# Application of Priority Service Pricing for Mobilizing Residential Demand Response in Belgium

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*Abstract*—**Demand-side management is a promising approach for dealing with the increasing integration of renewable energy resources. In order to mobilize residential demand response, we revisit a paradigm based on priority service pricing. In this paradigm, electricity supply is perceived as a service that can be offered with various degrees of quality, where the specific measure of quality considered in this paper is reliability. The motivation of priority service pricing is to achieve massive mobilization of residential demand response resources while respecting the requirement of consumers for simplicity, privacy and control. In this paper, we apply priority service theory on Belgium to design such a contract for residential consumers.**

## I. INTRODUCTION

The operation of power systems has become increasingly challenging due to the large-scale integration of renewable energy sources. Demand-side management is a promising approach for overcoming this challenge, especially in light of the recent large-scale deployment of new metering and control technologies in various jurisdictions. The LINEAR project in Belgium unveils substantial demand response potential in the residential sector [1]. In the domain of demand-side management, researchers have focused on price-based control and direct load control. The former method is based on price signals provided to consumers, whereby consumers react to the price signal by adjusting their electricity consumption. However, if the price is too volatile, consumers face substantial price uncertainty, which is politically objectionable. In direct load control, household appliances, such as electric vehicles and air conditioners, would be controlled directly by aggregators [2]–[4]. Nevertheless, this method is criticized as being too intrusive and ideally control is imposed behind the meter.

Another paradigm based on priority service is proposed in [5], with the underlying economic theory dating back to [6]. In this paradigm, electricity supply is perceived as a service that can be offered with various degrees of quality. Specifically, the authors describe contracts whereby power is offered to consumers with various degrees of reliability. Higher degrees of reliability correspond to higher prices. The proper pricing of the contracts guarantees that consumers self-select a level of reliability that corresponds to the reliability that the system can actually offer, and indirectly reveal their valuation for power. This is achieved with minimal information, as the aggregator is merely aware of the system demand function without being able to discriminate consumers by valuation. Once consumers select contracts, loads are dispatched in order of decreasing reliability, which is efficient since consumers with greater valuation are induced to self-select contracts with higher reliability. Moreover, consumers can subscribe to different reliability levels with different capacities, so that they are only constrained behind the meter and are free to adjust the set-points of their household appliances according to the available capacity of each reliability level and their preferences. Following this paradigm, an appliance-level control algorithm based on distributed computing is developed in [7] and a stochastic analysis on pricing capacity increments is presented in [8].

The goal of this paper is to apply priority service theory for designing a contract for residential consumers in Belgium, and to illuminate certain implementation challenges that emerge. We first revisit priority service theory in Section II. Section III presents the process to design a priority service-based price menu for Belgium. Section IV compares the new price menu with the existing Belgian tariff and with optimal economic dispatch. Section V concludes the paper and provides directions for future research.

## II. PRIORITY SERVICE THEORY

This section presents priority service theory based on [6]. We first describe the consumer choice model and the cost model, and then explain how an optimal price menu is designed and how it is discretized into a finite number of priority classes.

### A. Consumer and Production Models

Without loss of generality, each consumer can be simply characterized by a single unit of demand and associated marginal willingness-to-pay $v$, which ranges from 0 to $V$. The aggregate demand function is represented by $D(\cdot,\omega)$ and the willingness-to-pay function is represented by $P(\cdot,\omega)$, both contingent on the 'state of the world' $\omega$. A demand response aggregator offers a menu of capacity strips with reliability $r$ and price $p$, with higher reliability corresponding to higher price. The objective of each consumer is to choose from the menu $M = \{p, r\}$ an option that maximizes expected surplus. Assuming risk-neutral consumers, for each $v$, the consumer's problem is to solve

$$S(v) = \max\{r \cdot v - p | (r,p) \in M\}. \tag{1}$$

Regarding the cost model, we assume that the supply is uncertain due to random outages of generators and renewable energy fluctuations, We denote $X_i$ as the installed capacity of unit $i$, whereas the random function $Y_i(X_i,\omega)$ denotes the available capacity. The short-run cost function is denoted as $C(z,\omega)$.

