the start of the treatments where they were used.

Participants were not subject to any time restriction within which to make their choices. However, there was a time counter on their computer screen counting down seconds from 180 to 0. Once the first three minutes were over, the counter remained at zero and the message "Please make a decision" appeared, indicating that a reasonable amount of time had passed already. In this way subjects were left free

Table 2.
Time Structure of Treatments according to Type of Period

Period	Type of Period	Treatment in which included	T1 (Bonus) T2 (Sanction)
1	Normal	T0 / T1 / T2	NO
2	Supply Restrictions	T0 / T1 / T2	NO
3	High Demand	T0 / T1 / T2	NO
4	S. Restriction + High Demand	T0 / T1 / T2	NO
5	Normal	T0 / T1 / T2	NO
6	S. Restriction + High Demand	T0 / T1 / T2	YES
7	High Demand	T0 / T1 / T2	YES
8	Supply Restrictions	T0 / T1 / T2	NO
9	Supply Restrictions	T1 / T2	YES
10	High Demand	T1 / T2	NO
11	S. Restriction + High Demand	T1 / T2	NO
12	Normal	T1 / T2	NO
13	S. Restriction + High Demand	T1 / T2	NO
14	Normal	T1 / T2	NO
15	High Demand	T1 / T2	YES
16	Supply Restrictions	T1 / T2	NO
17	S. Restriction + High Demand	T1 / T2	YES
18	High Demand	T1 / T2	NO
19	Supply Restrictions	T1 / T2	YES
20	High Demand	T1 / T2	NO
21	Supply Restrictions	T1 / T2	NO
22	S. Restriction + High Demand	T1 / T2	NO

Source: Own elaboration.

Table 3.
Summary of Experimental Treatments

Treatment	Prices	Bonus	Sanction	N. of periods	Markets	Subjects
T0	Fixed	--	--	8	4	40
T1	Dynamic	YES	NO	22	4	40
T2	Dynamic	NO	YES	22	4	40
			TOTAL	52	12	40

Source: Own elaboration.

to make their choice in whatever time they needed, but were made aware of the amount of time judged to be reasonable to take a decision.¹⁰ We present a capture of the main computer screen shown to the experiment participants in Figure 2.

Participants were also asked to fill in a questionnaire in which they had to declare their preference among the fixed price scheme, the dynamic pricing mechanism with sanctions and the dynamic pricing mechanism with bonuses.¹¹ This preference was elicited at the end of each treatment, so that it was possible to keep track of the changes in individual preferences due to the subject having increased information and practical experience of more mechanisms each time.

The experimental session lasted approximately 5 hours, including two 30' breaks between treatments to allow the students to rest. Participants received a unique payment as a function of the gains obtained in one of the three treatments, randomly chosen from a draw by hand in front of them. This Random Lottery Incentive mechanism avoids undesired income effects between treatments, whereby students' behavior over time could be influenced by their accumulated gains.

Payments were privately handed out in cash to each student at the end of the session. Students were paid on the basis of how much they had gained proportionally to the total gains of the subjects of their type in the experiment. Average earnings were 86€, about 17€ per hour dedicated to the experiment.

¹⁰ It is important to note that subjects hardly ever used up the 3 minutes, only some of them spent some more time the first period in which they were faced with a new pricing scheme.

¹¹ Definitions of the two dynamic pricing schemes (with bonuses and with sanctions) were presented in the questionnaire itself (see Instructions in the Appendix).

Figure 2.
Screenshot from the experiment

1 out of 22

Remaining time 137

Peak Non Trans. E.	Value	Valley Non Trans. E.	Value	Peak Trans. E.	Value	Valley Trans. E.	Value
From 0 to 4570	1.80	From 0 to 2650	1.80	From 0 to 760	1.80	From 0 to 760	1.80
From 4571 to 4835	1.44	From 2651 to 2770	1.44	From 761 to 788	1.44	From 761 to 788	1.26
From 4836 to 5100	1.12	From 2771 to 2890	1.12	From 789 to 816	1.12	From 789 to 816	0.96
From 5101 to 5365	0.84	From 2891 to 3010	0.84	From 817 to 844	0.84	From 817 to 844	0.70
From 5366 to 5630	0.60	From 3011 to 3130	0.60	From 845 to 872	0.60	From 845 to 872	0.48
From 5631 to 5895	0.40	From 3131 to 3250	0.40	From 873 to 900	0.40	From 873 to 900	0.30
From 5896 to 6160	0.24	From 3251 to 3370	0.24	From 901 to 928	0.24	From 901 to 928	0.16
From 6161 to 6425	0.12	From 3371 to 3490	0.12	From 929 to 956	0.12	From 929 to 956	0.06
From 6426 to 6690	0.04	From 3491 to 3610	0.04	From 957 to 984	0.04	From 957 to 3610	0.00

Electricity Provider Data

Network Status: High Demand+Supply Restrictions

Price (EXCUS/kWh): **Between 0.24 and 0.42**

Valley sub-period

High Demand + Supply Restrictions

Price (EXCUS/kWh): **Between 0.10 and 0.17**

My Energy Demand

Trans. Energy (kWh): (4570-6690)

Trans. Energy (kWh): (0-984)

Valley sub-period

Trans. Energy (kWh): (2650-3610)

Trans. Energy (kWh): (0-984)

Due to an exceptional congestion of the network an overconsumption sanction protocol has been activated.

The surcharge added to the market price for each consumed kWh will be: **0.50**

RESULTS

Table 4 presents descriptive statistics of energy quantities consumed in all experimental treatments.¹² Observe that participants are highly sensitive to the different types of periods, sub-periods, and energy. Besides, the variability among participants' decisions appears to be moderate.

Benchmark Environment (T0). Generally speaking, individuals of both types decided optimally after one period of learning. As an example, Figure 3 illustrates the observed mean consumption of non-transferable and transferable energy versus their predicted level in the peak sub-period, and for the three treatments.¹³ Focusing on the top left box of each panel, representing the benchmark case, we can observe that average non-transferable and transferable energy consumed quantities are within the ranges of optimal choices.¹⁴

Result 1: *Experimental subjects behave optimally in the benchmark environment.*

By construction, periods with supply restrictions do not change consumers' behavior in the regime with fixed prices, and consumption of all types of energy increases in high demand periods.

The Effect of Dynamic Pricing. In Treatments 1 and 2, the dynamic pricing mechanism is introduced whereby individuals make their consumption choices knowing only the expected range of energy prices. Going back to the boxes T1 and T2 of Figure 3, we observe that, in the periods with no incentives (bonuses or sanctions), observed consumption is always within the ranges of its optimal level, considerably lower than observed consumption under the fixed prices regime (T0). That is, subjects behave optimally even in the presence of a more complex pricing mechanism, an indication that they are able to understand this mechanism and adjust to it (we will comment later on the effects of incentives). Participants in the experiment by Adilov et al. (2004) also demonstrated their ability as buyers to solve a non-trivial inter-temporal optimization problem in their real time pricing system.

