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***Abstract*—In this paper, a segmented energy tariff design is proposed to incentivize consumers to flatten load demand. This energy tariff focuses on consumption levels instead of consumption periods. Energy storage is an effective strategy to help to maintain the imported energy from grid below the threshold without affecting the comfort of energy consuming. From economic perspective, both battery size and segmented energy prices should be considered to minimize the total energy cost. For the considered home battery system, when the threshold value and battery size is larger than 0.45 kWh and 3 kWh respectively, the imported energy from grid is zero. When the price ratio is larger than 9, it is beneficial for consumers to response to load flattening with battery to reduce energy cost. It is recommended that policy makers or electricity regulators take the tariff incentive into account to make it attractive for consumers to respond to load flattening.**

***Index Terms*—segmented energy tariff, load flattening, energy cost, price ratio**

I. Introduction

Peak load reduction refers to reducing load consumption in peak hours either by cutting down appliances or shifting peak load demand to off-peak hours [1]. Peak load demand occurs only for several hours in a day. More generation capacity is required to supply the peak demand. The price of energy generated by peak power plants is generally higher than the base load power plant. The excess of electricity consumption during peak hours affects the stability and reliability of the electricity grid, it raises the failure possibility of a power system [2]. Peak load shaving is an effective way to solve these problems. The strategies for shaving load peak demand include: demand side management (DSM), integration of energy storage system (ESS) and integration of electric vehicle to the grid (EVTG) [1, 3]. These strategies are different ways to achieve peak load shaving. DSM achieves peak load shifting by cutting down part of appliances during peak hours or shift it to off-peak hours, these behaviours affect the comfort of using energy. EVTG provides ancillary services to the grid by charging during off-peak hours and discharge during peak-hours to feed power back to the grid [4]. It helps to reduce grid burden during peak hours, while it affects the use of EV owners. ESS achieves peak load shifting by using energy storage to supply energy during peak hours. It allows the consumers to use energy as usual.

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Peak load shaving has a positive impact on the grid operator. On one hand, from the technical perspective, the action of peak load shaving contributes to improved power quality, reliability and efficient use of the existing generators and networks. On the other hand, from the economic perspective, peak load shaving contributes to cost reduction. It helps the power producer to avoid building the power plants that are scheduled especially for peak demand hours, in such a way, it reduces the energy generation cost. It also enables the transmission and distribution operators to defer the update of the networks and extend the lifespan of the networks [5]. Moreover, lowering peak demand aims at the future scenario to save network cost, because it is not required to design the capacity of the network system much higher than actually needed.

Studies on peak shaving in terms of ESS are mainly focused on the areas of optimal operation of the energy storage system [6], optimal energy storage system sizing [7], and economic feasibility analysis [8]. It lacks study on how tariff influences consumers to respond to load flattening. Currently, the energy price is flat and network charge is fixed for residential consumers in many countries, for example, in the Netherlands [9]. There is no incentive for residential consumers to react to peak load shaving under this pricing scheme. While, some countries are using the time of use (TOU) electricity price, for example, in Italy, all consumers connected to the low voltage network pay at TOU price if they do not have a specific supplier in the liberalized market [10]. TOU electricity price takes the consumption period into account. It incentivizes consumers to reduce energy consumption during peak hours.

In this paper, a segmented energy tariff design is proposed to incentivize consumer to flatten their load demand at all the time instead of shaving load from peak to off-peak hours. Battery is used as the strategy to keep the load consumption profile from grid below the predefined consumption level at all the time, without affecting the comfort of consuming energy. Battery will be charged when the load demand is less than the threshold at the amount of the difference between the threshold and load demand at that time, and discharge when load demand is larger than the threshold at the amount of the difference between load demand and the threshold at that time. The threshold indicates at which consumption level the price will be changed. The price ratio between the two prices at the two consumption levels, battery size and the threshold are also analyzed with a case study to see how they influence the performance of load flattening from both technical and economic perspectives.

The remainder of this paper is organized as follows. Section II describes the proposed tariff design methodology. Influencing factors and performance indicators on load flattening under segmented energy tariff design are analyzed in Section III. Result analysis of a case study is shown in Section IV. Section V summarizes the work.

