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A Simple Distribution Energy Tariff under the Penetration of DG

Javier Borquez, Hector Chavez *, Karina A. Barbosa and Marcela Jamett and Rodrigo Acuna

Departamento de Ingenieria Electrica, Universidad de Santiago de Chile, Estación Central, Santiago 9160000, Chile; javier.borquez@usach.cl (J.B.); karina.barbosa@usach.cl (K.A.B.); marcela.jamett@usach.cl (M.J.); rodrigo.acunama@usach.cl (R.A.)
* Correspondence: hector.chavez@usach.cl

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Abstract: In a scenario where distributed generation infrastructure is increasing, the impact of that integration on electricity tariffs has captured particular attention. As the distribution sector is mainly regulated, tariff systems are defined by the authority. Then, tariffs must be simple, so the methodology, criteria, and procedures can be made public to ensure transparency and responsiveness of the customers to price signals. In the aim of simplicity, tariff systems in current practices mostly consist of volumetric charges. Hence, the reduction of the energy purchased from the distribution network jeopardizes the ability of the tariff system to ensure recovery of the total regulated costs. Although various works have captured this concern, most proposals present significant mathematical complexity, contrasting with the simplicity of current practices and limiting its regulatory applicability. This work develops a tariff system that captures the basic elements of distribution systems, trying to maintain the simplicity of current practices, ensuring recovery of the total regulated cost under the penetration of distributed generation, and incentivizing through price signals operational efficiency. A simulation will be presented to discuss numerical results.

Keywords: distributed photovoltaics; distributed storage; distributed energy economics

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1. Introduction

Distribution systems are normally regulated monopolies where the authority set electricity rates. In such a scenario, an electricity tariff system is a rate structure that aims to guarantee regulatory and economic aspects.

From a regulatory perspective, the methodology, employed criteria and procedures of the tariff system must be made public to ensure transparency [1]. In this sense, the tariff systems must be as simple as possible to guarantee that each actor can understand the aim of the methodology and respond to the tariff system in a harmonic manner. Thus, simplicity is a very important feature in tariff systems, as seen in current practices [2,3].

From an economic perspective, tariff systems must simultaneously guarantee cost recovery and efficiency, which makes tariff design a difficult task. In terms of costs, the tariff systems must ensure that energy and network costs are recovered, as tariff systems are a regulated by the authority [1]. In addition, a tariff system must send adequate economic signals both in the short and long term to improve the efficiency of the distribution system [1].

Generally, regulatory and economic aspects of tariff systems are not consistent each other. For example, the best way of guaranteeing efficiency is to reflect marginal prices in the tariff system; however, marginal prices do not recover network costs and the marginal pricing theory is mathematically complex. On the other hand, one can define an average flat rate to ensure full recovery of costs. This approach would be the simplest, but it would be economically inefficient, as no responsiveness from demand would exist. Thus, there exists a trade-off between the tariff system principles [1], which makes the problem difficult to solve. The fact that tariff systems depend on a multiplicity of factors is discussed in detail in [4].

This need for simplicity has captured particular attention in the literature. In [5], an experiment is conducted in Ireland to test consumer behaviour towards smart meters and time-of-use tariffs. The results suggest that consumers struggle to match their electricity usage to appropriate tariffs, and that a general aversion to more complex tariffs can lead to sub-optimal choices. Similarly, in [6], an experiment on German consumers was conducted, obtaining similar findings. The results suggest that consumer reactions to dynamic tariffs are strongly related to the cognitive effort they make in order to understand the tariff system to estimating the bill amount. It concludes that it will be challenging to convince European consumers to select complex dynamic tariffs. In [7], the consequences for the cost-reflectivity, predictability, and robustness of different types of network tariffs are investigated. The study finds that predictability (how accurately a customer can estimate the total bill from the understanding of the tariff system) is the central factor for the sustainability of a tariff system, even more important than cost reflectivity. Therefore, it can be seen that simplicity is a crucial aspect of a tariff system.

In their aim for simplicity, most tariff systems are based on a single charge that is proportional to the energy consumption, in addition to other fixed charges. These tariff systems are generally called volumetric [8], as the cost of energy and network are represented in one single charge. As a volumetric tariff is the simplest way electricity can be priced, it is widely used in practice [2,3].

