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Residential demand-side flexibility provision under a multi-level segmented tariff

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***Abstract*—This paper proposes a multi-level segmented tariff to encourage consumers to provide demand response using a battery. The aim of the tariff is to (i) properly reflect consumers' contribution to the distribution grid cost while ensuring cost recovery for the distribution network operator and (ii) to provide consumers with a financial incentive to flatten their load profile and avoid peak demand. An optimization problem is formulated to describe how consumers can provide demand response by managing their batteries. To evaluate the effectiveness of the proposed multi-level segmented tariff, four case studies were conducted. The results indicate that the multi-level segmented tariff is the most effective in reducing coincident peak demand, with a reduction of 22%. Policymakers and regulators are recommended to consider multi-level segmented distribution tariffs, as it provides an incentive to consumers to manage their assets to provide demand response.**

***Index Terms*—Cost recovery, Cost reflectivity, Demand-side flexibility, Distribution network, Multi-level segmented tariff**

I. Introduction

Distribution network tariffs are used to recover the investment and operation costs of the distribution networks [1, 2]. Cost reflectivity is a key principle in distribution network tariff design [3, 4], especially at a time when large investments in these networks are required: costs should be ideally allocated to those users who cause them [5, 6]. This should incentivize consumers to use the available network capacity efficiently and manage their distributed energy resources (DERs) based assets accordingly.

Traditionally, distribution network tariffs were based on the volume of electricity consumption (volumetric distribution tariff (€/kWh)), where consumers pay a flat rate per kWh of energy consumption. It does not take into account the time of day that the energy is consumed and their consumption levels. It also does not reflect the costs that consumers cause in the distribution grid [7] since the network cost is mostly driven by the system peak. Alternatively, consumers may pay a fixed annual fee, such as in the Netherlands: consumers pay a fixed network charge per year with a physical connection limit to the network of 17.3 kW per household [8]. However, due to the varying consumption patterns of households and the increasing penetration of DERs, such volumetric or flat tariffs may lead to a distribution network cost allocation that no longer reflects the individual consumer's contribution to distribution network costs. Indeed, the contribution to the system peak (one of the main drivers of network costs) of one household may be substantially lower than that of another, while both pay the same distribution fees. As a result, households with a lower contribution to the system peak are effectively subsidizing those with a higher contribution to the system peak [9].

Other distribution network tariffs, such as coincident peak pricing (€/kW), consider consumers' contribution to the system peak demand, and are cost reflective [10, 11]. However, the system peak is hard to predict, which makes it challenging for consumers to anticipate and change their behavior. Non-coincident peak pricing (€/kW) considers individual peak demand by determining the moment of highest demand within a month or year, which is less cost-reflective, and individual peak consumption may still be difficult to control [12].

In contrast, segmented energy pricing ties the distribution tariff to the level of electricity consumption, where a volumetric component (€/kWh) affects the energy consumption above a certain threshold measured over a program time unit [13]. Typically , there is only one threshold, which limits the ability to distinguish the consumption levels of different consumers. In addition, this pricing signal may not be granular enough to sufficiently mitigate the system peak if each consumer sticks to the threshold. Multi-level segmented energy pricing attempt to overcome these issues. The basic idea of this pricing method is that the electricity consumption is divided into several thresholds, and a tariff is assigned to each threshold. The higher the threshold is, the higher the tariff is. Consumers can save network costs by reducing their overall demand to a threshold with a lower tariff. For instance, the study of [14] employs a three-stage pricing for residential customers. The pricing is based on the annual total electricity consumption, specifically total annual energy consumption in kWh. Consumers are charged at different energy prices per kWh depending on their consumption level. Verbist et al. [15] introduce a dynamic three-level distribution network tariff specifically for electric vehicles. This tariff does not take any load besides the electric vehicle demand into account, and charges electric vehicles based on their utilization of the network's capacity.

In addition, the increasing penetration of DERs amplifies the issues above and makes these tariffs less cost-reflective. The existing network tariffs do not provide incentives to consumers to manage their DERs properly and provide demand-side flexibility to the distribution network[16, 17]. However, consumers have been shown to be able to provide flexibility to the distribution grid by managing their DERs assets in response to tariffs [17, 18]. Therefore, the second objective of this paper is to investigate how consumers provide flexibility by managing their DERs under the multi-level segmented tariff and what are their impacts on the distribution grid. In this paper, we illustrate the ability of multi-segmented electricity pricing to unlock demand-side flexibility, modeled here as battery storage. The distribution grid can utilize the flexibility provision from the households by implementing the multi-level segmented energy tariff to avoid or postpone reinforcement.