### B. Optimal Price Menu

In order to design the optimal price menu which induces consumers to choose the reliability level that the system can offer on aggregate under efficient dispatch, we need to compute the function $R(v)$ that describes the reliability level that a consumer with valuation $v$ would obtain under efficient dispatch. Denote by $\hat{p}(\omega)$ the spot price, associated with a given random outcome $\omega$, which is given by

$$\hat{p}(\omega) = \min\{\max[P(z,\omega), C(z,\omega)] | z \geq 0\}. \tag{2}$$

This is the intersection of the marginal willingness-to-pay function and the marginal cost function. Then the service reliability of a type $v$ consumer is given by

$$R(v) = \Pr\{\hat{p}(\omega) \leq v\}. \tag{3}$$

As shown in [6], the price menu which maximizes social welfare is as follows:

$$M^\star = \{p^\star(v), r^\star(v) | 0 \leq v \leq V\}, \tag{4}$$

$$r^\star(v) = R(v), \tag{5}$$

$$p^\star(v) = \int_0^v [r^\star(v) - r^\star(u)]du. \tag{6}$$

### C. Finite Number of Priority Classes

When implementing a priority service menu in practice, it is expected that there is finite number of priority classes. We first divide consumers into $n$ priority classes based on their valuation, say $[0, v_1], [v_1, v_2], \ldots, [v_{n-1}, v_n]$, where $0 = v_0 < v_1 < \ldots < v_{n-1} < v_n = V$. Suppose that the service is provided to consumers in such a manner that consumers in a higher value class are given a higher priority and pay more, but within each class, all consumers are treated equally and therefore are served in a random order. Then the probability that a consumer with a valuation $v$ between $v_i$ and $v_{i+1}$ will be served is

$$r(v) = r_i = \int_{v_i}^{v_{i+1}} \left[\frac{D(v) - D(v_{i+1})}{D(v_i) - D(v_{i+1})}\right] dR(v) + R(v_i). \tag{7}$$

Using integration by parts, we rewrite the above expression as

$$r(v) = r_i = \frac{\int_{v_i}^{v_{i+1}} R(v) dD(v)}{D(v_{i+1}) - D(v_i)}. \tag{8}$$

The interpretation of Eq. (8) is as follows. The denominator is the demand between valuation $v_i$ and $v_{i+1}$ while the numerator is the realized supply. Since within this priority class consumers are treated equally and served in a random order, $r_i$ is the average reliability in this priority class.

The corresponding price is given by

$$p(v) = p_i = v_0 r_0 + \sum_{j=1}^{i} v_j (r_j - r_{j-1}). \tag{9}$$

## III. APPLYING PRIORITY SERVICE IN BELGIUM

In this section, we apply priority service theory, as presented in the previous section, to the Belgian residential sector. Firstly, we calibrate aggregate demand functions for residential consumers and describe how we treat the supply side. Then we run Monte Carlo simulations of economic dispatch in order to obtain the valuation-reliability curve $R(v)$ defined in the previous section. Subsequently, we develop price menus with different numbers of priority classes.

### A. Demand Functions

Synthetic load profiles (SLP) from [9] are used in order to estimate residential electricity consumption, so as to calibrate demand functions of residential consumers. There are two types of SLPs concerning residential consumers, S21 and S22. Each of them is a time series with 15-minute resolution and the sum equals to 1, so SLPs describe normalized electricity consumption profiles of different types of consumers. S21 is used for households with a night/day consumption ratio less than 1.3, whereas S22 is used for households with a night/day ratio of 1.3 or more. S21 accounts for 82% of grid connections in Belgium, while S22 accounts for 18% [10]. The total electricity consumption in 2015 (including industrial, commercial and residential consumption) is available from [11] and residential consumption makes up for 21% [12] of total demand. Let $E_{IDR}$ denote the total electricity consumption of year 2015, then the aggregated electricity consumption profiles for S21 and S22 type households are given by

$$Profile_{S21} = E_{IDR} \times 21\% \times 82\% \times S21, \tag{10}$$

$$Profile_{S22} = E_{IDR} \times 21\% \times 18\% \times S22. \tag{11}$$

As S21 and S22 are used by utility companies in order to design flat tariffs and time-of use tariffs respectively, it is assumed that 82% of the demand is under a flat tariff, whereas 18% is under a time-of-use tariff.

Considering 16 cases which represent different 'states of the world' (seasons, weekday or weekend, day or night), we calibrate 16 different demand functions for both S21 and S22 type households, and then aggregate the S21 and S22 households into 16 demand functions for residential consumers. We assume that every demand function is linear, with a certain elasticity at the historically observed price-quantity pair. Specifically, the demand functions are calibrated according to Eqs. (12)-(14).

$$\frac{D(v) - D_0}{D_0} = e \cdot \frac{v - v_0}{v_0}, \tag{12}$$

$$\implies D(v) = \frac{D_0 \cdot e}{v_0} \cdot v + D_0(1 - e). \tag{13}$$

In these equations, $D_0$ is the average demand quantity of a certain household type in a certain case and $v_0$ is the observed valuation corresponding to this quantity, which is given by $P_0/0.985$, where $P_0$ is the current tariff and $0.985$ is the realized reliability in our model if residential demand is fixed and served after industrial and commercial demand is satisfied. Elasticity is denoted by $e$, which is different during the day and night according to [13]. $D_0$ can be calculated using the results from Eqs. (10) and (11), and $P_0$ is available from Electrabel [14].