Although simple and widely used, volumetric tariffs are very limited in terms of guaranteeing recovery of the total regulated costs under the penetration of Distributed Generation (DG). In terms of determining volumetric tariffs, the authority intends to define a volumetric charge that covers the energy and network costs; the energy cost is by nature proportional to the amount of energy, and the network cost is determined by assuming a representative average power profile of customers to obtain an estimate of network usage. However, if a significant penetration of DG occurs, the amount of energy withdrawn from the grid will decrease, and the tariff collection may not be enough to cover total network costs. This problem is described in detail in [9–11].

The definition of tariff systems for a harmonic integration of DG has captured particular attention in the literature, but most of the approaches are of a very complex nature, contrasting with the need for simplicity. In [12], the behavior of photovoltaic DG respect to distribution tariffs is analyzed. In the analysis, three simple tariff mechanisms are considered, and the relationship between different DG technologies is analyzed using a game theory approach. Although representative of the collective behavior of distribution customers, the work proposes a very complex model that is difficult to extend to a tariff definition. In addition, the tariff mechanism that is presented is assumed volumetric, which does not guarantee cost recovery when a large DG penetration scenario is considered. Similarly, in [13], the behavior of distributed storage systems respect to distribution tariffs is analyzed. Considering the particular case of Findland, this work discusses the benefits of a distribution customer with storage, and the benefits of the distribution system operator. Mainly associated with new domestic storage and smart meters, the study shows that the use of storage can be profitable for some cases where power-based distribution tariffs are considered. The analysis also assumes that the tariff structure does not change with the integration DG. A similar approach is presented in [14], where the influence on the tariff structure is not considered.

Most approaches that consider, to some extent, recovery of regulated costs under the integration of DG are mathematically complex in the context of tariff systems. The work in [15] deals with volumetric tariff limitations, but considers an optimization problem capturing the basic features of the problem in a very complex manner. The work proposes that distribution customers behave optimally, so tariff parameters are tuned iteratively until a set of parameters for the tariff are obtained, constrained to recovery of the total regulated cost. However, together with the complexity of the approach, a change in the conditions (an increment in DG penetration for example) requires a new run of the algorithm and a new set of parameters. In [16], a Local Marginal Pricing (LMP) approach is extended to a tariff for the Nigerian case. As the focus is cost representativeness, the impact of a LMP formulation complexity on a distribution customer level did not capture particular attention. A similar approach is presented in [17], where a more generalized optimization framework is presented. In [18], the minimization costs of the customer is represented without considering recovery of the regulated cost. In [19], a dynamic tariff system is proposed to incentive distribution customers to install photovoltaic (PV) DG and storage based on feed-in tariffs. In line with current practices that maintain design simplicity, the tariff system is based on fuzzy rules that represent physical constraints of the network and the objective of incentivizing PV and storage. Although the cost recovery of the PV and storage from the customer size is considered, the recovery of network cost is not represented, as the formulation focus is on feed in tariff definition. In [20], a tariff structure for each day is calculated by formulating and solving a binary linear optimization problem, as well as [21] that proposes an optimization framework to represent the tariff system in order to maximize social welfare. As it can be seen, the problem of tariff systems under the penetration of DG is clear, but the various approaches in the literature overlook the need for simplicity coming from the regulatory need of transparency and customer responsiveness.

This paper proposes a simple tariff system definition under the penetration of DG. The goal of the formulation is to consider the trade-off between simplicity, cost recovery, and efficiency by formulating a tariff system that guarantees recovery of the total regulated costs and incetivizes efficiency through prices with a simple mathematical formulation. A numerical example is presented in order to show the behavior of the proposed approach.

2. Work Contribution

As stated in Section 1, tariff systems must follow principles that make the implementation of the tariff system realistic. As explained in [1], simplicity and cost recovery are very important in a pragmatic solution, while efficiency must be ensured by sending adequate economic signals through prices to be "reasonably" efficient [1]. This way, the basic ideas of the proposed tariff system are:

- Guaranteeing recovery of the total regulated cost for each activity (generation, transmission, distribution, etc.).
- Incentivizing a customer behavior through prices that tends to efficiency. In this work, the tariff will incentivize customers to produce peak shaving that has well-understood systemic benefits [22,23].
- Keeping the mathematics and conceptual framework behind the tariff simple. In particular, the tariff system will consider algebraic systems and closed-form solutions.