II. SEGMENTED ENERGY TARIFF DESIGN

A. Tariff design principles

By designing electricity tariff, we take the following economic incentives into account [11, 12, 13, 14], these include:

(1) Allocative efficiency: Incentivizing consumers to use grid efficiently. It not only promotes consumers to reduce peak demand but also keeps consumption within the threshold at all the time under segmented energy tariff design.

(2) Productive efficiency: The energy should be delivered to consumers at the lowest possible cost. It should incentivize efficient infrastructure investment and operational cost. The segmented energy tariff design tries to reduce these costs by avoiding building the infrastructure that built for supplying peak demand.

(3) Cost reflectiveness: Consumers are charged at the costs of the energy they receive while considering their contribution to peak demand. Under segmented energy tariff, consumers are charged based on their consumption levels. It reflects their energy consumption over the threshold and how their consumption affects their energy bills.

B. Segmented energy pricing

Traditionally, more generation capacity is reserved to be used only for peak hours in a day, it increases the energy cost during the peak hours. TOU energy price includes peak and off-peak price in general, it is distinguished between peak and off-peak hours. Instead of focusing on consumption hours, an innovative energy pricing methodology - segmented energy pricing is proposed in this paper to incentivize consumers to keep their load profile within a predefined consumption level at all the time. The predefined consumption level is the threshold where price changes. Consumers are charged at a low energy price when consumption is below the consumption level, and high price above this level. The segmented energy pricing is formulated as:

$$P(h) = \begin{cases} P_b & E(h) \leq E_b & \text{(1a)} \\ P_e & E(h) > E_b & \text{(1b)} \end{cases}$$

where $E(h)$ is the hourly energy consumption, E_b is the predefined energy consumption threshold. $P(h)$ is the energy price in hour h. P_b is the energy price when energy consumption is less than the threshold. P_e is the energy price for the part of energy consumption exceeds the threshold.

Under the segmented energy pricing mechanism, the energy cost $C(h)$ in hour h is calculated as:

$$C(h) = \begin{cases} P_b \times E(h) & E(h) \leq E_b \text{(2a)} \\ P_b \times E_b + P_e \times (E(h) - E_b) & E(h) > E_b \text{(2b)} \end{cases}$$

C. Load flattening control

The objective of load flattening is to keep the imported energy from grid less than or equal to the predefined consumption level. An example of daily load flattening is shown in Figure 1. The blue curve is the normal load profile, the green area is the energy charged to battery from grid, and the red area is the energy discharged to load from battery. The black line is the final imported energy from grid. In this example, the threshold is the average value of the total daily consumption. It determines from which point the battery starts to charge and discharge. It is important to set an appropriate value for the threshold level to keep the imported energy from grid never exceeds the threshold. The limitations for load flattening control are:

(1) The total energy imported from grid in each hour should not exceed the threshold:

$$E_G(h) \leq E_b \tag{3}$$

where $E_G(h)$ is the hourly imported energy from grid.

(2) The energy state of battery always satisfies:

$$E_B(h+1) = E_B(h) + E_b - E(h) \tag{4}$$

$$E_{B\_min} \leq E_B(h) \leq E_{B\_max} \tag{5}$$

where $E_B(h)$ and $E_B(h+1)$ is the energy state of battery in hour h and $h+1$ respectively. E_{B_min} and E_{B_max} are the minimal and maximal energy state of the battery.

(3) To keep the imported energy from grid within the threshold, the threshold value should satisfy:

$$E_b \geq E_{D\_avg\_max} \tag{6}$$

where $E_{D\_avg\_max}$ is the maximal hourly average energy consumption during the day in the year.

Besides, the battery size should be large enough to charge enough energy to be used when demand is higher than the threshold. The threshold value impacts the selection of battery size.

III. INFLUENCING FACTORS AND PERFORMANCE INDICATORS ON LOAD FLATTENING

A. Influencing factors

1) Battery size: From technical perspective, the battery size should be large enough to satisfy energy dispatch. However, from economic perspective, battery size determines the annualized cost of battery. It takes a large percentage in the total energy cost. Therefore, in practice, the selection of battery is determined by the objective of a study, either to maintain the energy imported from grid always less than the threshold or to minimize the total energy cost.

