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Wright tariffs in the Spanish electricity industry The case of residential consumption

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Abstract

In this paper a capacity price model is developed for the Spanish electricity industry which allows the presentation of the Spanish utilization level tariffs as an example of duration tariffs (Wright tariffs) when duration is approximated by the ratio of consumption to power used. Using this model and data on the residential consumption of electricity, several optimal two-part tariffs are computed, considering different hypothesis on the configuration of the generating equipment. It has been found that the optimal tariff maintaining universal service increases welfare if the generating equipment and the output assigment to the different technologies are taken as given. Furthermore, if the regulator is concerned not only with efficiency, but also with distributive issues, then welfare losses associated with the existing regulatory regime are even larger. © 1999 Elsevier Science Ltd. All rights reserved.

JEL classification: L51; L94

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1. Introduction

In markets where the demand is not stable over time and production is not storable, firms must install a level of capacity that meets the highest foreseeable levels of demand. This is the case of the electricity market where the operation of its different components must be coordinated in order to meet demand in each time of use with adequate quality characteristics. For this reason the electric system needs to maintain a maximum generating capacity sufficient to meet the greatest energy demands, but since consumer behavior is not stable, some capacity remains idle during off-peak periods.

In order to reduce the costs of idle capacity, electric systems install several types of generating equipment. Base-load power is met with equipment having a high cost of acquisition (capital costs) but a low cost of operation. On the other hand, peak loads are met with equipment having a lower cost of acquisition and a higher cost of operation. The lower acquisition cost of the peaking equipment allows companies to reduce the cost of idleness in off-peak periods. This results in higher marginal operating costs when demand peaks.

To account for the particular characteristics of the electric sector, tariffs must be designed to separately account for capacity and operating costs, and reflect the differences in these costs among the technologies used. That is to say, tariffs must be designed in function of the two dimensions of electricity: power and duration. A variety of pricing is used in electricity industries. One form of electricity pricing is the Wright tariff used occasionally in the United States and prominently in the tariffs offered by Electricite de France (EDF) (see Wilson (1993) and Laffont (1994)). Wright tariffs attempt to reflect the long-run cost structure of the utility by setting charges based on the time that each unit of power is used during the year (duration). That is to say, a unit of power supplied for a specific duration in the long-run costs the utility the capital cost of one unit of generating capacity and an operating cost proportional to the duration and the operating cost of that type of generator.[1] However,

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[1] American regulatory agencies have opposed Wright tariffs favoring instead a philosophy of 'immediate causation' of short-term costs, and therefore time-of-use tariffs based on the capacity and operating costs of the marginal generator. However, a few utilities have introduced so-called load-factor tariffs that essentially are Wright tar-

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the implementation of these tariffs requires knowledge of the exact consumption pattern of each consumer during the time for which sophisticated and expensive individual meters would be needed. In some countries this problem has been solved by approximating an individual consumption pattern by the 'utilisation level' defined as the ratio of consumption to power used. So, the yellow and green tariffs in France set fixed prices and energy charges based on different categories of utilisation. The Spanish tariff structure also differentiates tariffs by utilisation levels.

In this paper a model is developed in order to study the design of Wright tariffs when the utilisation level is used as an approximation to duration and the restriction that the producer must cover its costs is considered. This model is used to compute optimal two-part tariffs for the utilisation level of the Spanish residential sector considering several hypotheses on the configuration of the generating equipment. This will allow us to estimate the degree of optimality of the current tariff and to obtain an approximation of the efficiency losses attributable to the existing regulatory regime in the case of Spain. This model is an application of Oren et al. (1985) where the duration of consumption is approximated by the utilisation level and the price schedule is restricted to a two-part tariff.

Most studies in economic literature derive optimal tariffs for electricity without explicitly considering its multi-dimensional character. These studies do not consider the existence of capacity and operating costs, and they use the average cost as an approximation to the marginal cost. Dimopoulos (1981) examines the implications of implementing different pricing schemes for electricity using data from the Wisconsin Power and Light Company. He uses a marginal cost of electricity based on estimated marginal costs depending on the time of day calculated in other studies. Buisan (1992) obtains an optimal two-part tariff for household consumption of electricity in Spain with data from 1989 and determines welfare losses due to the Spanish tariff actually used that year. In order to do this, she uses an average cost associated to an estimated demand profile of residential consumption as an approximation to marginal cost. In this paper electricity is presented as a two-dimensional product and it is shown that, by using utilisation levels as an approximation to duration, the marginal cost is the sum of a share of capacity cost and operating cost of the efficient technology for the duration. It is also shown that the costs can be expressed as a function of individual consumption and so, the results with uni-dimensional prices are applicable (see Goldman et al. (1984) and Brown and Sibley (1986)).

The assumptions that are common in the literature on nonlinear pricing in the sense of not considering rent effects and the inability of product resale are adopted. The regulator may supervise the consumption of individuals and he knows the distribution of consumer types and their preferences. It is assumed that the regulator uses the concept of utilisation level, defined as the ratio of consumption to power used, as an approximation to the consumption pattern of the individuals.

The structure of the paper is as follows. In the Section 2 the basic framework of the capacity price model is presented. Section 3 adapts the model for the case in which duration is approximated by utilisation levels. In the Section 4 the parameters used in the empirical analysis are specified. Section 5 is dedicated to computing two-part tariffs by utilisation levels for residential consumers and to efficiency analysis. Finally, conclusions are presented.

2. Basic concepts

2.1. Load-duration curve

In the case of services such as electrical power where supply is comparatively stable with respect to demand, this can be described in two ways: by demand at different hours of the day and by the load-duration curve giving the numbers of hours that demand exceeds a given level. Fig. 1 presents the load-duration curve of the Spanish electricity system for 1993.

The two axes of the load-duration curve may be interpreted as the consumption rate and the time duration, and its magnitudes are referred to as capacities. The

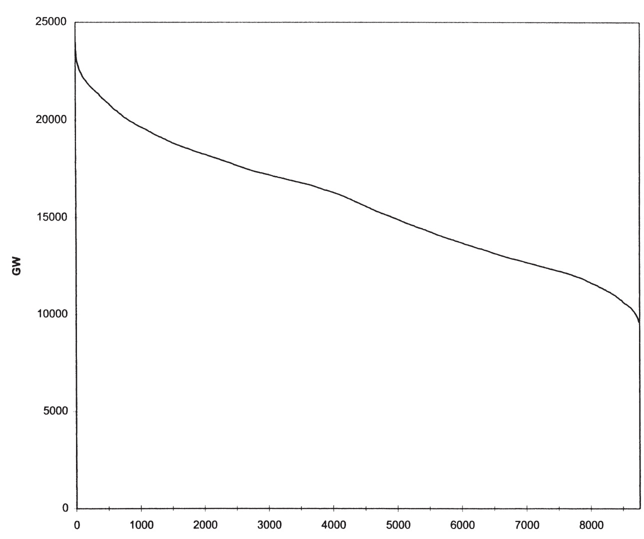

Fig. 1. Load-duration curve, 1993 (CSEN).