This way, the contribution of the work is to comprise the most important features of a tariff system in the presence of DG integration in a simple manner. In one hand, various approaches have represented cost recovery and efficiency systematically, but with complex mathematical formulations that complicates regulatory implementations. On the other hand, various actual implementations maintain a level of simplicity that allows its regulatory applicability [2,3]; however, most of these approaches are based in volumetric tariffs that overlook cost recovery and efficiency in the presence of DG. Thus, this work proposes a tariff system considering the trade-off between mathematical complexity and regulatory applicability.

3. Formulation of the Tariff System

The tariff system will consider that there is an operating period for which cost recovery must be ensured. The operating period will be divided in N intervals in which prices will be defined. In order to simplify the notation, the fixed network charges, namely generation capacity, transmission, distribution, and others, will be represented by a unique cost per day C_D. The energy cost will be represented by a constant price π_R that represent a flat-price generation contract; the representation of more complex energy prices is left for future work. Then, the idea of the proposed formulation is to establish prices for injection π_k^{sell} and consumption π_k^{buy} for each operating period k that incetivize peak shaving.

The tariff system considers the following definitions:

N: number of equal time intervals within an operating period,
$k \in \mathcal{K}$: set of equal time intervals within an operating period,
$i \in \mathcal{I}$: set of customers,
C_D: cost of the physical operation of the distribution grid (\$/day),
π_R: price of energy supplied by a generation company (\$/kWh),
E_R: energy supplied by a generation company (kWh/day),
π_k^{buy}: price of energy purchased from the grid in period k (\$/kWh),
π_k^{sell}: price of energy sold to the grid in period k (\$/kWh),
E_{ik}^{buy}: energy purchased from the grid in period k by customer i (kWh), and
E_{ik}^{sell}: energy sold to the grid in period k by customer i (kWh).

An initial concern of a tariff system is to guarantee cost recovery. Mathematically, the following necessary conditions can be formulated:

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{I}}\left(\pi_k^{buy}E_{ik}^{buy} - \pi_k^{sell}E_{ik}^{sell}\right) = C_D + \pi_R E_R. \tag{1}$$

Note that this definition internalizes the cost of physical operation and energy into one single charge, similar to the idea of volumetric tariffs. Now, let $\overline{E}$ be the average of net demand (E_k^{net}) over a period of operation:

$$\overline{E} = \frac{1}{N}\sum_{k\in\mathcal{K}}\left(E_k^{buy} - E_k^{sell}\right) = \frac{1}{N}\sum_{k\in\mathcal{K}} E_k^{net}, \tag{2}$$

where

$$E_k^{sell} = \sum_{i\in\mathcal{I}} E_{ik}^{sell};\;\; E_k^{buy} = \sum_{i\in\mathcal{I}} E_{ik}^{buy}, \tag{3}$$

are, respectively, the total net energy consumed and injected.

Similarly, it can be seen that the total energy E_R consumed from customers is given by:

$$E_R = \sum_{k\in\mathcal{K}} E_k^{net} \tag{4}$$

Then, from Label (1):

$$\begin{aligned}\sum_{k\in\mathcal{K}}\left(\pi_k^{buy}E_k^{buy} - \pi_k^{sell}E_k^{sell}\right) =& C_D + \pi_R E_R \qquad (5)\\ =&\frac{\overline{E}}{\overline{E}}C_D + \pi_R E_R\\ =&\frac{1}{\overline{E}}\frac{1}{N}\sum_{k\in\mathcal{K}} E_k^{net} C_D + \pi_R \sum_{k\in\mathcal{K}} E_k^{net}\\ =&\sum_{k\in\mathcal{K}}\left(\frac{C_D E_k^{net}}{N\overline{E}} + \pi_R E_k^{net}\right).\end{aligned} \tag{6}$$

Thus, from (3), a sufficient condition for (1) to hold is:

$$\pi_k^{buy}E_k^{buy} - \pi_k^{sell}E_k^{sell} = \frac{C_D E_k^{net}}{N\overline{E}} + \pi_R E_k^{net}. \tag{7}$$