¹² Notice that, given that there are only 10 buyers in our electricity market, each of them consumes a quantity of energy representing the demand of about 700 average real consumers.

¹³ In the Figures and Tables we show the behavior of the more energy dependent consumer, given that no qualitative difference is observed between the two types of consumers.

¹⁴ Apart from the first period when learning did not take place yet.

Table 4.
Descriptive Statistics of transferable and non-transferable energy consumed by type of consumer

Mean energy consumed (Standard Deviation)		More energy dependent consumer				Less energy dependent consumer			
Treatment	Period	PNTE	VNTE	PTE	VTE	PNTE	VNTE	PTE	VTE
T ₀	N	5,897 (357)	3,291 (161)	776 (51)	206 (51)	3,860 (127)	2,154 (84)	614 (20)	139 (20)
	SR	6,064 (128)	3,324 (58)	76 (0)	220 (16)	3,906 (68)	2,174 (55)	587 (144)	100 (0)
	HD	6,345 (124)	3,452 (55)	760 (0)	224 (0)	3,920 (73)	2,165 (86)	610 (0)	144 (0)
	SR + HD	6,251 (414)	3,407 (186)	760 (0)	224 (0)	3,935 (35)	2,187 (31)	618 (32)	135 (32)
T _{1/T2}	N	5,807 (161)	3,361 (47)	499 (255)	478 (256)	3,727 (96)	2,193 (55)	413 (233)	339 (231)
	SR	5,571 (132)	3,275 (53)	423 (248)	552 (253)	3,594 (95)	2,135 (48)	387 (236)	360 (235)
	HD	6,043 (153)	3,474 (50)	572 (252)	403 (254)	3,758 (106)	2,212 (50)	449 (230)	304 (229)
	SR + HD	5,857 (173)	3,387 (65)	559 (259)	415 (257)	3,677 (87)	2,196 (43)	388 (238)	365 (238)
	SR + B	5,265 (377)	3,274 (61)	424 (273)	531 (275)	3,378 (208)	2,134 (52)	251 (213)	501 (213)
	HD + B	5,614 (401)	3,481 (41)	386 (270)	529 (296)	3,521 (215)	2,211 (51)	291 (240)	446 (243)
	SR + HD + B	5,617 (359)	3,391 (53)	463 (287)	495 (277)	3,543 (198)	2,178 (46)	312 (239)	431 (245)
	SR + S	4,801 (375)	3,272 (60)	131 (76)	844 (72)	3,162 (221)	2,109 (80)	120 (120)	631 (218)
	HD + S	5,444 (367)	3,477 (36)	144 (77)	828 (71)	3,362 (285)	2,202 (70)	111 (97)	638 (94)
	SR + HD + S	5,351 (354)	3,368 (90)	131 (83)	842 (78)	3,363 (282)	2,177 (80)	132 (147)	619 (147)

PNTE: Peak Non-Transferable Energy; VNTE: Valley Non-Transferable Energy; PTE: Peak Transferable Energy; VTE: Valley Transferable Energy; N: Normal period; SR: period with Supply Restrictions; HD: High Demand period; B: Bonus; S: Sanctions.

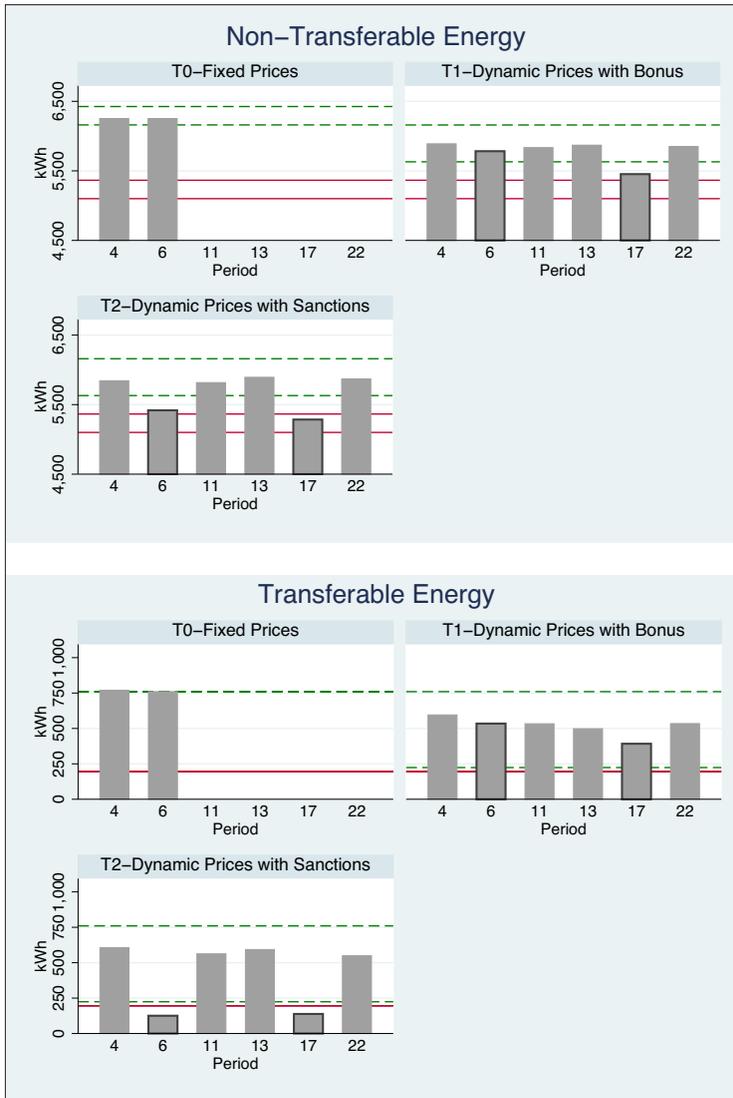
Table 5 presents the results of Wilcoxon tests comparing the average individual energy consumption under different regimes.¹⁵ One first result we draw from these tests is that Peak energy consumption (both transferable and not) is significantly reduced under the dynamic pricing scheme with respect to the fixed prices one for any kind of network status (see comparison FP-DP in the Table). This decrease in energy consumption in the Peak sub-period reflects the fact that the Treatment 1 market-clearing price in peak times would always be higher than 12 cents (the fixed price in T0), for any type of period (Table 6 presents the Wilcoxon tests on differences between prices). Moreover, subjects decide to shift part of the transferable electricity consumption to the Valley, a sign that they expect lower prices in that sub-period.¹⁶

In general, energy consumption in Valley increases with dynamic prices under any network status, but not by much, so that total energy consumed is lower under dynamic pricing than under fixed prices (last column in Table 5).

¹⁵ The Wilcoxon test is appropriate for small non-normal data distributions in matched samples experimental designs.