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iffs by another name. On the other hand, differentiated demand charges offered by some American electric companies can also be interpreted as involving the principles of a Wright tariff to encourage load levering (see Wilson, 1993).

maximum capacity level represents the maximum consumer demand vertically ('demand peak'), and horizontally, the maximum time interval in which the system operates (for example, a year). In the case of electrical energy consumption the dimensions are power and duration, and the load-duration curve can be interpreted as the number of hours $H(l)$ for which the power demanded is at its least l, or as the smallest power level $L(h)$ that is demanded for a duration of no more than h hours. $H(\cdot)$ and $L(\cdot)$ are non-increasing, with $L(0)$ and $L(1)$ denoting peak and load demand respectively, supposing that duration is expressed as a fraction of the time period considered.

The area under the load-duration curve represents the consumption set Q in kilowatt-hours (kWh) of the individual. In this sense, the load-duration curve may be interpreted as a function of the distribution that determines the probability (in a fraction of cycle hours) that the power demand by the individual will be greater than a determined level.

2.2. Costs

In order to determine the costs associated to a consumption set Q determined by a load-duration curve, it is considered that the electrical system uses different production technologies. In the linear case

$$c_i(h)=f_i+v_ih, \qquad (1)$$

is the cost per kilowatt using technology i for a duration h, where f_i is the unitary capacity cost (amortised cost of generating equipment per kilowatt of power), and v_i is the operating cost per kilowatt-hour (kWh). These capacity and operating costs are such that each technology is the most efficient in some range of the duration, as long as there is infinite divisibility.[2]

Projecting the efficiency range of each technology onto the load-duration curve we may obtain the optimal capacity configuration (optimal technology mix), that is to say, the number of kW of each technology that must be installed in order to supply the energy requirements of the system. Thus, in a three technologies case, as in Fig. 2, the low capacity cost technology (I) will be used to satisfy the peak load, while the low marginal cost technology (III) will be more appropriate for the base load, and the intermediate technology (II) meets the needs of the shoulder load.

The total cost of supply for consumption set Q, determined by the load-duration curve with the optimal technology mix, may be obtained for a particular duration range using the cost functions corresponding to the technologies dispatched in that range. It should be noted that the efficient operating cost of any generating unit as a function of duration is given by the lower envelope of each technology's particular cost function. This envelope may be interpreted as a nonlinear cost function of capacity use, and its concavity reflects the fact that technologies with low operating costs are assigned to capacity units that are used for longer periods of time. In the linear case, the efficient cost envelope will be

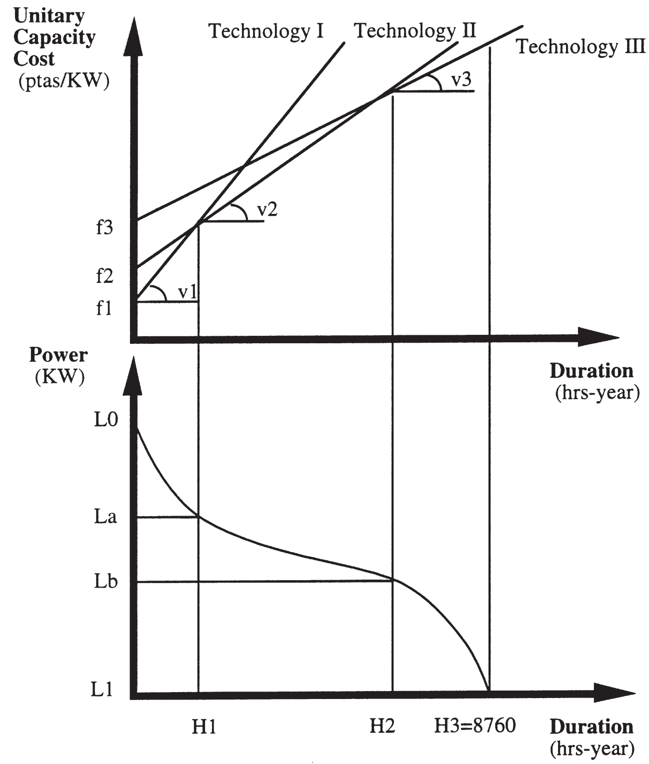

Fig. 2. Optimal mix of production technologies.

$$e(h)=\min_i c_i(h), \qquad (2)$$

where $i(h)$ indicates the efficient technology for duration h.

The total cost of the consumption set when horizontal slices are considered can be obtained by adding the costs originated by each kilowatt of power used, which will depend on the technology that has supplied them and on the duration. Thus, for example, in Fig. 3 it is found that a kilowatt of power l in the interval $L_b<l<L_a$ gives rise to a capacity cost f_2 and a marginal operating cost v_2 since it is supplied by technology II, which is the most efficient for a kilowatt of duration h, $H_1<h<H_2$. The total cost associated with a load-duration curve like that of Fig. 3, with a maximum power demand of L, when three technologies intervene will be given by

$$C(L)=C_0+\int_{L_1}^{L_b}(f_3+v_3H(x))dx+\int_{L_b}^{L_a}(f_2+v_2H(x))dx \qquad (3)$$

[2] With infinite divisibility each kilowatt is produced by a technology and thus an optimally configured generating system may not include technologies that are cost dominated.

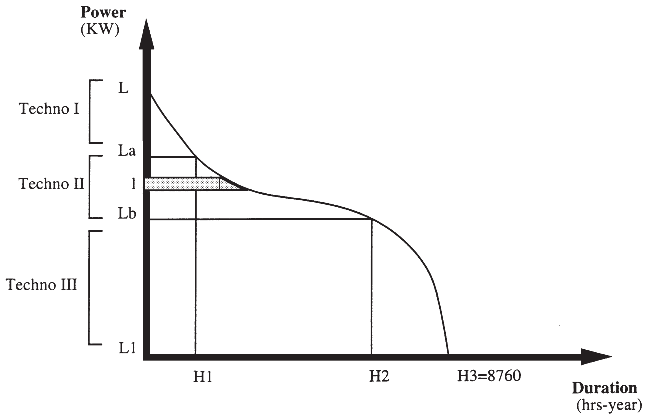

Fig. 3. Horizontal slice costs of load-duration curve.

$$+\int_{L_a}^{L}(f_1+v_1H(x))dx$$

where C_0 represents fixed costs not associated with production (stranded and administrative costs).[3]

2.3. Wright tariffs and utilization level tariffs

Wright tariffs fix prices taking into account the number of hours each kilowatt that is demanded is used and, accordingly, they take as a reference the horizontal slice costs of the load-duration curve that were analyzed in the previous section. In this sense these tariffs attempt to adapt to the cost structure derived from the generating equipment in order to meet the load-duration curve. That is to say, a unit of power supplied for a specific duration in the long-run costs the utility the capital cost of one unit of generating capacity and an operating cost proportional to the duration and the operating cost of that type of generator.[4]

Direct implementation of Wright tariffs requires, nevertheless, knowledge of the exact load-duration curve of each individual, for which sophisticated and expensive individual measuring equipment would be needed. In some countries this problem has been solved by approximating individual load-duration curves with the utilisation category defined as the ratio of consumption to power used by the consumer, and represents a direct relation with the individual's consumption pattern. In fact, it has been found that the proportion of consumption in a peak-load period is decreasing on the utilization level, while the proportion of consumption in a base-load period is increasing.

The utilization level summarises in one variable (quantity consumed) the information of the two dimensions of electricity, power and duration, which allows for the design of tariffs based exclusively on individual consumption. This also explains that in utilization level tariffs one cannot consider usage prices and capacity prices, and that different parts of the tariff contribute to covering usage and capacity costs.