Note that (7) is a condition on each period k, but requires information from all periods to compute $\overline{E}$. This leads to an *ex-post* definition of the tariff system because one needs to first know the behavior of customers' energy demand and injections for the entire period to then obtain prices consistent with such choices of demand and injection. Assume that E_{ik}^{sell} and E_{ik}^{buy} are known for all $i \in \mathcal{I}$ and $k \in \mathcal{K}$. In such a case, (7) has no unique algebraic solution as one equation and two variables (π_k^{buy}, and π_k^{sell}) exist. Additional conditions are necessary to define a unique solution to (7). One additional condition can be defined to incentivize peak shaving behavior as follows:

$$\pi_k^{buy} - \pi_k^{sell} = \alpha_k \frac{E_k^{net} - \overline{E}}{\overline{E}}, \tag{8}$$

where α_k ($/kWh) is a given non-negative scalar function. If $E_k^{net} > \overline{E}$, then $\pi_k^{buy} > \pi_k^{sell}$, so the customer is incentivized to use storage for self consumption to avoid energy consumption from the grid. If $E_k^{net} < \overline{E}$, then $\pi_k^{buy} < \pi_k^{sell}$, the customer is incentivized to consume from the grid taking advantage of a better price. The term α_k ($/kWh) is intended to modulate/control the price differentiation effect. Thus, the tariff rule formed by (7) and (8) consists of a linear system as follows:

$$\begin{bmatrix} E_k^{buy} & -E_k^{sell} \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \pi_k^{buy} \\ \pi_k^{sell} \end{bmatrix} = \begin{bmatrix} \frac{C_D E_k^{net}}{N\overline{E}} + \pi_R E_k^{net} \\ \alpha_k \frac{E_k^{net} - \overline{E}}{\overline{E}} \end{bmatrix}. \tag{9}$$

Note that system (9) has a unique solution for all $E_k^{buy} \neq E_k^{sell}$ that is, $E_k^{net} \neq 0$. In this case, the prices of energy consumed and injected at instant k, are given by:

$$\left.\begin{array}{l} \pi_k^{buy} = \pi_R + \frac{C_D}{N\overline{E}} - \alpha_k \frac{E_k^{net} - \overline{E}}{\overline{E} E_k^{net}} E_k^{sell} \\ \pi_k^{sell} = \pi_R + \frac{C_D}{N\overline{E}} - \alpha_k \frac{E_k^{net} - \overline{E}}{\overline{E} E_k^{net}} E_k^{buy} \end{array}\right. , \quad E_k^{sell} \neq E_k^{buy}. \tag{10}$$

If, for some k, $E_k^{sell} = E_k^{buy}$, or $E_k^{net} = 0$, the pricing rule becomes indefinite. The condition for which $E_k^{sell} = E_k^{buy}$ occurs when generation matches demand, and demand from the distribution system is not needed. In that case, the distribution system cannot ensure regulated cost recovery, which is a general problem of distribution systems when a large penetration of DG occurs. This issue is complicated because it presents the situation when there is no need for energy from the transmission/generation system, and the distribution system is somehow self-sufficient. This topic is beyond the scope of this work, although the tariff system shows the problem from its underlying mathematical definition.

Note that the price determination in (10) is simpler than state-of-the-art methods in terms of processing time and implementation. The tariff system in (10) is based on a simple arithmetic operations of rational numbers. This is less computationally expensive than current approaches based on optimization [16–21], which are numerically implemented with iterative algorithms normally based on repetitive inverse matrix computations. In this sense, the proposed tariff system results in shorter processing time than those based on optimization programs. In addition, one can see that the proposed approach does not need real-time metering, as the tariff computation is ex-post. Note that expression (10) requires the hour-by-hour power consumption of customers at the end of the tariff period, so there is no need for real-time metering. In fact, the proposed tariff system can be implemented with existing offline metering technologies, where the hour-by-hour reading can be manually obtained from the meter data-logger to then compute the prices and the total bill of customers. Then, the proposed tariff system is simple in terms of the metering infrastructure that is required to be implemented.

One limitation of the proposed tariff system is that optimization approaches represent welfare maximization explicitly, while the proposed approach represents economic efficiency through peak shaving. Optimization approaches represent welfare maximization as an explicit constraint that ensures both recovery of regulated costs and profit maximization of customers. The proposed formulation also ensures recovery of regulated costs, but do not guarantee profit maximization of customers; instead, the tariff system incentivizes peak shaving that leads to economic efficiency. However, the complexity of the optimization proposals is a limitation while considering the impact of customer understandability on the performance of a tariff system [5–7]. A more accurate (but simple) representation of welfare maximization is left for future work.

4. Interpretation of the Tariff System

In the wholesale generation operation, market participants present offers of their energy generation/consumption, and an optimization program makes a decision on which participants are dispatch/serve; the objective of the optimization is to minimize the operating costs under the physical constraints of the electric system. This way, energy prices approach the real value of electricity, and competition is incentivized as prices, and dispatch/served quantities are known after offers are made explicit. Various authors have proposed to implement the same structure for modern distribution systems, encountering multiple implementation issues. The most critical complexity is the fact that distribution users must submit generation/consumption offers. This way, distribution tariff systems are meant to be simple, tending to volumetric rates that are easy to understand but with significant limitations in terms of representing the cost of electricity and that of the infrastructure to transport and distribute such electricity.