We need to get round T&D costs because $P_0$ is made up of energy cost and T&D costs while production cost in the framework of priority service only refers to energy cost, yielding

$$D(v) = \frac{D_0 \cdot e}{v_0} \cdot (v + TD) + D_0(1 - e). \tag{14}$$

where $TD$ denotes transmission and distribution costs, and is obtained from Electrabel [14].

### B. Supply Side

On the supply side, we also consider 16 cases corresponding to the demand side.

*1) Derating of Conventional Generators:* The entire conventional generator fleet consists of 70 units, with a capacity of 16.6 GW. The long-term maintenance schedule of units is accounted for by derating the maximum capacity of the units. Specifically, the forecast available capacity (by fuel type) of units is published by Elia [11]. In addition, every conventional unit follows a 1% failure rate independently [15], as determined by the state of the world $\omega$.

*2) Other Sources of Supply:* Pumped hydro, run-of-river resources and imports follow average historical values in each of the 16 cases. Instead, wind and solar production are fitted by empirical distributions for each of the 16 cases.

### C. Optimal Economic Dispatch

In order to obtain the reliability curve $R(v)$ described in section II, we need to compute the spot price $\hat{p}(\omega)$ under optimal dispatch. This is obtained by formulating an economic dispatch problem with the objective of maximizing social welfare. After running 1000 Monte Carlo samples (where we sample conventional generator failures and renewable production) for each of the 16 cases, we obtain the valuation-reliability curve for the entire year shown in Fig. 1.

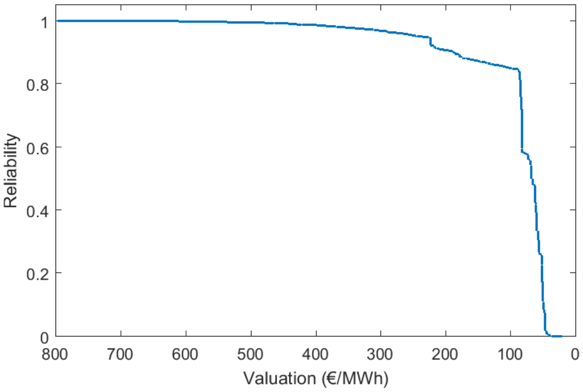

Fig. 1. Valuation-reliability curve for the entire year

TABLE I
PRICE MENU ($n = 3$)

| p(€/MW/h) | r | Val$^-$(€/MWh) | Val$^+$(€/MWh) | Subs(MW) |
|---|---|---|---|---|
| 7.37 | 0.37 | 19.748 | 100 | 155.57 |
| 67.03 | 0.97 | 100 | 797.275 | 1351.72 |
| 90.94 | 1 | 797.275 | $V_{\max}$ | 753.33 |

### D. Designing the Menu

With $R(v)$ at hand, the next step is to design a price menu with a finite number of priority classes following Eqs. (8) and (9). Let $V_{\max}$ denote the maximum of $V_j$, where $V_j$ is the intercept of the demand functions with the valuation axis for each case $j$ among the 16 possible cases. Then choose $n$ breakpoints in $[0\ V_{\max}]$. Eq. (8) for case $j$ and $v_i \leq v \leq v_{i+1}$ is rewritten as

$$r_j(v) = r_{j,i} = \begin{cases} \frac{\int_{v_i}^{v_{i+1}} R(v) dD_j(v)}{D_j(v_{i+1}) - D_j(v_i)} & v_{i+1} \leq V_j \\ 1 & v_i \geq V_j \\ \frac{\int_{v_i}^{V_j} R(v) dD_j(v)}{D_j(V_j) - D_j(v_i)} & v_i \leq V_j \leq v_{i+1} \end{cases} \tag{15}$$

Following formula (15), we calculate reliability set for the 16 cases respectively and then following Bayes' theorem, we take the weighted average of the reliability set to get a uniform one, i.e., $r_i = \sum_{j=1}^{16} weight_j \times r_{j,i}$ . After that, we calculate the prices following formula (9).

Tables I - III present the price menus when $n = 3,\ 5,\ 9$. A certain option in the price menu, taking the first option in Table I as an example, is interpreted in the following way: if a consumer's willingness-to-pay for a slice of 1 $MW$ of power that lasts for one hour is between 19.748 € and 100 €, then he will pay 7.37 € to subscribe to this option and will be served 37% of the time. In the welfare results that we report in the following section, we consider a subscription period of one year.