¹⁶ We can see in the VEP column in Table 6 that this expectation is fulfilled only in normal periods.

Figure 3.
Average Peak energy consumption in a high demand period with supply restrictions



Dashed lines: equilibrium interval of energy consumption in the market without incentives; *solid lines:* equilibrium interval of energy consumption in the market with incentives (bonuses or sanctions); *periods 6 and 17* are the ones with incentives.

Table 5.
Wilcoxon test on differences between mean consumed quantities by subject, for the more energy dependent consumers

Comparison	Period	PNTE	VNTE	PTE	VTE	PE	VE	E
FP-DP	N	0.005 (+)	0.040 (-)	0.000 (+)	0.000 (-)	0.001 (+)	0.000 (-)	0.025 (+)
	SR	0.000 (+)	0.005 (+)	0.000 (+)	0.000 (-)	0.000 (+)	0.000 (-)	0.000 (+)
	HD	0.000 (+)	0.124 (-)	0.001 (+)	0.002 (-)	0.000 (+)	0.001 (-)	0.000 (+)
	SR + HD	0.001 (+)	0.021 (+)	0.001 (+)	0.001 (-)	0.001 (+)	0.020 (-)	0.001 (+)
DP(T1)-DPB	SR	0.001 (+)	0.878 (+)	0.649 (-)	0.534 (+)	0.010 (+)	0.481 (+)	0.001 (+)
	HD	0.001 (+)	0.044 (-)	0.035 (+)	0.072 (-)	0.000 (+)	0.049 (-)	0.001 (+)
	SR + HD	0.001 (+)	0.933 (-)	0.362 (+)	0.362 (-)	0.003 (+)	0.492 (-)	0.001 (+)
DP(T2)-DPS	SR	0.000 (+)	1.000(=)	0.000 (+)	0.000 (-)	0.000 (+)	0.000 (-)	0.000 (+)
	HD	0.000 (+)	0.458(+)	0.000 (+)	0.000 (-)	0.000 (+)	0.000 (-)	0.000 (+)
	SR + HD	0.000 (+)	0.173(+)	0.000 (+)	0.000 (-)	0.000 (+)	0.000 (-)	0.000 (+)
DPB-DPS	SR	0.000 (+)	0.739(+)	0.000 (+)	0.000 (-)	0.000(+)	0.000 (-)	0.000 (+)
	HD	0.005 (+)	0.596(+)	0.000 (+)	0.000 (-)	0.002(+)	0.000 (-)	0.020 (+)
	SR + HD	0.003 (+)	0.131(+)	0.000 (+)	0.000 (-)	0.000(+)	0.000 (-)	0.004 (+)

In dark gray: significantly positive differences at 5% level; in clear gray: significantly negative differences at 5% level; FP: Fixed Prices; DP: Dynamic Prices; DPB: Dynamic Prices with Bonus; DPS: Dynamic Prices with Sanctions; FP-DP: the test is on the difference between mean individual consumption under the Fixed Price regime and the mean individual consumption under the Dynamic Pricing scheme, etc.; PNTE: Peak Non-Transferable Energy; VNTE: Valley Non-Transferable Energy; PTE: Peak Transferable Energy; VTE: Valley Transferable Energy; PE: Peak Energy; VE: Valley Energy; E: total Energy; N: Normal period; SR: period with Supply Restrictions; HD: High Demand period.

Result 2: *Compared to the fixed prices structure, the dynamic pricing mechanism has the effect of reducing the consumption in Peak times and slightly increasing it in Valley, leading to an overall saving of total energy consumed.*

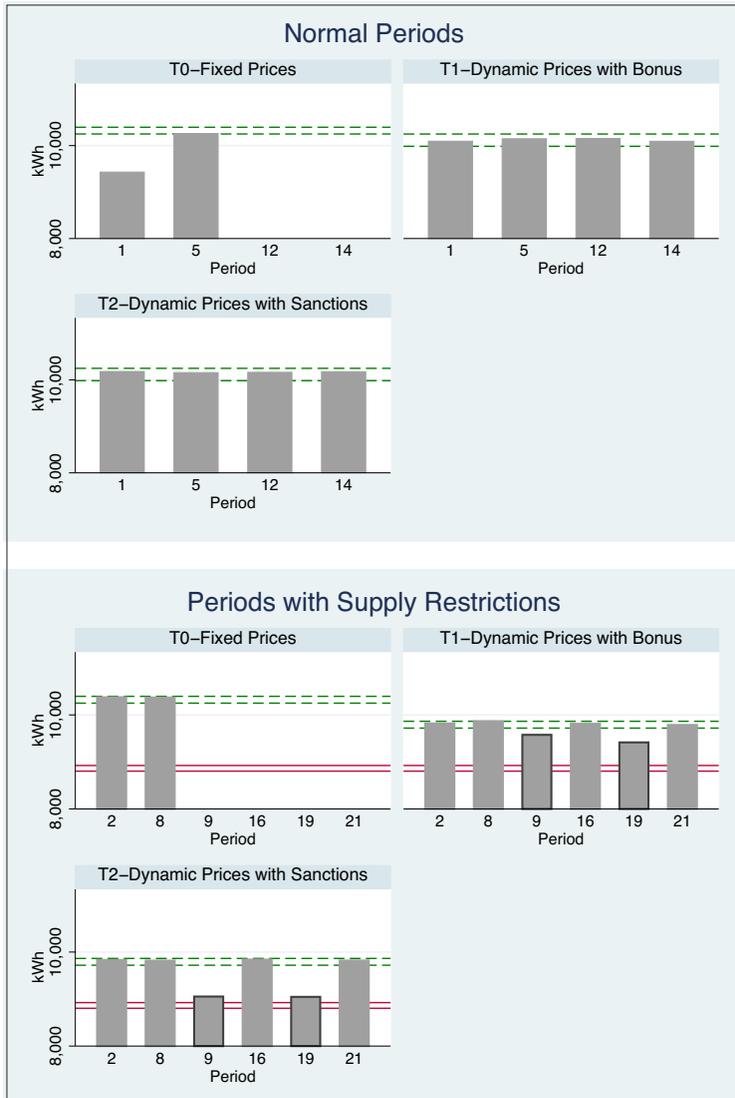
Last, in Treatments 1 and 2, where prices are allowed to change, a period characterized by a supply restriction has the effect of increasing prices and reducing energy consumption, so that the market is more efficient than in the fixed price case. Figure 4 compares average consumption between normal and supply restrictions periods for the more energy dependent consumers, in the three treatments. As commented above, supply restrictions have no effect under fixed prices. In contrast, under dynamic pricing (T1 and T2) the quantity of energy consumed in the periods with supply restrictions is much lower than the amount consumed in the normal periods, always in the range of optimal behavior at least when no incentives are in place.