In the case of the proposed tariff system, prices are known after the operating period, depending on the behavior of the participants; however, the rule does not require customers to submit offers. Instead, customers have the option of not performing any action over their energy profile, or considering a more active role and respond to the tariff system incentives. On the other hand, the rule results in high prices for energy when demand is high respect to average demand, and otherwise, when demand is low. This way, a following-rule customer will tend to flatten out net demand, which tend to reduce long term costs in distribution systems. This way, the tariff system incentivizes efficiency through peak shaving, and guarantee cost recovery with an algebraic, closed-form mathematical formulation consistent with the requirements of regulatory simplicity.

5. Customer Model

In order to show the functioning of the proposed tariff system, a customer model will be presented. It is important to note that the customer model is developed with the objective of illustrating the functioning of the tariff system in a simple manner.

The customer model aims to resemble a simple logic behavior intending to reduce the electricity bill of the customer by managing an Energy Storage System (ESS) and in the presence of a Photovoltaic system (PV). The logic is simple: if the prices for energy consumption are high, the customer will tend to discharge the EES to reduce its energy consumption from the network. If the prices for energy consumption are low, the customer will tend to charge the ESS to take advantage of the low price to use the stored energy in periods of high prices. In order to represent this logic in a simple manner, a fuzzy logic controller is selected because of the similarity between the fuzzy rule structure and the logic described above. As the customer model is not the central contribution of the work, the development of the fuzzy controller will be simple and it will not represent more complex phenomena such as maximization of the collective profit of customers and retailers or the interaction between customers (which leads the problem to a game). Actual data of customers will be considered, but the intelligence of the fuzzy controller will be only representative of simple logic rules.

Since the tariff system is ex-post, the fuzzy controller will need a forecast of the period to be represented. The tariff system determines the prices after knowing the behavior of customers for the period under analysis, in order to make decisions based on simple logic rules, the fuzzy controller must have a forecast of the behavior of customers. In order to represent the forecast error, forecast error for PV and demand are obtained from the literature.

5.1. ESS Dynamics

A first element to be defined is the functioning of the ESS. Although numerous approaches define optimal battery charge/discharge policies, such policies are more focused on preserving the chemical life of batteries and other aspects related to operating concerns [24]. The proposed model for storage is simple enough to capture the conservation of energy in a storage device as follows:

$$SOC_{i,k}^{STRG} = SOC_{i,k-1}^{STRG} + E_{i,k}^{STRG}, \tag{11}$$

$$\underline{SOC}_{i,k}^{STRG} \le SOC_{i,k}^{STRG} \le \overline{SOC}_{i,k}^{STRG}, \tag{12}$$

where $SOC_{i,k}^{STRG}$ is the state of charge of the storage system of customer i at period k, $\underline{SOC}_{i,k}^{STRG}$ and $\overline{SOC}_{i,k}^{STRG}$ are the minimum and maximum storage capacity, respectively, and $E_{i,k}^{STRG}$ is the amount of energy deployed by the storage system (if $E_{i,k}^{STRG} < 0$, the storage system is charged from the grid).

Then, the energy balance of customer i at period k is

$$E_{i,k}^{buy} = \max\left(E_{i,k}^{DEM} - E_{i,k}^{PV} - E_{i,k}^{STRG}, 0\right), \tag{13}$$

$$E_{i,k}^{sell} = \max\left(-E_{i,k}^{DEM} + E_{i,k}^{PV} + E_{i,k}^{STRG}, 0\right), \tag{14}$$

where $E_{i,k}^{DEM}$ is the customer demand profile, and $E_{i,k}^{PV}$ is the output of the PV system.

5.2. Forecast Information Available to the Fuzzy Controller

The fuzzy representation of customers is assumed to have forecast information of solar generation (namely $\widehat{E_k}^{sell}$) and of the demand profiles (namely $\widehat{E_k}^{buy}$) of the system under analysis, so a forecast of the total power profile (namely $\widehat{E_k}^{net}$) is available in the absence of ESS actions for each period k. Solar irradiance forecasting methods and implementations are widely known [25], as well as forecasting methods for load [26,27]. Forecasting of load in the distribution level has also been treated in the literature [28].