The remainder of this paper is organized as follows. Section II describes the proposed multi-level segmented tariff design with mathematical formulations to show its underlying principles. The multi-level segmented tariff updating and flexibility provision model are presented in Section III, by formulating the decision problem of the consumer. The analysis of four case studies is the subject of Section IV. Section V concludes and provides recommendations for future work.

II. Multi-level segmented tariff design

The basic principle behind the proposed multi-level segmented tariff is that the cost of additional power is increased at every threshold, which leads to a segmented tariff structure, as presented in Fig. 1.

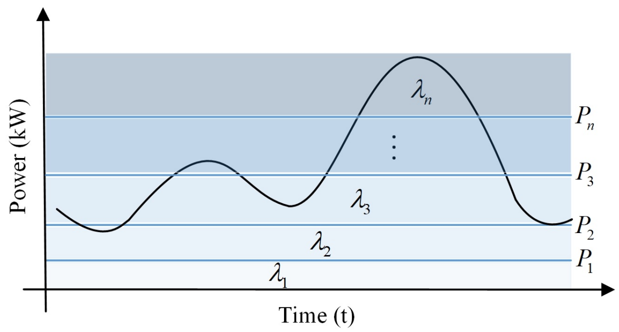


Fig. 1: Multi-level segmented tariff (λ_n: network usage price (€/kW); P_n: a measure of the power consumption level, e.g., the average power consumption over a program time unit; $\lambda_1 \leq \lambda_2 \leq \lambda_3 \leq \cdots \leq \lambda_n$)

P_1 to P_n (kW) are the power threshold levels. λ_1 to λ_n (€/kW) represent the incremental cost per unit of electricity for power consumption between the corresponding thresholds. For instance, λ_2 (€/kW) is the distribution for the part of electricity consumption $P_t - P_1$ or $P_2 - P_1$ when $P_t \in (P_1, P_2]$ or $P_t > P_2$. Note that the power consumption is defined as the average over the program time unit.

Under the multi-level segmented tariff, the distribution network payment per program time unit of one consumer is computed as follows:

$$C_t = \begin{cases} \lambda_1 \times P_t & P_t \leq P_1 \\ \lambda_1 \times P_1 + \lambda_2 \times (P_t - P_1) & P_1 < P_t \leq P_2 \\ \lambda_1 \times P_1 + \lambda_2 \times (P_2 - P_1) & \\ +\lambda_3 \times (P_t - P_2) & P_2 < P_t \leq P_3 \\ \cdots & \\ \lambda_1 \times P_1 + \lambda_2 \times (P_2 - P_1) & \\ +\lambda_n \times (P_t - P_{n-1}) & P_{n-1} < P_t \leq P_n \end{cases} \tag{1}$$

where P_t (kW) is the average power consumption over program time unit t.

Cost recovery, non-discrimination, and transparency are three of the principles that should be at least followed in all tariff design [19, 20]. In line with these principles, the multi-level segmented tariff proposed in this research focuses on cost efficiency and cost reflectivity. It aims to incentivize consumers to use the distribution network efficiently, which promotes efficient investment in turn. The network cost paid by the consumers should reflect their contribution to the distribution network cost, this corresponds to the principle of cost reflectivity.

III. Multi-level segmented tariff updating strategy and flexibility provision model

A. *Multi-level segmented tariff updating strategy*

In order to make sure a distribution network operator (DSO) can recoup its investment, it is necessary to set an appropriate tariff. The tariff should also incentivize demand response from the consumers to use available network capacity efficiently. On one hand, it helps reduce network operation issues, such as network congestion. On the other hand, it may put cost recovery at risk if consumers respond by reducing their consumption. Hence, it will be important to tune the tariff in accordance with the expected response from consumers.

There could be multiple setups for the segmented and multi-level segmented tariff. In this study, a fixed ratio is assigned between the three prices of a three-segment tariff, according to:

$$\lambda_2 = \beta_1 \lambda_1 \tag{2}$$

$$\lambda_3 = \beta_2 \lambda_1 \tag{3}$$

β_1 and β_2 represent the ratio between the two prices, with $\beta_2 > \beta_1 > 1$, the values of which can be adjusted in practical applications. This simplifies the tariff determination because once λ_1 is determined, λ_2 and λ_3 are determined automatically. For the determination of λ_1, we adopt a bisection method that iterates until it satisfies cost recovery of the DSO (tolerance: 0.01 €). Larger values of β_i provide stronger incentives to reduce peak demands, and thus will influence consumers' utilization of the distribution network's capacity.