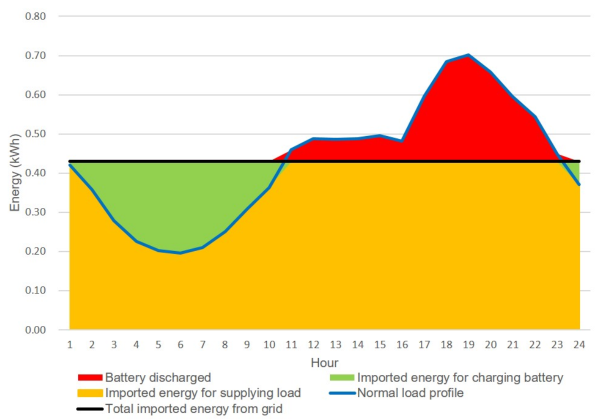

Fig. 1: An example of daily load flattening

2) The threshold: From technical perspective, as illustrated in Section II-C, the threshold value should be set at least as the maximal hourly average energy consumption during the day in the year, such that the energy imported from grid over the threshold is zero at every time during the year. Besides, the threshold value affects the energy prices at different consumption levels.

3) Price ratio: The gap between high and low energy prices is an important factor that affects the willingness of consumer to flatten their load profile with battery. If the gap between the two energy prices is very low, the investment in battery will increase the energy cost greatly. Consumers are not willing to respond to load flattening. If the gap is large enough that energy cost is higher than the case of installing a battery, consumers are willing to respond to load flattening. In this paper, the ratio between the two prices is defined as:

$$R = \frac{P_e}{P_b} \tag{7}$$

This ratio is used to measure to which extent energy tariff influences consumers' motivation to respond to load flattening.

B. Performance indicators

1) Load factor: Load factor is an important parameter to evaluate the variability of load demand and the efficiency of the energy utilization. It is defined as the ratio between average and peak power demand [1, 15]:

$$LF = \frac{P_{avg}}{P_{peak}} \tag{8}$$

where LF is load factor, P_{avg} is the average power demand, and P_{peak} is the peak power demand.

It is expected that the load factor is high. It indicates that the load demand profile does not vary a lot, and the power plant is being used efficiently.

2) Total energy cost: The economic benefit for consumers is that they can reduce energy cost by flattening their energy consumption from grid. The total annualized cost paid by consumers is:

$$C_T = C_B + \sum_{h=1}^{8760} C(h) \tag{9}$$

where C_B is the annualized battery cost, it is determined by its size. $C(h)$ is the hourly energy cost, it is determined by the energy price at different consumption levels, as defined in 2b.

IV. Case Study and Result Analysis

A. Input data

To illustrate the economic benefits of consumers who respond to load flattening motivated by segmented energy tariff, a home battery system is modeled in this study. The technical and economic data used in the model is described in the following sections.

1) Load demand profile: In this research, a household load profile (which is the average load profile of 10,000 households) in the Netherlands is used to assess the performance of segmented energy tariff on load flattening. The hourly metered data for electricity consumption for one year is obtained from Liander open data platform [16]. The load demand in winter days is much higher than in summer days. It is also high during late afternoon hours, and low during early morning hours. The total annual load consumption is 3124 kWh for the selected household. The maximal and minimal hourly electricity consumption during the year is 0.75 kWh and 0.16 kWh. The maximal and minimal hourly average electricity consumption during the day in the year is 0.45 kWh and 0.29 kWh respectively.

2) Battery data: Table I shows the techno-economic data of battery used in this study. The capital cost is 200 €/kWh considering the installation cost [17]. The operation and maintenance cost is 1% of the capital cost. The lifetime is 10 years. It is assumed that there is no energy losses for charging and discharging battery. The maximal and minimal state of charge (SoC) is 90% and 20%, respectively.

TABLE I: Techno-economic data for battery

Capital cost (€/kWh)	Life time (Years)	SoC_{max} (%)	SoC_{min} (%)
200	10	90	20

3) Energy prices: The energy price is flat for residential consumers in the Netherlands, it is 0.21 C/kWh in 2019 [18]. For segmented energy price, it is assumed that the energy price is 0.15 €/kWh for energy consumption below the threshold, for the energy price over the threshold is determined by the ratio between the two prices.