In the case of the Spanish electricity industry, the tariff structure in 1993 presents a double differentiation. First, it differentiates tariffs by level of voltage distinguishing between high and low voltage tariffs. This differentiation tries to reflect the cost of transmission losses which are inverse to level of voltage. Second, tariffs differ according to the utilization or load-factor of the consumer. At low voltage levels there are tariffs for normal utilization and long utilization. At higher voltages there are three groups of general tariffs for low, normal and long utilization, respectively. Furthermore, the tariff schedule presents special tariffs for specific types of use such as public transport, agriculture and so on.[5] In this sense, Spanish electricity pricing follows a the methodology of Wright tariffs, and this structure will be maintained for some years within new regulation introduced by the 1997 Electricity Act, at least for the domestic and small business consumers in the 'franchise market', who will be supplied by local monopolies (see Kuhn and Regibeau (1998)).

3. A theoretical model of utilization level tariffs

3.1. Consumption set

The use of the utilization level concept in order to approximate the duration of the consumption of the kilowatt-hours used is equivalent to considering the individual's consumption set to be a rectangle of height equal to the power used L and a base equal to the utilization level h_u (see Fig. 4). That is to say, each group of consumers is associated with the most efficient technology for a duration range equal to his utilization level.

3.2. The cost function

Consider a rectangular load-duration curve that reflects consumption corresponding to L kilowatts of power used for a maximum duration of h_u, which is determined by the ratio between consumption q and the power used, h_u (h_u=q/L).

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[3] In Appendix A the case of cost aggregation using vertical intervals is presented. A more general cost formula is presented in Oren et al. (1985).

[4] In the short run the cost structure may be modified by demand or operating cost variations, thus time-of-use tariffs associated with real system demand each hourly period are also used.

[5] Each tariff has a charge for power (ptas/kW) and a charge for energy (ptas/kWh). For consumers in low voltage the power charge is based on subscribed demand but for consumers in high voltage it can be based on a metered maximum demand, according to what the consumer wants.

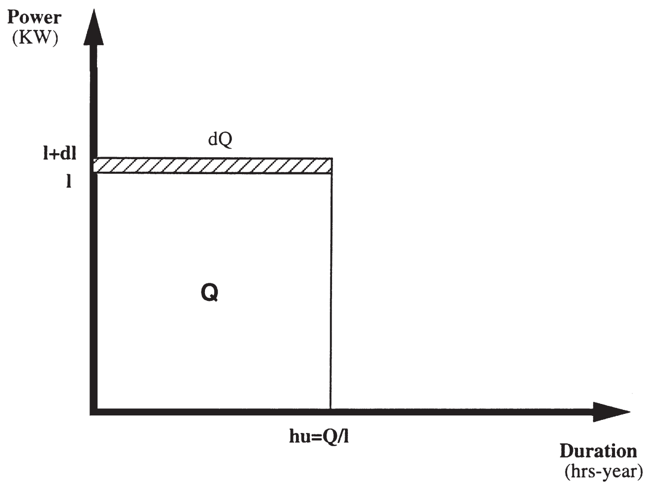

Fig. 4. Rectangular load-duration curve for an utilization level h_u.

The cost of supplying consumption set q with an optimal mix of production technologies, that is to say, when consumption is supplied completely by the efficient technology for duration h_u is

$$C(L)=C_0+L(f_i+v_i h_u), \tag{4}$$

where f_i and v_i represent the unitary capacity cost and the unitary operating cost for the efficient technology for a duration h_u, L are the kilowatts of power used, and C_0 non-productive productive fixed costs.

Using the definition of utilisation level ($h=q/L$), the cost function may be expressed by

$$C(q)=C_0+mq, \tag{5a}$$

where m represents the marginal cost of consuming an additional good, and may be defined as

$$m=\left(\frac{f_i}{h_u}+v_i\right) \tag{5b}$$

Thus, for a particular and constant utilisation level, h_u, costs are a function of kWh consumption.

It is implicitly assumed that consumers do not vary their consumption pattern and that the only way to raise their consumption is to raise the power used. Under this assumption it makes sense to think of marginal cost as the cost increment caused by using an additional kW of power to be consumed for a duration of h_u. Thus, the marginal cost will be the sum of the capacity and operating costs of the efficient technology, as can be seen in the cost function given.[6]

However, the cost of supplying consumption set q depends on the optimal technology mix used to meet the system load-duration curve. In this sense, the costs incurred in the supply of a consumption set q will result from aggregating the costs incurred by the different generating technologies used. If it is supposed that $j=1,\ldots,s$ technologies are used, with technology s being the most efficient for duration h_u, the costs of supplying consumption set q will be

$$C(q)=C_0+\sum_{j=1}^{s-1}\left(\frac{f_j}{h_u}+v_j-\frac{f_s}{h_u}-v_s\right)q_j+\left(\frac{f_s}{h_u}+v_s\right)q, \tag{6}$$

where $q_j=h_u l_j$ are the levels of consumption supplied by technologies $j=1,\ldots,s-1$, not efficient for duration h_u, with l_j being the power used from each technology.[7]

3.3. Individual demands

The heterogeneity of consumers has a central role in nonlinear pricing because the payment structure is designed to induce self-selection between consumers. These differences are reflected in the consumption choices. In this way to increment efficiency the consumers pay different prices in function of their consumption. This heterogeneity is represented by parameter $\theta\epsilon[\underline{\theta},\theta]$ which is characterised by a distribution function $F(\cdot)$ with density pattern $f(\cdot)$ (distribution of consumer types). The gross benefit obtained by a consumer of type θ is $U(q,\theta)$ if he purchases q units or, in terms of the consumer's surplus, it is $S(q,\theta)$, with $S_q>0$, $S_{qq}<0$, $S_\theta>0$ and $S_{q\theta}>0$. A higher θ implies both a higher gross surplus and a higher willingness to pay for an extra unit.

3.4. Distribution of consumer types

For the purposes of nonlinear pricing it is necessary to know the preferences and the frequency distribution of consumer types. In the case where the valuation of the consumers for the good is not directly observed but the current tariff is such that consumers with different preferences demand different amounts of the good, the distribution of observed consumption can be used to approximate the distribution of consumer types (see Brown and Sibley, 1986; Castro et al., 1997; Mitchel, 1978). This will be the case analyzed in this paper because the current tariff is a two-part tariff.

3.5. Social welfare

If $T(q)$ is the tariff paid for consuming q units of the good, net consumer surplus can be defined as the difference between gross consumer surplus and payment, $S(q,\theta)-T(q)$.

A modified Social Welfare Function of Feldstein

[6] This assumption seems relatively reasonable for the residential sector which is characterised by a homogeneous and constant consumption.

[7] This was the case of the residential sector electrical supply in 1993 which is studied in the next section.

(1972) is used where the participation level is considered endogenous. In particular, social welfare derived from the consumption of the product is defined as the weighted sum of the monetary value of the net surplus of all the consumers

$$W=\int_{\theta_*(T)}^{\infty}[S(q,\theta)-T(q)]u'(\theta)f(\theta)d\theta, \quad (7)$$

where the weight assigned to each subscriber $u'(\theta)=\theta^{-\eta}$ is a function of the consumer type θ and presents a constant demand elasticity η. Thus the larger η is, the larger the weight assigned to the welfare of consumers with low consumption levels is. Parameter θ_* identifies the marginal consumer that is indifferent between purchasing and not purchasing for the given tariff, that is, $S(q,\theta^*)-T(q(\theta_*))=0$. All consumers with type $\theta \geq \theta_*$ purchase a positive amount and those with type $\theta < \theta_*$ do not consume.