B. *Flexibility provision model*

Electricity costs of consumers include three components: supply costs, grid costs, government taxes, and levies [21].

The electricity supply costs are in the form €/kWh, plus a fixed supply cost for administration costs, which is €7.87 per month per electricity connection. This research focuses on distribution network tariffs so electricity supply cost is assumed to be flat, i.e., not varying with time. As a result, consumers only respond to the grid tariffs.

In this case, it is assumed that consumers can only purchase electricity from the grid. Therefore, their strategy is to buy electricity from the grid when the distribution tariff is low and store it in a battery for usage when the distribution tariff is high. In addition, it is also assumed that each household installs the same size battery. In this study, the investment in batteries is not taken into account.

The objective of the consumers is to minimize their distribution network payments, which is formulated as follows:

$$\text{Minimize} \sum_{t=1}^{T} C_t \cdot \Delta t \tag{4}$$

with C_t following (1), subject to

$$P_t^{import} = P_t + P_t^{cha} - P_t^{dis} \tag{5}$$

$$E_t^{bat} = E_{t-1}^{bat} + \eta P_t^{cha} \Delta_t - (1/\eta) P_t^{dis} \Delta_t \tag{6}$$

$$0.1 E_{max}^{bat} \leq E_t^{bat} \leq 0.95 E_{max}^{bat} \tag{7}$$

$$E_0^{bat} = E_T^{bat} \tag{8}$$

$$0 \leq P_t^{cha} \leq P_{max}^{bat} \tag{9}$$

$$0 \leq P_t^{dis} \leq P_{max}^{bat} \tag{10}$$

The power balance constraint (5) ensures that the demand from the households is satisfied by supply at all times, for $\forall t \in \{1, 2, \ldots, T\}$. P_t^{import} (kW) is the power purchased from the grid (average over the program time unit). Equation (6) describes the charging/discharging process of the battery, whereas (7) makes sure that the state of charge of the battery remains within certain limits. Equation (8) enforces boundary conditions for the state charge of the battery. Equations (9) and (10) make sure the charging and discharging of the battery occur within the power limits of the battery. Note that this model assumes perfect foresight on behalf of the consumer on their future energy consumption.

IV. Case Study and Result Analysis

A. Input data and assumptions

1) Distribution network cost: This case study is based on the tariffs of Dutch DSO Stedin [22]. Consumers pay a one-off grid connection fee plus some annual costs, such as periodic connection fees, meter rental, and capacity rates. For the case study, only the annual capacity rate plus VAT is considered for a connection capacity of less than 3 × 25 Amps, as other costs are fixed and not affected by their electricity consumption. The annual capacity rate is €274.91 for per consumer connection. This is the cost the DSO needs to recover from each consumer.

2) Load demand profile: In this case study, electricity consumption data from 100 households is utilized, sourced from UK Power Networks [23]. The annual electricity consumption ranges from 1,291 kWh to 5,994 kWh.

3) Thresholds determination: In this case study, two thresholds are chosen for the multi-level segmented tariff design. We use the average of the minimum and maximum annual electricity consumption, which is 3643 kWh, to represent the typical annual consumption of households. The corresponding hourly electricity consumption is 0.4158 kWh. The first threshold is set at 0.5 kW, set to the typical hourly electricity consumption of these households (rounded up to the nearest tenth). The second threshold is set to three times the average hourly electricity consumption, which amounts to 1.3 kW (after rounding up to the nearest tenth). In addition, $\beta_1 = 2$ and $\beta_2 = 12$ for the case study.

4) Battery data: We assume that each household is equipped with a battery of the same size. The average daily electricity consumption of households is around 10 kWh, and a battery size of 6 kWh is selected to store or shift 60% of the average daily electricity consumption of the households. The charging and discharging efficiency is 95%. The maximum and minimum state of charge (SoC) is set at 95% and 10%, respectively. The battery has a power rating of 2 kW.

B. Cases

In this research, three tariffs, (1) a volumetric tariff (€/kW), (2) a single-level segmented tariff (€/kW), and (3) a multi-level segmented tariff (€/kW), are compared to evaluate their performance and investigate their impacts on the distribution grid. A one-year simulation is conducted for each case to determine appropriate price levels while households minimize their network costs with respect to the tariff. The results of the three cases will be compared to the reference case with a fixed network tariff (i.e., an annual fee (€/year)).