B. Technical parameters analysis

1) Annual imported energy over threshold: It is expected that the imported energy over the threshold is zero, then the consumers do not need to pay the cost of energy at a higher price. Figure 2 shows the impact of battery size and the threshold value on the total annual imported energy over the threshold. The imported energy over the threshold decreases with the increase of threshold value and battery size. When the threshold value is equal to the maximal hourly energy consumption during the day in the year (0.45 kWh), the minimal battery size is 3 kWh for making the imported energy over the threshold zero. In practice, consumers should select the battery size according to the threshold value to keep the energy imported energy from grid within the pre-defined threshold.

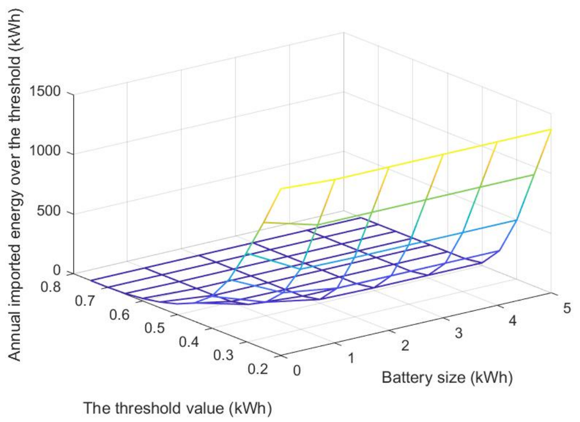

Fig. 2: Annual imported energy over the threshold

2) Load factor: The average hourly energy consumption in the year is 0.36 kWh, and the peak load demand is 0.75 kW and 0.45 kW before and after load flattening. Therefore, the load factors are 0.48 and 0.80, respectively. The load factor increases by 67% after load flattening, which means that the energy system is being used efficiently due to the contribution of load flattening by consumers. The load demand profile seen from grid side does not vary a lot, it tends to be flat after load flattening.

3) Annual imported energy from grid: In this part, we study the imported energy from gird under the condition that battery size is 3 kWh and the threshold value is 0.45 kWh. Figure 3 shows the hourly imported energy from grid during the whole year. The result shows that the hourly imported energy is always less than or equal to the threshold. Figure 4 shows the hourly imported energy for charging battery over the whole year. It shows that battery is mainly used in winter days to help maintain the imported energy from grid within the threshold.

C. Economic parameters analysis

In this part, the economic influencing factors are analyzed. Under the segmented energy tariff design, firstly, the impact of battery size and price ratio on the total energy cost is studied. The threshold value is taken as the maximal hourly average energy consumption during the day in the year (0.45 kWh) in this case. Figure 5 shows the annual energy cost under different battery sizes and price ratios. When the battery size is greater than 3 kWh, the price ratio does not have impact on the total energy cost, because the imported energy over the threshold is zero. Under this condition, the energy cost is determined

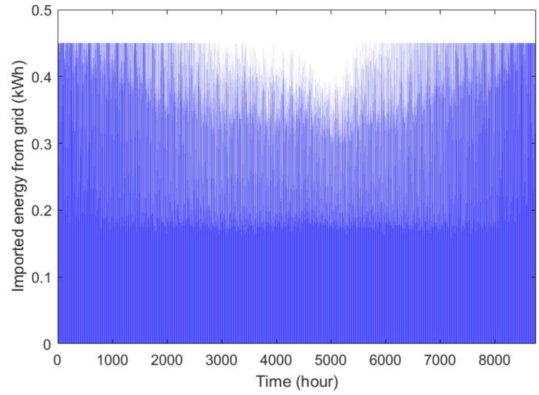

Fig. 3: Imported energy from grid over the whole year

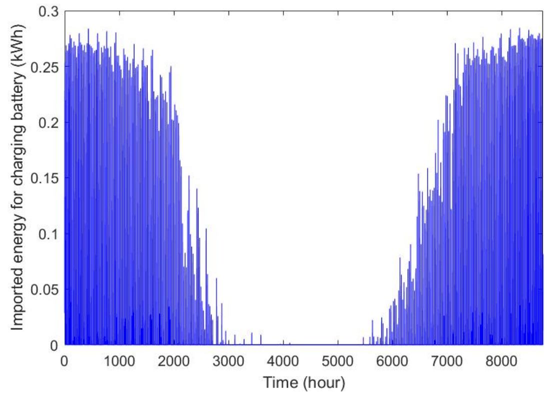

Fig. 4: Imported energy for charging battery over the whole year

by the battery size and the energy price below the threshold. In practice, it is an optimization problem to decide the size of battery to minimize the total energy cost considering the energy prices at different consumption levels. However, it may not ensure the imported energy from grid is always below the threshold. When the battery size is 3 kWh, the threshold value is 0.45 kWh, the annual energy cost is €535.