TABLE II
PRICE MENU ($n = 5$)

| p (€/MW/h) | r | Val$^-$ (€/MWh) | Val$^+$ (€/MWh) |
|---|---|---|---|
| 0.91 | 0.046 | 19.748 | 55 |
| 33.01 | 0.63 | 55 | 100 |
| 58.3 | 0.883 | 100 | 223 |
| 81.95 | 0.989 | 223 | 797.275 |
| 90.94 | 1 | 797.275 | $V_{\max}$ |

TABLE III
PRICE MENU ($n = 9$)

| p (€/MW/h) | r | Val$^-$ (€/MWh) | Val$^+$ (€/MWh) |
|---|---|---|---|
| 0.288 | 0.0146 | 19.748 | 50 |
| 12 | 0.249 | 50 | 57 |
| 17.37 | 0.343 | 57 | 60 |
| 24.94 | 0.469 | 60 | 67 |
| 31.58 | 0.568 | 67 | 81 |
| 51.7 | 0.817 | 81 | 100 |
| 58.3 | 0.883 | 100 | 223 |
| 81.95 | 0.989 | 223 | 797.275 |
| 90.94 | 1 | 797.275 | $V_{\max}$ |

## IV. ANALYSIS OF RESULTS

When consumers subscribe to the price menu according to Eq. (1), they will reveal their valuation, so we can build an aggregate demand function for each case based on the subscription quantity. The last column in Table I shows the subscription quantity in one of the 16 cases. The revealed demand function and the true demand function are illustrated in Fig. 2. It will be shown later that, using the revealed demand function, we can capture most of the benefits in terms of social welfare, even though the revealed demand function is notably different from true demand function.

We now compare the results of the following three policies:

(1) Optimal economic dispatch: we use the demand functions calibrated in Section III-A;
(2) Current fixed tariff: residential demand is fixed to its historically observed value;
(3) Priority service pricing: this policy is also simulated through economic dispatch, but the demand functions are the ones revealed when consumers subscribe to the price menu.

The influence of the number of options in the menu on social welfare in shown in Fig. 3. The social welfare gain from policy (1) compared with policy (2) is 173.1 million €, while that of policy (3) when $n = 3$ is 126.5 million €. Therefore, by implementing priority service pricing with 3 options, we can harvest 73.1% of the benefits.

The detailed comparison between policies (1), (2) and (3) when $n = 3$ is shown in Table IV. This comparison does not consider transmission and distribution costs and is only restricted to residential consumers, since industrial and commercial demand is fixed and guaranteed to be satisfied. Production cost is estimated through Monte Carlo simulation. Company revenues under the priority service tariff are calculated as:

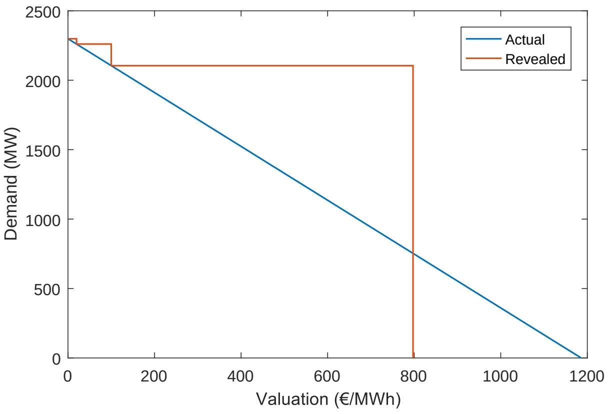

Fig. 2. Self-revealed demand function from subscription quantity

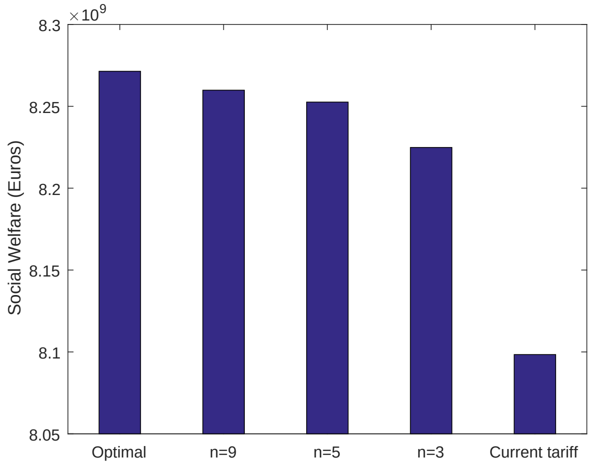

Fig. 3. Comparison of social welfare

$$\sum_{i=1}^{n}(p_i \times Subs_i) \times 365 \times 24, \tag{16}$$

where $p_i$ is the price of $i$-th option in the menu and $Subs_i$ denotes the corresponding subscription quantity. Under the current fixed tariff, in periods of shortage consumers are treated equally, regardless of their valuation. Following random rationing, consumer benefits are calculated as