C. Result analysis

The net electricity demand of the households under different tariffs on a summer day and a winter day is presented in Fig. 2 and Fig. 3. The net electricity demand under the volumetric tariff (green line) remains the same as in the reference case (fixed tariff). Households have no incentive to charge or discharge their battery since the price is the same at each hour. Households reduce their peak demand the most under the multi-level segmented tariff (red-dashed line) compared to the single-level segmented tariff (orange-dashed line) and volumetric and fixed tariffs, both on the summer and winter days. The system peak demands of the households are 63.4 kW and 73.5 kW under the multi- and single-level segmented tariff, a reduction of 22% and 10% compared to the system peak demand under the fixed and volumetric tariffs (81.5 kW). The results indicate that the multi-level segmented tariff is the most effective among the four network tariffs in reducing the peak demand and flattening the consumption profile.

The resulting prices and costs recovered (revenues) under different tariffs are summarized in Table I. Cost recovery is ensured under the three tariffs, as intended by the tariff updating strategy.

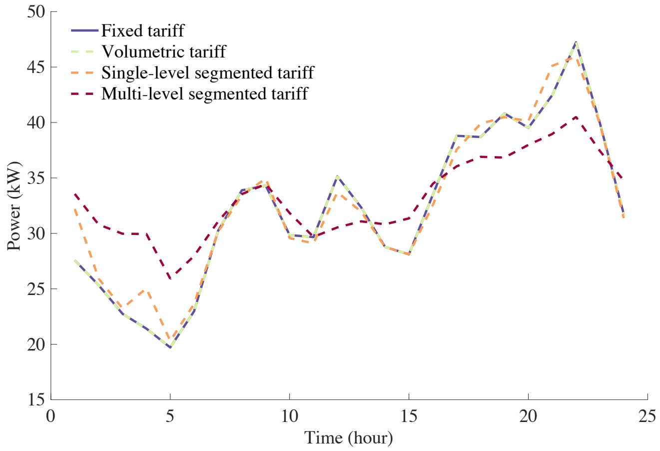


Fig. 2: Net electricity demand under different tariffs on a summer day

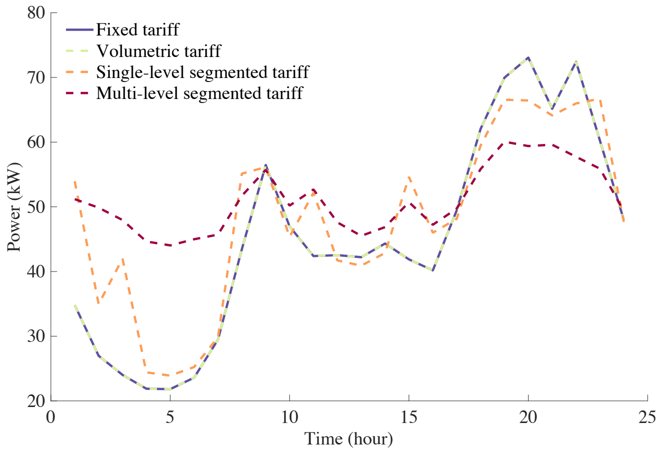


Fig. 3: Net electricity demand under different tariffs on a winter day

TABLE I: Prices and revenues under different tariffs in a year for 100 households

Network tariffs	Fixed tariff (€/year)	Volumetric tariff (€/kW)	Single-level segmented tariff (€/kW)	Multi-level segmented tariff (€/kW)
Prices	274.91	0.0849	λ_1= 0.0815 λ_2 = 0.9780	λ_1 = 0.0745 λ_2 = 0.1489 λ_3 = 0.8936
Annual DSO revenue (€)	27491	27491	27491	27491

D. *Comparison among the three cases*

The distribution network payment for each household under different network tariffs is calculated and compared with possible factors that may affect the network costs. The relation of their coincident peak, individual peak, and average electricity consumption with their distribution network payments under different network tariffs are presented in Fig. 4. It is immediately clear that under a fixed tariff, the tariff payments do not depend on the consumption pattern.

Fig. 4(a) shows that, at times of aggregate peak demand, most households are able to maintain their electricity consumption within the defined threshold value of 1.3 kW with the help of batteries under the single- and multi-level segmented tariffs. It indicates that the two tariffs are effective in reducing the coincident peak demand within the defined threshold compared to fixed and volumetric tariffs. Moreover, most households can maintain their coincident peak demand within the first threshold, which contributes the most to reducing their coincident peak demand under the multi-level segmented tariff.