Secondly, the influence of price ratio and the threshold value on annual energy cost without battery is studied. Figure 6 shows the annual energy cost under different price ratios and threshold values. The higher the price ratio and the lower the threshold value are, the higher the annual energy cost is. When the threshold is 0.45 kWh, the annual energy cost increases from €469 to €912 with the increase of price ratio from 1 to 20. When the price ratio is around 9, the energy cost is close to the energy cost under flat energy tariff, which is €656. When the price ratio is 4, the annual energy cost is €539. This economic signal indicates that when the energy price ratio is larger than 4, it is beneficial for consumers to install batteries to reduce their energy cost. As long as the price ratio is between 4 and 9, consumers can reduce their energy cost by responding to load flattening under segmented energy tariff compared to flat energy tariff. In practice, attention should

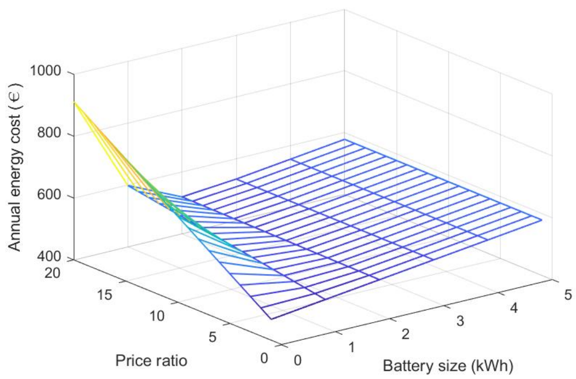

Fig. 5: Annual energy cost under different price ratios and battery sizes

be paid to the energy price below the threshold, the higher the threshold value, the higher the energy price should be. However, in this study, it is assumed that the energy price below the threshold is fixed under any value, in order to study the influence of price ration on the energy cost. In addition, the higher the price ratio, the higher the revenue for electricity producers or retailers, there should be some limitations on the price ratio to ensure productive efficiency.

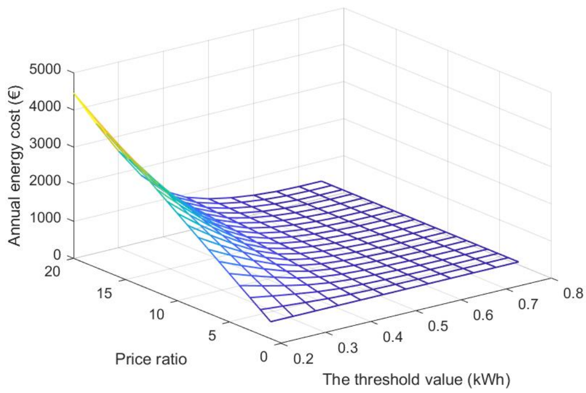

Fig. 6: Annual energy cost under different price ratios and threshold values

V. Conclusions and discussions

In this paper, segmented energy tariff is designed and analyzed how it contributes to load flattening with the dispatch of energy storage. This energy tariff focuses on energy consumption levels instead of consumption periods. It inventivizes consumers to keep the load demand with the predefined threshold instead of reducing load demand only in peak hours. The results show that load flattening contributes to increasing load factor, which indicates that energy generation and electricity network are being used efficiently. It is beneficial to power system in terms of system operation and cost. The threshold value and battery size are the two parameters that determine if the imported energy from grid could be kept within the predefined consumption level. The energy cost is influenced by battery size and segmented energy prices. In practice, segmented energy tariff can be a useful instrument to achieve load flattening if the battery cost can be accounted in the energy savings. It is worth considering adopting consumption level based tariff to make load flattening attractive for consumers, such as segmented energy tariff proposed in this paper.

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