3.6. Optimal tariff

A regulated firm that produces only one type of product is considered. This firm has to satisfy a budget constraint, that is, total revenues must be equal to total costs plus an exogenously specified amount, B. This exogenous amount, B, can be positive, in concept of a profit or surplus above costs, zero when the firm must strictly cover costs, or negative when government subsidies are permitted. The objective of the regulated firm is to maximise social welfare. The optimal tariff is derived then by maximising social welfare

$$W=\int_{\theta_*(T)}^{\infty}[S(q,\theta)-pq-A]u'(\theta)f(\theta)d\theta, \quad (8a)$$

subject to the firm's budget constraint

$$\int_{\theta_*(T)}^{\infty}T(q(p,\theta))f(\theta)d\theta-C(Q)-B=0, \quad (8b)$$

and by having that the marginal consumer θ_* obtains a non-negative net surplus

$$S(q,\theta_*)-T(q(p,\theta_*))\geq 0. \quad (8c)$$

Total consumption is defined as

$$Q=\int_{\theta_*(T)}^{\infty}q(p,\theta)f(\theta)d\theta. \quad (8d)$$

4. Specification of the parameters

In order to compute the optimal tariff by utilization level for residential consumption of electricity, data on consumption, revenues and prices referring to tariff 2.0 for 1993 of the Spanish electricity system have been used (see appendix). The year 1993 is used as the base year since it represents a normal year prior to the first regulatory reform in 1994. Tariff 2.0 of the Spanish tariff structure is targeted for consumers who used power in the 0.77 kW to 15 kW range, practically all residential consumers. In 1993 there were more than 17 million subscribers to tariff 2.0 that represented more than 93% of the total number of consumers, with an approximate consumption of 36 920 gigawatt-hours (GWh) through the year, which accounted for 28.8% of total consumption. The total revenue generated by the tariff was more than 747 340 million pesetas (ptas), this amounted to 40% of the total revenues of the industry.

4.1. Residential utilization level

In order to compute the utilization level of the residential sector, considering a similar consumption pattern for all the subscribers to tariff 2.0, and taking into account that it is not possible to know the power really used by it, 61.61% of the system's maximum demand of power (23 990 MW) is considered as power used for residential consumers. This assumption is based on the fact that the billed power in tariff 2.0 amounted to 61.61% of total billed power in 1993. Thus, given the 36 920 Gwh of residential demand in 1993 a utilization level of 2498 hours is obtained, that is, a short utilization level is obtained.

4.2. Costs

In 1993 demand was covered by a mixed thermo-hydrolectric generating system, in which the hydroelectric power represented 31.72% of total installed power, with a production of approximately 18% of total production.

The hydro technology of the Spanish system has the role of regulating the system meeting demand peaks in all time periods. Thus, it cannot be concluded that hydro technology is responsible for a specific level of utilization. In this sense, its costs cannot be assigned to a particular consumption, but rather all consumers, regardless of their utilization level, are responsible for covering its costs. In this way, taking into account that consumption of tariff 2.0 in 1993 represented 28.8% of total consumption, it is assumed that 28.8% of hydroelectric production (6705 MWh) has been assigned to meet residential demand.

In terms of equipment, the Spanish electric system has several types of generating technologies: nuclear, coal, hydro, and oil/gas, all of which were used to cover electrical demand in 1993. In Table 1 the most important cost characteristics as well as total output of the generating equipment are presented. Capacity costs are obtained considering the standard costs of amortisation and retri-

Table 1
Technologies data in 1993 (1 pta=0.0065 $ USA)[a]

Technology	Power (MW)	Capacity cost (ptas/kW)	Operating cost (ptas/kWh)	Production (GWh)
Nuclear	7401	46977	1.2494	53538
Anthracite	5961	13691	5.6351	28976
Brown lignite	1950	20674	5.1593	11960
Black lignite	1450	20793	5.8228	8178
Imported coal	1314	17404	3.2560	8601
Oil/Gas	7910	4732	4.8571	1795
Hydro	16996	7900	0.7499	23282

[a] Source: Regulatory Comission of Spanish electricity (CNSE) and Red Electrica de Espana, S.A. (REE).

bution, and the fixed costs of operation and maintenance set by the Stable Legal Framework (SLF), the legislative act that regulates the Spanish electricity industry, for each active generating plant. Variable costs are obtained by aggregating fuel costs, and variable costs of operation and maintenance.[8]

4.3. Demand

It is assumed that the individual demand function is isoelastic, and depends on the price p paid for each unit consumed and on the parameter θ that identifies each consumer type (this will depend, among other things, on the consumer's income level).

$$q(p,\theta)=a\theta p^{-b}, \tag{9}$$

where a is a scale parameter and b represents the price elasticity of demand. Note that the demands are ordered according to parameter θ, in such a way that if each consumer consumes according to his preferences, a larger valuation for the product (a larger θ) results in higher consumption.

The results of the demand estimation for the Spanish residential sector in Castro (1996), where the price elasticity of demand is estimated to be -1.8, are taken.[9]

4.4. Distribution of consumer types

For the estimation of the distribution of consumer types the observed frequencies of consumption for 1993 are used.[10] These frequencies are distributed in a sample space divided into 29 intervals, all of an amplitude of 500 kWh, with the exception of the last one which includes all users with a consumption of 14 000 kWh or higher (see Appendix A). The observed frequencies will be denoted by f_i,i=1,…,29.

The observed consumption distribution presents two distinct patterns, the lower levels of consumption present a clearly linear structure while higher levels of consumption present a slow nonlinear decrease of mass more adequately fitted with a Pareto density. Thus the fitted frequency is given by

$$f_\theta(r,k,\theta_0,\alpha)=\begin{cases} r(\theta-\theta_a) & \text{if } \theta_\alpha<\theta<\theta_0 \\ \alpha k^\alpha \theta^{-\alpha-1} & \text{if } \theta_0<\theta<\infty \end{cases}, \tag{10a}$$

which must verify the following conditions

$$r(\theta_0-\theta_a)=\alpha k^\alpha \theta_0^{-\alpha-1} \tag{10b}$$

$$\int_{\theta_a}^{\theta_0} r(\theta-\theta_a)d\theta+\int_{\theta_0}^{\infty}\alpha k^\alpha\theta^{-\alpha-1}=1, \tag{10c}$$

where θ_a is the smallest type, θ_0 is the value of θ where the density function changes from linear to Pareto, r is the parameter of the linear part and α, k are the parameters of the Pareto part.

The associated distribution function will then be

$$F_\theta(\theta_0,\alpha)=\begin{cases} \frac{r}{2}(\theta-\theta_a)^2 & \text{if } \theta_a<\theta<\theta_0 \\ k^\alpha(\theta_0^{-\alpha}-\alpha^{-\alpha})+\frac{r}{2}(\theta_0-\theta_a)^2 & \text{if } \theta_0<\theta<\infty \end{cases}. \tag{11}$$

In order to make the continuous theoretical distribution $F(\theta)$ compatible with the discrete sample information, the discrete probabilities that $F(\theta)$ assigns to the 29 consumption intervals for which there exist observed frequencies are obtained. The theoretical probabilities are denoted by p_i, i=1,…,29. In terms of $F(\theta)$ will be

$$p_i=\begin{cases} F_q(500i)-F_q(500i-500) & \text{if } i\le 28 \\ 1-F_q(500i-500) & \text{if } i=29 \end{cases}. \tag{12a}$$

and using the definition of F_q will be

$$p_i(\theta_0,\alpha) \tag{12b}$$

$$=\begin{cases} F_\theta\left(\frac{p^b 500i}{a}\right)-F_\theta\left(\frac{p^b(500i-500)}{a}\right) & \text{if } i\le 28 \\ 1-F_\theta^q(500i-500) & \text{if } i=29 \end{cases}.$$

which is a function of the distribution parameters θ_0, α.