Bonuses versus Sanctions. Both bonuses and sanctions, when applied, have the desired effect of decreasing consumption in Peak times. If we compare in Table 5 the non-incentivized periods in T1 (T2) to those periods of the same type in which a bonus (sanction) is in place, we can observe that Peak non-transferable energy consumption is significantly reduced in the latter case, for any type of period. From the top panel of Figure 3 we can clearly see this effect at work, although we can notice that subjects need one learning period (especially in T1, with the bonus) to adjust to the change in the market. Comparing the observed mean non-transferable energy consumption levels with the corresponding predicted ones in the Figure, the observed reduction due to a bonus results less than optimal. In Treatment T2, in contrast, sanctions appear to be more effective, given that the optimal amount of energy consumption is always reached at least in the second period in which the incentive is in place. This pattern is observed for every type of consumer and all incentivized periods.¹⁷

Thus, the Critical Peak Pricing (DPS) system appears to be far more effective in decreasing the demand in the Peak sub-period than the Peak Time Rebate (DPB), despite the fact that the two incentives were designed to induce the same energy savings. This result is confirmed in the bottom section of Table 5 (DPB-DPS): mean individual consumption of Peak electric energy is significantly lower under the system with sanctions than in the one with bonuses. Consumption of Valley energy does not receive any bonus or sanction, so that Valley non-transferable energy in particular is not affected by these incentives. Bonuses and sanctions have no effect on or slightly increase the amount of transferable energy consumed in Valley (column VTE in Table 5).

¹⁷ Additional graphs are available upon request.

Figure 4.
Average energy consumption in normal and supply restrictions periods



Dashed lines: equilibrium interval of non-transferable energy consumption in the market without incentives; *solid lines:* equilibrium interval of non-transferable energy consumption in the market with incentives (bonuses or sanctions); *periods 9 and 19* are the ones with incentives.

Result 3: *Both bonuses and sanctions significantly reduce consumption of energy in Peak times, nonetheless sanctions are more effective. Furthermore, these savings do not translate into much higher off-peak consumption.*

As far as prices are concerned, both bonuses and sanctions lead to a significant decrease in the market-clearing price of electricity in Peak times (column PEP, rows DP(T1)-DPB and DP(T2)-DPS in Table 6). Only the sanctions, however, have the effect of generating a sufficiently high level of transferability of energy towards the Valley as to significantly increase the prices in this sub-period. This effect is observed for every state of the network under sanctions (column VEP, row DP(T2)-DPS in Table 6), while bonuses do not lead to any significant changes in Valley prices.

Consumer and producer surplus. The dynamic pricing mechanism significantly reduces consumer surplus with respect to the fixed prices environment. The difference between mean consumer surpluses in these two treatments is significant, as can be seen in Table 7, which shows the related Wilcoxon test.

Within the treatments with dynamic prices, the system with bonuses leads to an increase in consumer surplus (see row DP(T1)-DPB in Table 7) due to the transfer more than compensating the decrease in consumption it produces. Sanctions, on the other hand, significantly decrease consumer surplus (row DP(T2)-DPS in the Table), given that the penalty and the reduction in consumption reinforce each other. As an extreme case, Figure 5 presents the consumer surplus in the periods with supply restrictions for the three treatments. The negative effect of the sanctions in this case is such that consumer surplus falls close to zero, while bonuses slightly increase consumer welfare with respect to non-incentivized periods.

The effects on producer surplus go in the opposite direction. Producers are better off in the presence of dynamic prices. Bonuses reduce producer surplus, while sanctions have an ambiguous effect, since the gains from the sanctions are counterbalanced by the decrease in sales.¹⁸ For example, Figure 6 shows the case of the high demand periods, where the bonuses significantly reduce producer surplus, while sanctions do not have a clear-cut effect.

Adding together all these effects on consumer and producer surpluses, overall welfare is higher under the dynamic pricing mechanism than under fixed prices, consistently with the results in Adilov et al. (2004). However, if bonuses or sanctions are applied, the dynamic pricing system loses efficiency (with sanctions being the worse in terms of total surplus). Table 8 presents the results of a Wilcoxon test on the difference between the mean total welfare under various regimes.

¹⁸ Results of the Wilcoxon test are available from the authors upon request.

Table 6.
Wilcoxon test on differences between equilibrium market prices

Comparison	Period	PEP	VEP
FP-DP	N	0.034 ^a (-)	0.023 ^b (+)
	SR	0.034 ^a (-)	0.023 ^b (-)
	HD	0.028 ^a (-)	0.046 (-)
	SR + HD	0.033 ^a (-)	0.046 (-)
DP(T1)-DPB	SR	0.034 ^c (+)	1.000 (=)
	HD	0.028 ^c (+)	0.317 (-)
	HD + SR	0.034 ^c (+)	0.317 (-)
DP(T2)-DPS	SR	0.034 ^d (+)	0.046 (-)
	HD	0.028 ^d (+)	0.046 (-)
	HD + SR	0.034 ^d (+)	0.046 (-)

In dark gray: significantly positive differences at 5%; in clear gray: significantly negative differences at 5%; FP: Fixed Prices; DP: Dynamic Prices; DPB: Dynamic Prices with Bonus; DPS: Dynamic Prices with Sanctions; FP-DP: the test is on the difference between the Fixed Price and the equilibrium price under the Dynamic Pricing scheme, etc.; PEP: Peak Energy Price; VEP: Valley Energy Price; N: Normal period; SR: period with Supply Restrictions; HD: High demand period.

Notes:

- a: Unilateral Hypothesis: PEP (FP) < PEP (DP);
- b: Unilateral Hypothesis: VEP (FP) > VEP (DP);
- c: Unilateral Hypothesis: PEP (DP) > PEP (DPB);
- d: Unilateral Hypothesis: PEP (DP) > PEP (DPS).

Table 7.
Wilcoxon test on differences between mean consumer surpluses, for the more energy dependent consumers

Comparison	Period	PCS	VCS	TCS
FP-DP	N	0.001 (+)	0.000 (-)	0.073 (+)
	SR	0.000 (+)	0.000 (-)	0.000 (+)
	HD	0.000 (+)	0.001 (-)	0.000 (+)
	SR + HD	0.000 (+)	0.002 (-)	0.001 (+)
DP(T1)-DPB	SR	0.000 (-)	0.198 (+)	0.001 (-)
	HD	0.681 (-)	0.679 (-)	0.156 (-)
	SR + HD	0.012 (-)	0.943 (-)	0.001 (-)
DP(T2)-DPS	SR	0.000 (+)	0.000(+)	0.000 (+)
	HD	0.000 (+)	0.003(+)	0.000 (+)
	SR + HD	0.000 (+)	0.001(+)	0.000 (+)
DPB-DPS	SR	0.000 (+)	0.002(+)	0.000 (+)
	HD	0.000 (+)	0.002(+)	0.000 (+)
	SR + HD	0.000 (+)	0.001(+)	0.000 (+)

In dark gray: significantly positive differences at 5%; in clear gray: significantly negative differences at 5%; FP: Fixed Prices; DP: Dynamic Prices; DPB: Dynamic Prices with Bonus; DPS: Dynamic Prices with Sanctions; FP-DP: the test is on the difference between mean consumer surplus under the Fixed Price regime and mean consumer surplus under the Dynamic Pricing scheme, etc.; PCS: Peak Consumer Surplus; VCS: Valley Consumer Surplus; TCS: Total Consumer Surplus; N: Normal period; SR: period with Supply Restrictions; HD: High Demand period.