$$[(V_{t,j}^{+} - V_{t,j}^{-}) \times D/2 + V_{t,j}^{-} \times D] \times 365 \times 24, \tag{17}$$

where $V_{t,j}^{+}$ and $V_{t,j}^{-}$ denote the highest and lowest valuation of household type $t$ (S21 or S22) in case $j$, respectively, and $D$ is the observed demand. The rationale behind this equation is shown in Fig. 4.

It is clear from Table IV that the profits of the company increase while the net welfare of consumers decreases by adopting priority service pricing. If this new tariff is implemented, smart meters have to be deployed. The typical cost of a smart meter is 184 € according to [16] and there are $4,575,959$

TABLE IV

Comparison between different policies (unit: million €)

| | Optimal Dispatch | Current Tariff | Priority Service |
|---|---|---|---|
| Revenues | 1585.2 | 1117.8 | 1282.6 |
| Production Costs | 964.1 | 1006.8 | 869.4 |
| Company Profits | 621.1 | 110.9 | 413.2 |
| Benefits | 9235.5 | 9105.2 | 9094.3 |
| Net Benefits | 7650.3 | 7987.4 | 7811.7 |
| Social Welfare | 8271.4 | 8098.3 | 8224.8 |

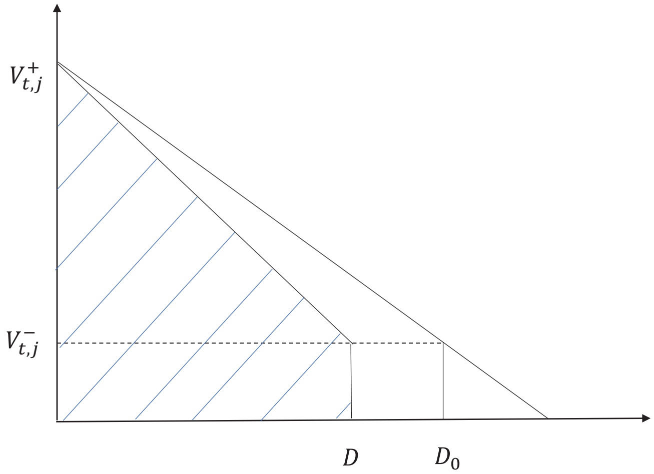

Fig. 4. Illustration of random rationing. In case of shortage, only a fraction $D/D_0$ of each horizontal slice is served.

households in Belgium [10], so the overnight investment cost is 842 million €. Assuming that the lifespan of a smart meter is 10 years and the interest rate is $r = 8\%$, we obtain the annualized cost $AC = r \times OC/(1 - 1/(1+r)^T) = 125.5$ million €, whereas the extra profits from the new tariff amount to 302.3 million €. Therefore, even if the firm covers the investment cost, it can benefit from priority service pricing, which means the company has incentives to implement the new tariff. However, consumers are disadvantaged. Under the existing flat tariff, consumers pay 60 €/MWh for a reliability of 98.5%. In contrast, they pay 67 € for a reliability of 97% if they switch to the new tariff, which can be a net loss for certain classes of consumers with sufficiently low valuations. A potential solution to address this issue is to incorporate T&D costs into the menu as a fixed charge on top of the subscription price. This is an interesting topic for future research. It is also necessary to point out that some consumers, whose valuation is so low that they do not subscribe to the current tariff, can receive service with a certain reliability under the new tariff.

## V. CONCLUSION

In this paper, we review priority service pricing and present its application to the Belgian market. The analysis of the price menu shows that a simple menu with 3 options can harvest 73.1% of the benefits. The utility company benefits from the new tariff, even if it fully covers the investment cost in new smart meters, so there is an incentive for the utility company to adopt the new tariff.

There are three directions that we plan to consider in future research. Firstly, we are interested in more complex tariffs that include an energy charge in addition to a capacity charge. Secondly, the effect of this new tariff on day-ahead market is worth evaluating. Furthermore, we think it is import to develop a model for a single household and see how a single household would react to the new tariff.

## ACKNOWLEDGMENT

This research was funded by the ENGIE Chair on Energy Economics and Energy Risk Management.

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