[8] These costs have been obtained considering all active plants in 1993, some of which were fully amortised and presented a null gross discounted value.

[9] There exist other estimates of the price elasticity of electricity demand in Spain, but all of them estimate a short-run elasticity. In Castro's study (1997) a model of long-run electricity demand to the Spanish residential sector is estimated, and a long-run elasticity is obtained, which is more appropriate for computing Wright tariffs.

[10] This is justified by the fact that the current tariff in 1993 is a two-part tariff (see Castro et al., 1997).

Following the discretization, the consumption space can be seen as a discrete 29-point space in which a probability mass function is defined. The observed frequency of each of these points ($f_1,\ldots,f_{29}$) are also available.

If any of the parameters on which the theoretical distribution function is dependent is unknown, it can be estimated by maximum likelihood. An alternative approach is to minimise the χ^2 statistic of the goodness of fit test of the observed frequencies to the theoretical probabilities $p_1,\ldots,p_{29}$; it is known that this is equivalent to the maximum likelihood estimation (see Read and Cressie (1988)).

Otherwise, the estimated parameters must be compatible with the observed model and data. In this sense, it must be taken into account that the constant term of the demand function, a, depends on (θ_0,α) since it is derived from the relation

$$Q_0=N\int_{\theta_a}^{\theta_0} a\theta p_0^{-b} r(\theta-\theta_a)d\theta + N\int_{\theta_0}^{\infty} \alpha\theta p_0^{-b}\alpha k^{\alpha}\theta^{-\alpha-1}d\theta, \tag{13a}$$

where Q_0 is the annual consumption with the current tariff structure, a two-part tariff with an entry fee A_0 and a marginal price p_0. Thus, the parameter a can be expressed as a function of (θ_0,α)

$$a=\frac{Q_0p_0^bN^{-1}}{I(\theta)}. \tag{13b}$$

with $I(\theta)=\int_{\theta_a}^{\infty}\theta f(\theta)d\theta$.

The parameters (θ_0,α) must give a value of a compatible with the data associated with the current tariff. In particular if θ_a is the smallest individual that participates in the current tariff, its net surplus must be non-negative. This is to say that,

$$S^N=S(q_0,\theta_a)-p_0q(p_0,\theta_a)-A_0=\frac{a}{b-1}\theta_a p_0^{1-b}-A_0 \geq 0, \tag{13c}$$

where p_0=15.02 ptas/kWh and A_0=2725.74 ptas are the marginal cost and entry fee of the current tariff.[11]

With the previously defined demand, θ is given by $\theta=(qp^b)/a$, and substituting it into the previous equation the following inequality is obtained

$$\frac{q_ap_0}{b-1}-A_0\geqslant 0. \tag{13d}$$

Taking into account that the consumption of the smallest type with the current tariff (q_a) was 200 kWh in 1993, the previous inequality is always verified.

The results of the estimation are presented in Table 2.[12]

5. Optimal tariff and welfare

To conduct efficiency comparisons with the current tariff, a two-part tariff pricing structure $T(q)=A+pq$, with a constant marginal price, p, per unit purchased and a fixed charge, A, per period, is considered. Both p and A are the same for all consumers. With the functional forms introduced in the previous section, the social welfare derived from consumption is given by

$$W=\int_{\theta_*(A,p)}^{\theta_0}\left[\frac{a}{b-1}\theta p^{1-b}-A\right]\theta^{-\eta}r(\theta-\theta_a)d\theta + \int_{\theta_0}^{\infty}\left[\frac{a}{b-1}\theta p^{1-b}-A\right]\theta^{-\eta}s\theta^{-\alpha-1}d\theta. \tag{14a}$$

Profits can be defined as

$$B=A\int_{\theta_*(A,p)}^{\theta_0} r(\theta-\theta_a)d\theta+A\int_{\theta_0}^{\infty}s\theta^{-\alpha-1}d\theta+pQ - C(Q), \tag{14b}$$

where Q represents the total output and is defined by

$$Q=\int_{\theta_*(A,p)}^{\theta_0} a\theta p^{-b}r(\theta-\theta_a)d\theta+\int_{\theta_0}^{\infty}a\theta p^{-b}s\theta^{-\alpha-1}d\theta. \tag{14c}$$

In this section three alternative scenarios are considered in order to analyze the efficiency of the Spanish electric system. In a first scenario the generating equipment and the assignment of output to the different technologies is taken as given. In this framework a first approximation to the efficiency losses associated exclusively to the current 1993 tariff versus an optimal tariff is obtained. In a second scenario the generating equipment is taken as given once again, however a change in the assignment of output to the different technologies is allowed. This gives a second approximation to the possible efficiency gains from an optimal tariff and an optimal output allocation versus the current 1993 tariff and output allocation. Finally, in a third scenario, the optimal generating equipment is simulated with the current technologies available in 1993. The possible efficiency gains

[11] The entry fee is computed by using the annual power term of tariff 2.0 for a consumer with power equal to the average power used.

[12] A FORTRAN minimisation routine with a penalisation function was used for the parameter estimation.

Table 2
Estimated parameters of the consumption distribution

Estimated parameters	θ_0	α	θ_a	r	k	Stat. (χ^2)
	1314.62	1.2018	239.95	5.705e−7	942.751	20.26 (37.7)

derived when none of the system characteristics are taken as given are also considered.

5.1. Non adapted generating equipment

5.1.1. Non optimal allocation of technology

In order to compute the optimal tariff in the non-optimal optimal allocation of technology scenario, 1993 production costs will be assigned to each consumer type. To do this, a particular production mix must be assigned to each consumer. If a consumer has a constant utilisation level then the production of the optimal technology for this utilisation should be assigned to that consumer. In the case of residential consumers, who are characterised by an utilisation level of 2498 hours, the optimal technology is oil/gas, the most efficient technology for durations smaller than 8000 hours given the technology data in Table 1. Thus all gas production for 1993 is assigned to residential consumers. But given that residential consumption for 1993 is greater than the gas production for this year, other technologies to meet the remaining residential demand must be considered. These technologies are assigned according to a 'second-best' criterion, that is, the next best technology given the constant utilisation level of residential consumers. Following this assignment procedure until total residential demand is covered the following production assignment for 1993 residential consumption is obtained: oil/gas (1795 GWh), imported coal (8601 GWh), black lignite (8178 GWh), brown lignite (11 641 GWh), and hydra (6705 GWh).[13] The average cost for a residential consumer derived from this assignment is 8650 ptas. Non-productive fixed costs plus profits associated to residential consumption are 11 783 ptas which are obtained as the difference between tariff revenues and productive costs.

According to the definition of marginal cost as the sum of the capacity and operating costs of the efficient technology, the marginal cost of residential consumption in 1993 is 6.75 pesetas, which is the marginal cost of oil/gas technology.