Table 8.
Wilcoxon test comparing total welfare

Comparison	Period	PW	VW	TW
FP-DP	N	0.034 ^a (-)	0.034 ^a (-)	0.034 ^a (-)
	SR	0.034 ^a (-)	0.034 ^a (-)	0.034 ^a (-)
	HD	0.034 ^a (-)	0.034 ^a (-)	0.034 ^a (-)
	SR + HD	0.034 ^a (-)	0.034 ^a (-)	0.034 ^a (-)
DP(T1)-DPB	SR	0.034 ^b (+)	0.072 ^b (-)	0.034 ^b (+)
	HD	0.034 ^b (+)	0.072 ^b (-)	0.034 ^b (+)
	SR + HD	0.034 ^b (+)	0.307 ^b (-)	0.034 ^b (+)
DP(T2)-DPS	SR	0.034 ^c (+)	0.034 ^c (+)	0.034 ^c (+)
	HD	0.034 ^c (+)	0.034 ^c (+)	0.034 ^c (+)
	SR + HD	0.034 ^c (+)	0.034 ^c (+)	0.034 ^c (+)
DPB-DPS	SR	0.034 ^d (+)	0.034 ^d (+)	0.034 ^d (+)
	HD	0.034 ^d (+)	0.034 ^d (+)	0.034 ^d (+)
	SR + HD	0.034 ^d (+)	0.034 ^d (+)	0.034 ^d (+)

In dark gray significantly positive differences at 5%; in clear gray: significantly negative differences at 5%; FP: Fixed Prices; DP: Dynamic Prices; DPB: Dynamic Prices with Bonus; DPS: Dynamic Prices with Sanctions; FP-DP: the test is on the difference between mean total surplus under the Fixed Price regime and mean total surplus under the Dynamic Pricing scheme, etc.; PW: Peak Welfare; VW: Valley Welfare; TW: Total Welfare; N: Normal period; SR: period with Supply Restrictions; HD: High Demand period.

Notes:

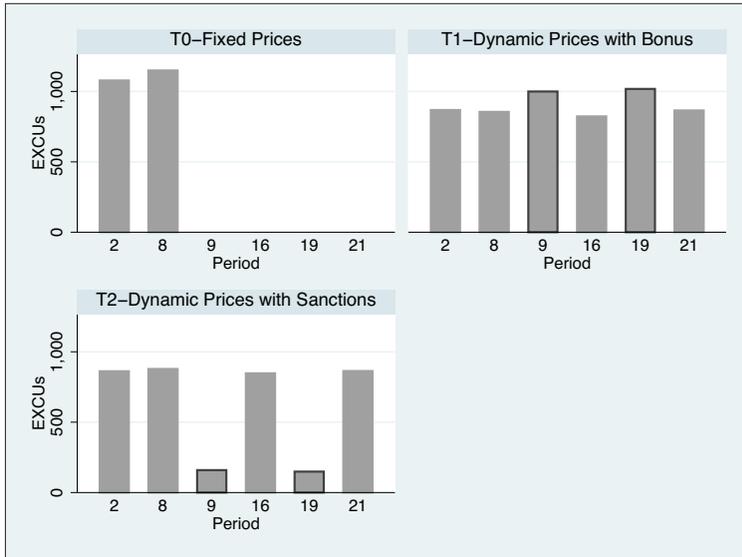
^a: Unilateral hypothesis: $PW/VW/TW (FP) < PW/VW/TW (DP)$;

^b: Unilateral hypothesis: $PW/VW/TW (DP) > PW/VW/TW (DPB)$;

^c: Unilateral hypothesis: $PW/VW/TW (DP) > PW/VW/TW (DPS)$;

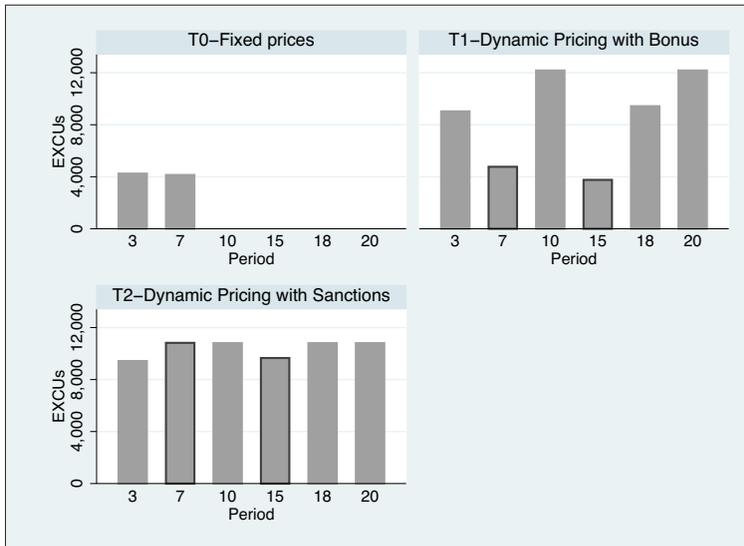
^d: Unilateral hypothesis: $PW/VW/TW (DPB) > PW/VW/TW (DPS)$.

Figure 5.
Consumer surplus in periods with supply restrictions



Periods 9 and 19 are the ones with incentives.

Figure 6.
Producer surplus in high demand periods



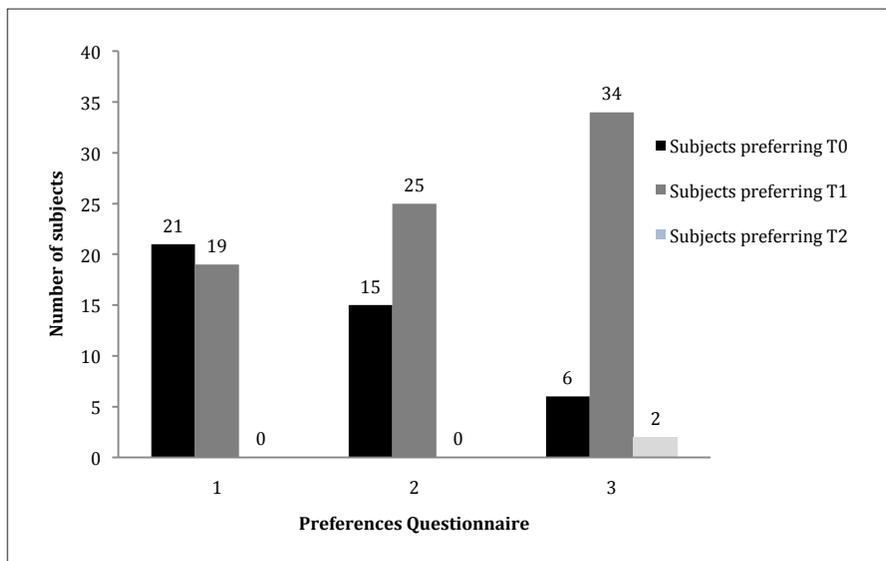
Periods 7 and 15 are the ones with incentives.