The relation between the distribution network payment and individual peak demand under the three tariffs is shown in Fig. 4(b). The single- and multi-level segmented tariffs help to reduce individual peak demand (a shift to the left), with a slightly larger shift for the multi-segmented tariff. The distribution network payments do not exhibit a clear relationship with the consumers' individual peak demand. However, the lower right corners in Figs. 4(a) and (b) do show that the three tariffs are effective in avoiding free-rider behavior, which would allow users who impact the network load a lot to pay very little. Although tariffs do not push individual peaks below the threshold value, it does limit their typical contribution to the system peak load.

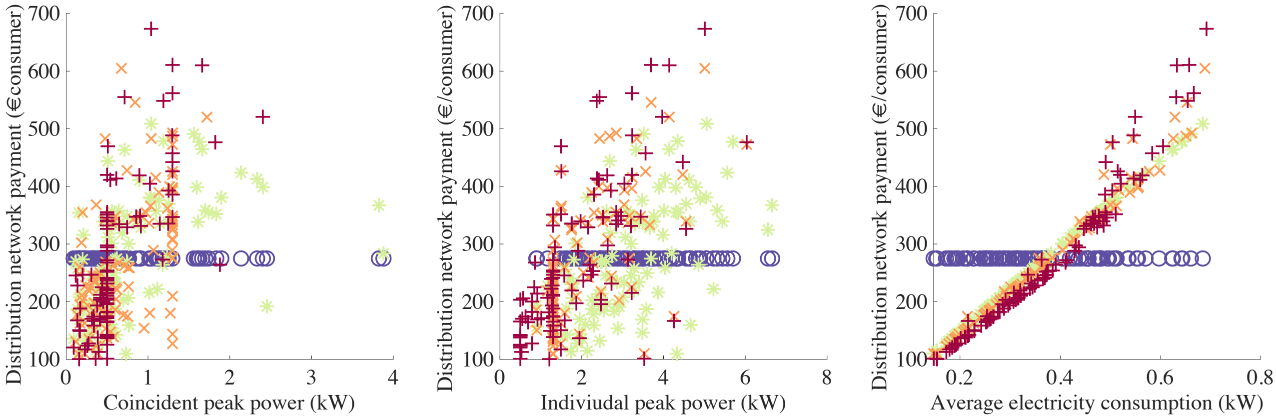
Fig. 4(c) shows the relationship between the network costs and average electricity consumption under the volumetric, single- and multi-level segmented tariffs. The volumetric tariff by definition shows an exact linear relationship, whereas the single- and multi-level segmented tariffs show a superlinear cost trend with respect to average consumption. This reflects the power-dependent cost structure of segmented tariffs.

In summary, in this case study, the multi-segmented tariff performs well on the three metrics tested in Fig. 4 and it is best at reducing overal peak loads (Fig. 2 and Fig. 3).

V. Conclusions

In this paper, a multi-level segmented tariff is designed and analyzed by examining its impact on the operation of households equipped with batteries. The tariff provides an incentive for demand-side flexibility provision as consumers aim to minimize their distribution network payments. The DSO will need to tune the tariff levels by taking consumers' responses into account to ensure cost recovery. A case study is presented to illustrate the effectiveness of the proposed multi-level segmented tariff by comparing it to three other tariffs: a fixed, a volumetric and a single-level segmented tariff. The results indicate that the multi-level segmented tariff contributes the most in terms of coincident peak demand reduction. It therefore contributes to reducing overall network investment needs, resulting in reduced network payments on the long term. Moreover, our results show that these costs are better allocated across consumers, in line with the tariff design principles of cost efficiency and cost reflectivity.

The primary goal of this research is to introduce the concept of a multi-level segmented tariff and to illustrate its effectiveness in reducing peak demand. However, there are still many aspects for further exploration, including (1) examining prices under uncertainties, (2) a detailed investigation of the impact of the multi-level segmented tariff on the operation of the distribution grid, and (3) the inclusion of a larger variety of DERs.



(a) Coincident peak (b) Individual peak (c) Average consumption

Fig. 4: Relation of the coincident peak, individual peak, and average consumption with distribution network payment of each consumer under different network tariffs.

○ Fixed tariff * Volumetric tariff × Single-level segmented tariff + Multi-level segmented tariff

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