The value of all parameters that are used in the computation of the different tariffs for the base case are presented in Table 3.[14]

In Table 4 the values of (p, A) for the current (c), optimal (o) and universal service tariff (s) are presented as well as the associated participation level (PL), and per consumer consumption level (q), average power used (l), and welfare (W). The optimal tariff is the result of maximising the social welfare subject to the budget constraint and that the marginal consumer has a non-negative net surplus. The universal service tariff is the optimal tariff maintaining the participation level of the current tariff.[15] In all cases tariffs are computed subject to a restriction of maximum power demanded by the residential sector. This restriction is determined allowing consumers a proportion of the system's overcapacity equal to their proportion of the total system's contracted power. This restriction limits a residential consumer to a maximum consumption of 3183 kWh.

As can be seen in Table 4, if the regulator is only concerned with efficiency thus giving all consumers an equal weight in the total welfare function (η=0), with a tariff structure similar to the current one, it is possible to achieve a greater efficiency level while maintaining universal service. On the other hand, greater η values give more importance to distributive concerns. For a

Table 3
Parameters of base case[a]

Parameter	Item	Value
Price elasticity	b	1.8
Marginal cost (ptas/kWh)	c	6.75
Pareto elasticity	α	1.2018
Constant demand	$\bar{a}$	109.3764
Average consumption (kWh)	q	2141.15
Utilization level (hrs.)	$\bar{h}_u$	2498
Average power used (kW)	l	0.8572
Smallest type	θ_a	239.9452

[a] Source: CNSE.

[13] Given the role of hydra technology as system regulator it cannot be attributed to a particular utilisation level so it is assigned proportionally to the consumption of each consumer type.

[14] The demand parameters are obtained using the IMSL multivariate minimisation subroutines.

[15] The appendix specifies how these tariffs are computed. The explicit solution to p and A have to be computed with numerical computation because it depends on if the value θ_* is in the linear or Pareto part of the distribution of consumer types. The model is solved by means of GAMS (see Brooke et al., 1988).

Table 4
Tariffs with non adapted generating equipment. (c: current tariff; o: optimal tariff; s: universal service tariff)

Tariff q_{max}=3183	p (ptas/kWh)	A (ptas)	PL (%)	$\bar{q}$ (kWh)	$\bar{l}$	$\bar{W}$
η=0						
c	15.02	2725	100.00	2141.15	0.857	37539
o=s	12.051	3561	100.00	3183.00	1.274	44470
η=2.91						
c=o=s	15.02	2725	100.00	2141.15	0.857	1.4408E−5

Table 5
Tariffs for several levels of maximun consumption

q_{max} η=0	Tariff	p (ptas/kWh)	A (ptas)	PL (%)	$\bar{q}$ (kWh)
4183	o	10.354	5360	99.994	4183
	s	10.633	4950	100.00	3986
5183	o	9.190	7810	99.726	5183
	s	10.633	4950	100.00	3986
6183	o	8.326	10802	98.939	6183
	s	10.633	4950	100.00	3986
7183	o	7.649	14335	97.475	7183
	s	10.633	4950	100.00	3986
8183	o	7.155	17989	95.437	8064
	s	10.633	4950	100.00	3986

large enough value of this parameter (η=2.91) the current tariff is optimal.

In order to analyze the influence of the maximum power restriction, in Table 5 the optimal tariff and the universal service tariff for several levels of maximum allowed consumption are presented. Table 6 presents the efficiency gains for all cases considered when the welfare function weight is η=0. When the maximum power demanded is determined by the installed generating system, the optimal tariff increases welfare by more than 18% maintaining universal service. These welfare gains increase with the maximum allowed consumption, achieving welfare gains of 47% if there is no maximum power constraint. However, if the participation level is reduced to 95.5% with respect to the current tariff, that means that more than 780 000 subscribers would not consume. In this case no maximum power constraint of the universal service tariff achieves welfare gains of 28.3% with respect to the current tariff.

In order to verify the robustness of the results several alternative hypotheses for the base case parameters, which are given in Table 7, are analysed. The optimal and universal service tariffs, as well as the participation level and the average consumption and power levels for each case, are given in Table 8 (with η=0). Case b^- computes the tariffs for a low elasticity assumption, this results in a lower fixed fee and a higher marginal price. This is because the more inelastic the demand is, the smaller the welfare gain and the greater the revenue loss from a price reduction are. In this sense a higher elasticity (case b^+) will result in a higher marginal price and a lower fixed fee.

With respect to the marginal cost it can be seen that a larger difference between marginal cost and average cost (defined as the ratio between total cost and total residential consumption) results in a need to fix a marginal price closer to marginal cost and verify the budget constraint with a larger fixed fee. When the marginal cost is larger the marginal price is closer the marginal cost. This result holds while the fixed fee is restricted to non-negative values.

Regarding the variation of the Pareto elasticity for the distribution of consumption, α, higher elasticity values result in a lower fixed fee and a higher marginal price, while lower values of α will result in a marginal price that approaches marginal cost. This is due to the fact that higher α values imply a higher proportion of consumers with low consumption values, and thus, raising the fixed fee in order to lower marginal price will strongly reduce market participation. Low α values, on

Table 6
Welfare associated with new tariffs for several levels of maximun consumption

q_{max} η=0	$\bar{W}$ (Current)	$\bar{W}$ (Optimal)	$\Delta\bar{W}$ (%)	$\bar{W}$ (Univ. serv.)	$\Delta\bar{W}$ (%)
3183	37539	44470	18.46	44470	18.46
4183	37539	48904	30.27	48161	28.30
5183	37539	51934	38.35	48161	28.30
6183	37539	53919	43.63	48161	28.30
7183	37539	55041	46.62	48161	28.30
8183	37539	55363	47.48	48161	28.30

Table 7
Parameters values for several hypothesis

Case	b	c	α
Base	1.8	6.75	1.2018
b^-	1.7	6.75	1.2018
b^+	1.9	6.75	1.2018
c^-	1.8	6.4	1.2018
c^+	1.8	7.1	1.2018
α^-	1.8	6.75	1.1518
α^+	1.8	6.75	1.2518

Table 8
Optimal and universal service tariffs under several hypothesis

Case η=0	Tariff	(ptas/kWh)	A (ptas)	PL (%)	$\bar{q}$ (kWh)	$\bar{l}$ (KW)
base	o	7.155	17989	95.437	8064	2.876
	s	10.633	4950	100.00	3986	1.596
b^-	o	7.488	16203	94.570	6925	2.722
	s	10.643	5462	100.00	3846	1.539
b^+	o	6.839	20379	96.147	9472	3.791
	s	10.473	4617	100.00	4248	1.700
c^-	o	6.776	18675	95.526	8896	3.561
	s	9.959	5216	100.00	4486	1.795
c^+	o	7.530	17318	95.395	7354	2.943
	s	11.253	4731	100.00	3601	1.441
α^-	o	7.126	18219	95.395	8123	3.251
	s	10.633	4950	100.00	3987	1.596
α^+	o	7.181	17789	95.465	8013	3.207
	s	10.633	4950	100.00	3987	1.596

the other hand, imply a smaller proportion of consumers with low consumption values and thus higher fixed fees cause relatively smaller efficiency losses in terms of a low participation level. For sufficiently low values, marginal price may equal marginal cost.