Result 4: *The most efficient system is the dynamic pricing without incentives.*

Preferences over incentives. Figure 7 presents the evolution of the subjects' preferences on pricing mechanisms, resulting from the survey filled in by participants at the end of each experimental treatment. After reading a definition of the two more complex dynamic pricing mechanisms, subjects were asked to choose their preferred regime among these two and the fixed pricing. As we can see from the Figure, 47% of the subjects declare to prefer the dynamic pricing scheme with bonus even in the first survey, before having experienced this scheme, with the rest choosing fixed prices. The percentage of individuals preferring the dynamic pricing mechanism with bonus then increases to 62.5% after their experience with the system in T1, and up to 85% after having participated in the sanctions treatment T2.

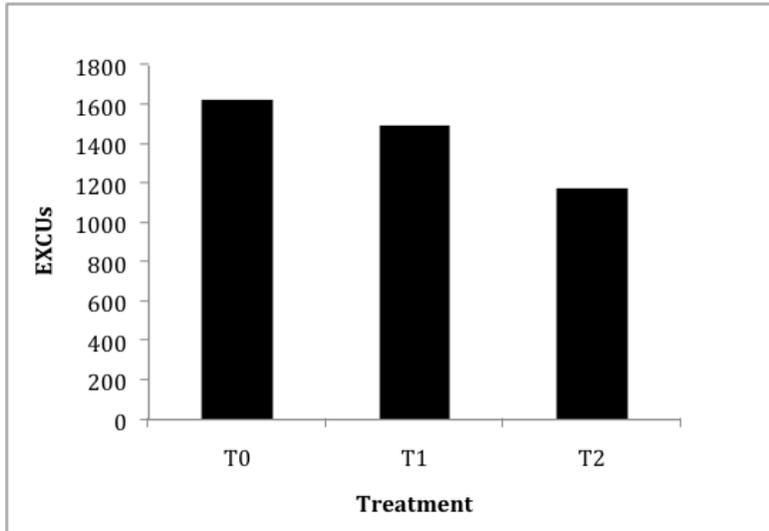
Interestingly, subjects prefer dynamic pricing with bonuses over fixed prices despite the fact that they gain more in the latter scheme. Figure 8 shows the mean gains in each of the three experimental treatments: average earnings in T0 were about 1,600 EXCUs, in T1 about 1,500 EXCUs, and in T2 almost 1,200 EXCUs.

Figure 7.
Subjects' preferences over pricing system



Source: Own elaboration.

Figure 8.
Mean gain by treatment



Source: Own elaboration.

Result 5: *Subjects prefer the dynamic pricing mechanism with bonuses, especially after experiencing it, and even more after experiencing the mechanism with sanctions, and despite the fact that their earnings were higher under the fixed prices regime.*

This result shows that individuals value factors other than earnings to assess a pricing mechanism. In particular, they seem to attribute relevance to being able to receive feedback in terms of prices from the energy market, thus having a more active role in managing their own demand. Also they obviously seem to prefer positive reinforcement rather than sanctions.

CONCLUSIONS

Our paper analyzes consumers' behavior in an experimental electricity market under three different pricing mechanisms. Subjects choose the quantity of electric energy they want to consume in peak and off-peak times, obeying certain restrictions on transferability of energy usage between the two sub-periods in a day. In the baseline framework

the energy price is fixed, that is, invariant to consumption schedule as well as to meteorological variations and network restrictions. This is the system used in most real electric consumption tariff schemes. The other two environments correspond to dynamic pricing mechanisms which can be used to actively manage electricity demand. The dynamic pricing schemes are characterized by the existence of a prediction on the expected prices that is communicated to the consumers before submitting their energy bids. Under the first environment, in some periods subjects get a bonus if they reduce their peak consumption below a certain level. Under the second, in some periods consumers are sanctioned for consuming in peak times. These two systems are designed in such a way as to allow for a neat comparison between them, given that they are aimed at motivating the same level of energy savings.

Individuals optimally adjust their behavior to different market environments, thus showing that they understand even the more complex dynamic pricing mechanisms with very short learning time (one period). Compared to the system with fixed prices, dynamic pricing is shown to lead to higher overall energy savings and is confirmed to be the most efficient system, leading to higher social welfare. The system with sanctions is by far the most effective one in cutting energy consumption in periods with exceptional congestion of the network (e.g. due to power outages or extreme weather conditions). Subjects declare to prefer the dynamic pricing system with bonus over the other systems, despite the fact that their gains were higher under fixed prices.

These results suggest that there is room for implementing active dynamic pricing mechanisms in real markets, given that they are fast and easy to learn and consumers might even prefer them to the dominant actual situation. At the same time, the higher efficiency of this system when compared to fixed pricing benefits both the environment and the utilities.

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APPENDIX

Instructions (Translated from Spanish)

This experiment is part of a study over the decision-making process in electricity markets, and will be composed of three parts, A, B and C.¹⁹ In each part, you will assume the role of a consumer who needs to consume electricity for your daily activities.

The choices you will make during the experiment will determine your gains and we are going to reward you in cash depending on these choices, according to the following rule: we are going to pay you depending on the gains you obtained in one of the 3 parts of the experiment, randomly chosen through a draw performed by hand in front of all the participants.

Please, do not try to communicate with any other participant for the whole duration of the experimental session.

General Information

You are one of 10 buyers in the electricity market. The sale of electric energy will take place in various sequential periods. Each period will be composed of two sub-periods, PEAK and VALLEY, corresponding to the daytime and the nighttime respectively.

Your utility from electric energy tells you how much you value the consumption of electricity. This utility will change depending on the quantity of energy consumption and on whether you are consuming during the PEAK or during the VALLEY. Additionally, the utility provided by the consumption of electricity will be different in certain periods, characterized by unfavorable weather conditions, which we will call HIGH DEMAND PERIODS. The utility from your electricity consumption will show on your computer screen in each period.

Figure A is an example of the computer screen you will see each period.

In the experiment, you will receive money for the electricity units you decide to buy. Your gains in any period are given by the utility provided by the electricity you consume in each block, from which you subtract the amount you paid for the energy consumed, with one exception. This exception refers to the first block of non-transferable energy in your utility function, which will be considered as a MINIMUM CONSUMPTION block, providing no gains.

Thus, you will find it in your interest to consume electric energy as long as the utility you obtain from it is higher or equal to the price you pay for it.

Moreover, in certain periods, called PERIODS with SUPPLY RESTRICTIONS, there might be energy supply restrictions motivating an increase in the costs of energy provi-

¹⁹ Parts A, B and C correspond to treatments T0, T1 and T2 respectively.

Figure A.
Example of screenshot from the experiment

Period

2 out of 22

Remaining time **1:37**

Peak Non Trans. E.	Value	Valley Non Trans. E.	Value	Peak Trans. E.	Value	Valley Trans. E.	Value
From 0 to 4570	0.90	From 0 to 2650	0.90	From 0 to 760	0.90	From 0 to 760	0.80
From 4571 to 4835	0.72	From 2651 to 2770	0.72	From 761 to 788	0.72	From 761 to 788	0.63
From 4836 to 5100	0.56	From 2771 to 2890	0.56	From 789 to 816	0.56	From 789 to 816	0.48
From 5101 to 5365	0.42	From 2891 to 3010	0.42	From 817 to 844	0.42	From 817 to 844	0.35
From 5366 to 5630	0.30	From 3011 to 3130	0.30	From 845 to 872	0.30	From 845 to 872	0.24
From 5631 to 5895	0.20	From 3131 to 3250	0.20	From 873 to 900	0.20	From 873 to 900	0.15
From 5896 to 6160	0.12	From 3251 to 3370	0.12	From 901 to 928	0.12	From 901 to 928	0.08
From 6161 to 6425	0.06	From 3371 to 3490	0.06	From 929 to 956	0.06	From 929 to 956	0.03
From 6426 to 6690	0.02	From 3491 to 3610	0.02	From 957 to 984	0.02	From 957 to 3610	0.00

Electricity Provider Data

Network Status

Price (EXCLUS/kWh) **0.12**

My Energy Demand

Non Trans. Energy (kWh)

Trans. Energy (kWh)

Peak sub-period

Supply Restrictions

0.12

Peak sub-period

(4570-6690)

(0-984)

Valley sub-period

Supply Restrictions

0.12

Valley sub-period

(2650-3610)

(0-984)

OK

sion. Last, a HIGH DEMAND PERIOD with SUPPLY RESTRICTIONS combines the characteristics of a HIGH DEMAND PERIOD and a PERIOD with SUPPLY RESTRICTIONS.

Period Type	Description
Normal Period	Standard situation.
High Demand Period	Adverse weather conditions. Ex: -20°C.
Period with Supply Restrictions	Reduction in the energy supply. Ex: electricity outage.
High Demand Period with Supply Restrictions	Combination of the two situations above.

The following terms will be used to describe the utility given to you by the consumption of electricity:

The peak non-transferable energy is the electricity that can be consumed only during the PEAK sub-periods.

The peak non-transferable energy utility represents your valuation of each block of energy consumption in the peak sub-period.

The maximum quantity of peak non-transferable energy represents the maximum quantity of energy that you can consume in a PEAK sub-period. Any quantity of peak energy above this maximum level gives you zero utility.

The valley non-transferable energy is the electricity that can be consumed only during the VALLEY sub-periods.

The valley non-transferable energy utility represents your valuation of each block of valley energy consumption.

The maximum quantity of valley standard energy represents the maximum quantity of energy that you can consume in a VALLEY sub-period. Any quantity of valley energy above this maximum level gives you zero utility.

Transferable energy is the electricity that can be consumed during the PEAK sub-periods or VALLEY sub-periods.

The utility of the transferable energy consumed during a PEAK (VALLEY) sub-period represents your valuation of each block of transferable energy consumed during the PEAK (VALLEY) sub-periods.

The maximum quantity of transferable energy represents the maximum quantity of transferable energy that you can consume in a period. Any quantity of transferable energy above this maximum level gives you zero utility.

Note: If you decide to consume a quantity X of transferable energy in a PEAK sub-period, then the maximum quantity of transferable energy that you will be able to consume in the following VALLEY sub-period is equal to the maximum quantity of transferable energy minus X .

In each period, information on the utility you receive corresponding to each consumption block for each type of energy will appear on your computer screen. Additionally, you will have access to a calculator so that you can carry out the calculations you find useful. Every period, your gains are given by the utility provided by the energy you consume minus the amount spent to buy this energy. The price of electricity will be determined in each period. The unit of account in the experimental session will be the EXCU.

As an example, assume you consume 5 units of peak energy in a PEAK sub-period, with a utility for this energy equal to 30 EXCUs per unit. Moreover, you consume 6 units of transferable energy, with a utility of 20 EXCUs per unit, and assume that the price of electricity is 10 EXCUs per unit. In this case, your gains would be $(5 \cdot 30 \text{ EXCUs}) + (6 \cdot 20 \text{ EXCUs}) - (11 \cdot 10 \text{ EXCUs}) = 160 \text{ EXCUs}$.

The amount of money you'll get will be obtained calculating your gains according to an exchange rate EXCUs/€.

Specific Information: Experiment Part A (T0)

In this part of the experiment, the price of electricity will always be the same, equal to 0.12 EXCUs per unit, during all sub-periods PEAK and VALLEY. As you know, the underlying costs of energy provision vary in certain **PERIODS with SUPPLY RESTRICTIONS**. However, in this part of the experiment, this change in costs does not affect the price you pay for energy. Your task is to choose the quantity of (peak and valley) non-transferable and transferable energy you wish to consume in each period. In order to make your decision easier, in each period you will be given information on the total quantity of each type of energy consumed in each sub-period, the expenditure incurred for your purchases, and the corresponding net gains (utility minus expenditure) obtained with your consumption. Additionally, you will receive information on your accumulated net gains up to that period.

The following is an example of the screen you will be able to see at the end of each period:

Figure B.
 Example of table summarizing the net gains from your decisions

Period		2 out of 22								
		CONSUMPTION	UTILITY	COST	BONUS	NET GAINS				
PEAK SUB-PERIOD	Non Transferable	5500	491	223						
Peak Price	Transferable	500	450	120						
0.240	Total Peak	6000	941	343	300	898				
VALLEY SUB-PERIOD	Non Transferable	3100	231	47						
Valley Price	Transferable	230	184	24						
0.105	Total Valley	3330	415	71		344				
	TOTAL	9330	1356	415	300	1241				
	ACCUMULATED					1990				
							Continue			

INSTRUCTIONS: EXPERIMENT PARTS B (T1) AND C (T2)

In this part of the experiment the price of electricity will be unknown. In each period, the price will be determined by the participants' choices as we explain in the following. Before each period begins, you will be given an INDICATIVE forecast of the energy prices in the PEAK and VALLEY sub-periods. This forecast will consist of an interval of prices for each sub-period. The final price will be closer to the minimum or to the maximum price in the interval depending on the consumption of transferable energy in each sub-period. If all consumers choose to consume ALL the transferable energy in the PEAK (VALLEY) sub-period, the price for the energy bought in PEAK will be the upper (lower) bound of the price interval corresponding to the PEAK, and the price for the energy bought in the VALLEY will be the lower (upper) bound of the price interval given for the VALLEY. The more (less) energy is transferred to the VALLEY, the more (less) the aggregate demand in the VALLEY and the less (more) the aggregate demand in the PEAK: as a consequence, the higher (lower) the price for the VALLEY and the lower (higher) the price for the PEAK.