Table 9 presents the efficiency gains derived under the optimal and universal service tariff with respect to the current tariff under the different hypotheses considered. In all the cases analysed the optimal tariff raises welfare by more than 36%, and can be as high as 61% in the high demand elasticity case. In any case it must be kept in mind that the level of participation is never greater than 96.147% of the one achieved with the current tariff. The universal service tariff, on the other hand, limits the efficiency gains attainable to a range from 22% to 35%.

5.1.2. *Optimal allocation of technology*

If the generating system is optimally configured given the different technologies that are in use in the Spanish electric system in 1993, the technology that is responsible for covering residential demand for a constant duration of 2498 hours would be oil/gas.

Table 10 presents the optimal and universal service tariffs for this case, without imposing any restrictions on capacity. The considerable reduction in costs when the generating system is optimally configured implies a significant reduction both in the marginal price and the fixed fee of the optimal tariff, and thus a high participation level (99.569%). In terms of efficiency, the welfare improvements are greater than 15% both for the optimal tariff and the universal service tariff.

On the other hand, to measure the distortions derived by the use of a non-adapted generating system it is necessary to consider the evolution of the Spanish electricity industry with a strong investment in oil/gas plants in the sixties and seventies that were not used after the oil crisis and that, at the current international prices, are again efficient given the installed generating system. The current generating system is composed mainly of very old plants, some of which are amortised, which results in a infravaluation of the capacity cost of the installed generating system. Table 11 presents the cost data of generating plants that have come into service since 1980.

Considering the data from Table 11, oil/gas is still the

Table 9
Efficiency gains under the different hypothesis

Case	$\bar{W}$ (Current)	$\bar{W}$ (Optimal)	$\Delta\bar{W}$ (%)	$\bar{W}$ (Univ. serv.)	$\Delta\bar{W}$ (%)
Base	37539	55363	47.48	48161	28.30
b^-	43230	58826	36.08	53035	22.68
b^+	33192	53706	61.80	45126	35.95
c^-	37539	57934	54.33	50753	35.20
c^+	37539	53098	41.45	46029	22.62
α^-	37560	55515	47.20	48198	28.27
α^+	37522	55232	47.80	48129	28.32

Table 10
Optimal and universal service tariffs for a generating system optimally configured

Tariff	p (ptas/kWh)	A (ptas)	PL (%)	$\bar{q}$ (kWh)	$\bar{l}$	$\bar{W}$
η=0						
o	6.750	10724	99.569	9030	3.195	65764
s	7.247	6727	100.00	7950	3.183	65450
η=0.229						
o=s	7.240	67274	100.00	7950	3.183	9931

Table 11
Technology costs for plants installed after 1980[a]

Technology	Capacity cost(ptas/KW)	Operating cost(ptas/kWh)
Nuclear	49126	1.2494
Anthracite	17488	5.6351
Brown lignite	22625	5.1593
Black lignite	26907	5.8228
Imported coal	20313	3.2560
Oil/Gas	9203	4.8571
Hydro	7900	0.7499
Combined cycle	12081	3.9550

[a] Source: CNSE and REE.

most efficient technology to serve residential consumption, and the cost function in this case is given by a fixed cost of 10 678 per consumer and a marginal cost of 8.54 ptas. The optimal and universal service tariffs for η=0 are given in Table 12 and will allow us to make efficiency comparisons with respect to an adapted generating system.

5.2. Adapted generating equipment

Table 13 presents the optimal and universal service tariffs for residential consumers when an adapted generating system is considered, that is, a system composed of the most efficient technologies available and operating in an efficient way. This scenario reflects a situation of long-run equilibrium in a competitive generation market. In particular gas fired combined cycle turbines technology, not present in the 1993 generating system, is the most efficient technology to serve residential consumption. The costs that are associated with this technology were obtained from European manufacturers and are estimated to be 11 084 ptas per installed kilowatt of capacity and 3955 ptas per hour of duration. This results in a marginal cost for the level of residential utilisation of 8.39.[16]

An approximation of the regulatory distortions in the Spanish system as of 1993 can be obtained comparing the welfare derived from the tariffs computed with a non-adapted generating system, where oil/gas and coal technologies are serving residential consumers, which follows from the costs studies in the MLE, and the welfare derived with the optimal tariffs that are obtained when residential consumption is served by combined cycle and coal technologies. As can be seen in Table 14, the efficiency gains derived from the use of combined cycle technologies are greater than 1.70% for the optimal tariff. These welfare gains could seem small with respect to the gains obtained by the tariff rebalancing effect. However, we must take into account that differences of welfare through technological effects depend on the differences in the marginal cost associated to the efficient technology for the residential utilisation level. And this difference is small because the installed oil/gas plants are partially amortised. In fact, using cost data from a

[16] These figures were obtained form CSEN, the Regulatory Commission of Spanish electricity industry, and Red Electrica de Espaa, S.A. (REE), the main transmission grid owner and System Operator in Spain.

Table 12
Optimal and universal service tariffs for an optimally configured generating system with plants installed after 1980 (η=0)

Tariff	p (ptas/kWh)	A (ptas)	LP (%)	$\bar{q}$ (kWh)	$\bar{l}$ (KW)	$\bar{W}$
o	8.614	10348	99.012	5817	2.328	52629
s	9.668	5342	100.00	4732	1.894	51973

Table 13
Tariffs for adapted generating equipment (η=0)

Tariff	p (ptas/kWh)	A (ptas)	LP (%)	$\bar{q}$ (kWh)	$\bar{l}$ (KW)	$\bar{W}$
o	8.456	10379	99.065	6015	2.407	53537
s	9.453	5438	100.00	4927	1.972	52913

Table 14
Effiency gains derived from the use of combined cycle technologies

Case	$\bar{W}$ gas	$\bar{W}$ combined cycle	$\Delta \bar{W}$ (%)
o	52629	53537	1.70
s	51973	52913	1.78

modern oil/gas plant, I have computed that higher welfare gains (by about 20 per cent) would be achieved.[17]

6. Conclusions

Tariff discrimination by utilisation level attempts to attain the efficiency gains associated with the use of capacity tariffs based on duration, by using information on consumption and used power. In this sense it incorporates the optimality concerns of a capacity price structure, but it relies on an assumption of homogeneity in the consumption duration patterns of different individuals.

In the case of the Spanish electricity industry two other factors may weaken the optimality objective of the tariff structure. First, the tariff establishes a limited number of utilisation ranges based on the distribution of consumers and not on the different costs of the technologies used in order to supply these consumers. Second, an objective function for the regulator is not specified.

In this paper several two-part tariffs for residential usage level are computed considering several alternative hypotheses for the installed generating system. Taking as given the generating equipment and the output assignment to the different technologies, the optimal tariff increases welfare by more than 18% maintaining universal service. On the other hand, the welfare losses associated to a non-optimal mix of production technologies are larger than 1.7%. These welfare losses are larger when the regulator is concerned not only with efficiency but also with distributive issues. In any sense, this means that the smaller consumers are penalized with the current regulatory framework.

It would be interesting to complement the current Spanish tariff structure based on utilisation levels with time-of-use tariffs. These would allow us to detect the divergences in demand and operating costs in the short term. In order to do this, a multiproduct formulation would be more useful.