Knowing the forecast for both sub-periods, you will have to choose the quantities of energy, non-transferable as well as transferable, to consume in the PEAK and in the VALLEY.

In order to determine the price, we add up the electricity demand of all consumers in the market. We then buy the electricity from those sellers that provide it for the cheapest prices. The price for the period will be the highest selling price offered to provide the demanded energy.

As an example, assume that buyers wish to purchase 10 units of electricity in total. Suppose that a seller sells 4 units at 1 EXCU each, a second seller offers 7 units at 2 EXCUs each, and a third seller offers 5 units at 3 EXCUs each. Four of the 10 units will be bought from the first seller and the remaining 6 units from the second one. In this case, the price in the period will be 2 EXCUs, which is the highest offered price necessary to satisfy the demand.

If consumers wished to purchase 12 units of electricity, one of the two additional units would be bought from the second seller, but the other one would have to be purchased from the third one, the consequence being that now the price of energy would be 3 EXCUs, the highest price necessary to satisfy the demand.

The prices offered by the sellers will be simulated by computer, and will not differ among periods, with the exception of the PERIOD with SUPPLY RESTRICTIONS, when the supply prices will be higher.

[Only for Part B (T1):] Additionally, in some PEAK sub-periods a bonus will be implemented which will consist in paying you an extra 0.5 EXCUs for each energy unit you consume under a certain reference level. This reference level will be based on your previous peak consumption in periods of the same type.

[Only for Part C (T2):] Additionally, in some PEAK sub-periods a sanction will be implemented which will consist in charging for each energy unit you consume an extra 0.5 EXCUs above the equilibrium market price in that period.

Given this pricing scheme, your task is to choose the quantity of (PEAK and VALLEY) non-transferable and transferable energy you wish to consume in each period. In order to make your decision easier, in each period you will be given information on the total quantity of each type of energy consumed in each sub-period, the expenditure incurred for your purchases, and the corresponding net gains (utility minus expenditure) obtained with your consumption. Additionally, you will receive information on your accumulated net gains up to that period.

The following is an example of the screens you will be able to see when having to take a decision and at the end of the period **[Part B (T1)]**:

Figure C.
Example of screenshot from part B (T1)

Period
2 out of 22
Remaining time 140

Peak Non Trans. E.	Value	Valley Non Trans. E.	Value	Peak Trans. E.	Value	Valley Trans. E.	Value
From 0 to 4570	0.90	From 0 to 2650	0.90	From 0 to 760	0.90	From 0 to 760	0.80
From 4571 to 4835	0.72	From 2651 to 2770	0.72	From 761 to 788	0.72	From 761 to 788	0.63
From 4836 to 5100	0.56	From 2771 to 2890	0.56	From 789 to 816	0.56	From 789 to 816	0.48
From 5101 to 5365	0.42	From 2891 to 3010	0.42	From 817 to 844	0.42	From 817 to 844	0.35
From 5366 to 5630	0.30	From 3011 to 3130	0.30	From 845 to 872	0.30	From 845 to 872	0.24
From 5631 to 5895	0.20	From 3131 to 3250	0.20	From 873 to 900	0.20	From 873 to 900	0.15
From 5896 to 6160	0.12	From 3251 to 3370	0.12	From 901 to 928	0.12	From 901 to 928	0.08
From 6161 to 6425	0.06	From 3371 to 3490	0.06	From 929 to 956	0.06	From 929 to 956	0.03
From 6426 to 6690	0.02	From 3491 to 3610	0.02	From 957 to 984	0.02	From 957 to 3610	0.00

Electricity Provider Data

Network Status

Price (EXCLUS/kWh)

Between 0.24 and 0.33

Peak sub-period

Supply Restrictions

Between 0.10 and 0.17

Valley sub-period

Supply Restrictions

My Energy Demand

Non Trans. Energy (kWh)

Trans. Energy (kWh)

(0-984)

(4570-6690)

(2650-3610)

(0-984)

(0-984)

OK

Due to an exceptional congestion of the network a saving Bonus protocol has been activated.

Your benchmark consumption in the peak sub-period that will be used to calculate your Bonus is: **6600**

The Bonus for each kWh that you save with respect to your benchmark consumption will be: **0.50**

Figure D.
Example of table summarizing the net gains from decisions taken in Part B (T1)

Period		2 out of 22								
		CONSUMPTION	UTILITY	COST	BONUS	NET GAINS				
PEAK SUB-PERIOD	Non Transferable	5500	491	223						
Peak Price	Transferable	500	450	120						
0.240	Total Peak	6000	941	343	300	898				
VALLEY SUB-PERIOD	Non Transferable	3100	231	47						
Valley Price	Transferable	230	184	24						
0.105	Total Valley	3330	415	71		344				
	TOTAL	9330	1356	415	300	1241				
	ACCUMULATED					1990				

Continue

QUESTIONNAIRE ON PREFERENCES

In the following, we present a brief description of two alternative markets for electric energy: Dynamic Prices with Sanctions (DPS) and Dynamic Prices with Bonuses (DPB).

[Only for Part A (T0)] Based on your experience in the fixed prices system, please indicate which alternative you prefer.

[Only for Part B (T1)] Based on your experience in the two mechanisms, please indicate which alternative you prefer.

[Only for Part C (T2)] We are at the end of the experiment. Based on your experience in the three mechanisms, please indicate which alternative you prefer.

Dynamic Prices with Sanctions (DPS)

In this scheme, price of electricity is unknown. The price of each period will be determined by the equilibrium between demand and supply in the market. Before each period begins, you will be given an ILLUSTRATIVE forecast of the energy price for each sub-period, PEAK and VALLEY. This forecast consists of an interval of prices for each sub-period. Additionally, in some PEAK sub-period, a sanction will be put in place which will consist of charging an additional amount per unit of energy on top of the market price in the PEAK.

Dynamic Prices with Bonuses (DPB)

In this scheme, price of electricity is unknown. The price of each period will be determined by the equilibrium between demand and supply in the market. Before each period begins, you will be given an ILLUSTRATIVE forecast of the energy price for each sub-period, PEAK and VALLEY. This forecast consists of an interval of prices for each sub-period. Additionally, in some PEAK sub-period, you will be given an extra reward for each energy unit you consume under a certain reference level. This reference level will be based on your previous peak consumption in periods of the same type.

Please **point out** which alternative you prefer among:

- 1) Fixed prices
- 2) Dynamic prices with sanctions
- 3) Dynamic prices with bonuses