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Appendix A. Aggregated costs in time periods

In the cost aggregation by vertical intervals the consumption costs for each time period are being considered. Fig. 5 shows, for example, that each hour h in

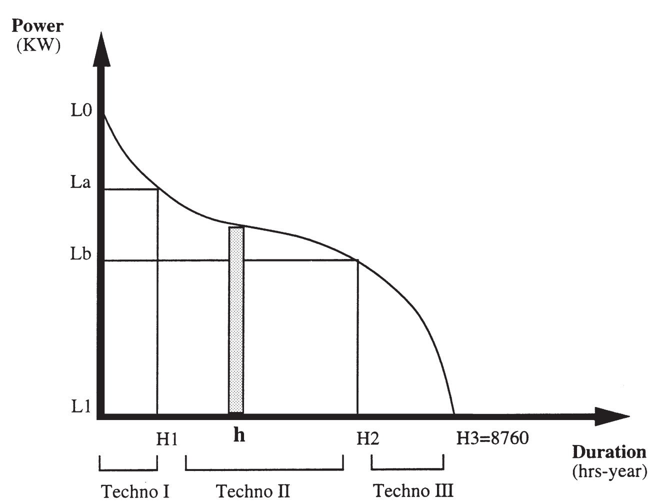

Fig. 5. Vertical slice costs of load-duration curve.

[17] Using data from CSEN, a modern oil/gas plant presents a marginal cost for the level of residential utilisation of 10.61 ptas. With this marginal cost the optimal tariff achieves a welfare level of 42 473.

which the consumer's load $L(h)$ is in the range $L_2<L(h)<L_1$ is identified with the source *II* that is the marginal generator in that hour. The marginal cost of energy is therefore v_2, but in addition, the inframarginal units of power are generated with the source *III*. The total cost of consumed energy in hour h is the sum of the marginal costs of energy from the sources used.

The total costs to meet the customer's load-duration curve can be derived by integrating the formula for the total cost of the consumption set by parts when horizontal intervals are considered, and can be written in the case of three technologies as

$$C(H)=C_0+f_1(L_0-L_a)+f_2(L_a-L_b)+f_3(L_b-L_1)-v_1H_1L_a +v_2(H_1L_a-H_2L_b)+v_3H_2L_b+\int_0^{H_1}v_1L(x)dx+\int_{H_1}^{H_2}v_2L(x)dx +\int_{H_2}^{H_3}v_3L(x)dx.$$

Appendix B. Two part tariff problem

B.1. Social welfare (W)

The social welfare derived can be written as

$$W=\int_{\theta_*(A,p)}^{\theta_a}\left[\frac{a}{b-1}\theta p^{1-b}-A\right]\theta^{-\eta}r(\theta-\theta_a)d\theta+\int_{\theta_0}^{\infty}\left[\frac{a}{b-1}\theta p^{1-b} -A\right]\theta^{-\eta}s\theta^{-\alpha-1}d\theta$$

With this equation the social welfare can be written as

$$W=\frac{a}{b-1}p^{1-b}r\left[\frac{\theta_0^{3-\eta}}{3-\eta}-\frac{\theta_a\theta_0^{2-\eta}}{2-\eta}-\frac{\theta_*^{3-\eta}}{3-\eta}+\frac{\theta_a\theta_*^{2-\eta}}{2-\eta}\right]-Ar\left[\frac{\theta_0^{2-\eta}}{2-\eta} -\frac{\theta_a\theta_0^{1-\eta}}{1-\eta}-\frac{\theta_*^{2-\eta}}{2-\eta}+\frac{\theta_a\theta_*^{1-\eta}}{1-\eta}\right]+\frac{a}{b-1}p^{1-b}s\frac{\theta_0^{1-\eta-\alpha}}{\alpha+\eta-1}-As\frac{\theta_0^{-(\alpha+\eta)}}{\alpha+\eta}$$

B.2. Profit (B)

The profit can be defined as

$$B=A\int_{\theta_*(A,p)}^{\theta_0}r(\theta-\theta_a)d\theta+A\int_{\theta_0}^{\infty}s\theta^{-\alpha-1}d\theta+(p-m)Q-cf$$

where Q represents the total output consumed and is defined as

$$Q=\int_{\theta_*(A,p)}^{\theta_0}ap^{-b}\theta r(\theta-\theta_a)d\theta+\int_{\theta_0}^{\infty}ap^{-b}\theta s\theta^{-\alpha-1}d\theta$$

Substituing and solving the integral the profit can be written as

$$B=Ar\left[\frac{\theta_0^2}{2}-\theta_a\theta_0-\frac{\theta_*^2}{2}+\theta_a\theta_*\right]+AK^{\alpha}\theta_0^{-\alpha}+(p-m)ap^{-b}r\left[\frac{\theta_*^3}{3} -\frac{\theta_a\theta_0^2}{2}-\frac{\theta_*^3}{3}+\frac{\theta_a\theta_*^2}{2}\right]+(p-m)ap^{-b}s\frac{\theta_0^{1-\alpha}}{\alpha-1}-cf$$

B.3. Marginal consumer surplus (EC_1)

The marginal consumer θ_* can be defined as the consumer with a null net surplus. This surplus can be defined using the last equation as

$$EC_*=\frac{a}{b-1}p^{1-b}\theta_*-A.$$

Then, the marginal consumer will be

$$\theta_*(A,p)=\left(\frac{b-1}{a}\right)Ap^{b-1}.$$

B.4. Tariffs computed

The optimal tariff is the result of maximising social welfare W subject to the following constraints

$B\geqslant 0$	(budget constraint)
$EC_*\geqslant 0$	(participation constraint)
$q\leqslant q_{\max}$	(maximun power constraint)

where W and B are the functions defined above.

The universal service tariff is the optimal tariff that maintains the participation level of the current tariff. Thus, it is the result of the above problem adding the following constraint

$\theta_*\leq\theta_*^c$(universal service constraint)

where θ_*^c in the marginal consumer with the current tariff.

The explicit solutions to p and A have to be computed with numerical computation because it depend if the value θ_* is in the linear or Pareto part of the distribution of consumer types.

Appendix C. Data

C.1. Frequencies of consumption

Table 15
Frequencies of consumption[a]

Interval (kWh)		Frequency(%)	Interval (kWh)		Frequency(%)
0	500	8.61	7501	8000	0.36
501	1000	19.17	8001	8500	0.28
1001	1500	18.70	8501	9000	0.21
1501	2000	14.73	9001	9500	0.17
2001	2500	10.79	9501	10000	0.13
2501	3000	7.71	10001	10500	0.10
3001	3500	5.48	10501	11000	0.08
3501	4000	3.90	11001	11500	0.07
4001	4500	2.80	11501	12000	0.05
4501	5000	2.03	12001	12500	0.04
5001	5500	1.48	12501	13000	0.04
5501	6000	1.10	13001	13500	0.03
6001	6500	0.82	13501	14000	0.02
6501	7000	0.61	14001	14500	0.02
7001	7500	0.47			

[a] Source: Red Eléctrica de España, S.A.

C.2. Tariff 2.0 in 1993

Table 16
Tariff 2.0 in 1993[a]

Parameter	Item	Value
Suscribers (thousands)	N	17243
Billed Power (MW)	P	60690
Consumption (GWh)	Q_0	36920
Billing (mil.ptas)	I	747340
Price (ptas/kWh)	p_0	15.02
Fixed fee (ptas)	A_0	2725.74
Power charge (ptas/kW, year)	$P.C.$	265

[a] Source: CNSE.

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