The forecast error for solar irradiance will be simulated with a Normalized Mean Absolute Error, NMAE%, of 1.5% (according to [29], 1% < NMAE% < 2%). The forecast error for demand has a NMAE% of 0.87%, according to [30]. Then, the fuzzy controller will have forecast information to make decisions on the use of the ESS.

5.3. Fuzzy Controller

This work proposes a set of fuzzy rules to represent customer behavior in response to the tariff system. A fuzzy controller [31] may not be an optimal choice in light of other approaches [32,33], but a set of fuzzy rules was found to be simple enough to show some responsiveness of customers to the proposed tariff system.

As mentioned below, the fuzzy controller is assumed to have forecast information of solar generation ($\widehat{E_k}^{sell}$) and of the demand profiles (namely$\widehat{E_k}^{buy}$). Then, a forecast of prices (namely $\widehat{\pi}_k^{buy}$) and $\widehat{\pi}_k^{sell}$) can be constructed by considering the values of $\widehat{E_k}^{sell}$, $\widehat{E_k}^{buy}$, and $\widehat{E_k}^{net}$ by using (10).

In terms of the inputs considered for the fuzzy controller, these are $\widehat{E}_{i,k}^{net}$, $\widehat{\pi}_k^{buy}$, and $\widehat{\pi}_k^{sell}$. In order for the controller to capture the difference between $\widehat{\pi}_k^{buy}$, and $\widehat{\pi}_k^{sell}$, it was found that the difference between prices $\Delta\widehat{\pi}_k = (\widehat{\pi}_k^{buy} - \widehat{\pi}_k^{sell})$ was a better choice for an input. The output of the fuzzy controller is the power delivered or absorbed by the ESS $E_{i,k}^{STRG}$.

The various rules for the fuzzy system and fuzzy variables are described in Table 1.

Table 1. Fuzzy variables.

Variable	Domain	Unit	Memberships	Type	Functions
$\widehat{E}_{i,k}^{net}$	[−2.5,2.5]	kW	(NN,N,Z,P,PP)	Input	Figure 1
$\widehat{\pi}_k^{buy}$	[55,75]	$/kWh	(L,M,H)	Input	Figure 2
$\Delta\widehat{\pi}_k$	[−10,10]	$/kWh	(N,Z,P)	Input	Figure 3
$E_{i,k}^{STRG}$	[−1,1]	kW	(N,Z,P)	Output	Figure 4

In Table 1, the symbols L, M, H represent, respectively, Low, Medium, and High; while NN, N, Z, P, and PP represent very Negative, Negative, Zero, Positive, and very Positive, respectively.

The logic of the rules is simple, as mentioned above. For example, if the price difference is such that it is very convenient to consume, but PV production is high, the logic action would be to charge the storage system aggressively to both absorb the energy from the PV system and consume from the distribution system. Similarly, if PV production is low, and demand is high, the storage system must discharge aggressively to follow profit maximization if the injection price is high. In all rules, the SOC constraint (11) is considered to avoid unfeasible conditions for the ESS (either fully depleted or fully charged).

The membership functions of each variable are presented in Figures 1–4.

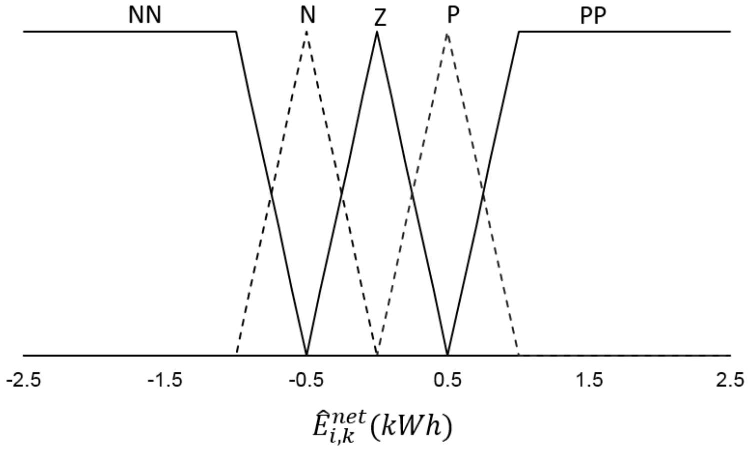

Figure 1. Membership functions for $\hat{E}_{i,k}^{net}$.

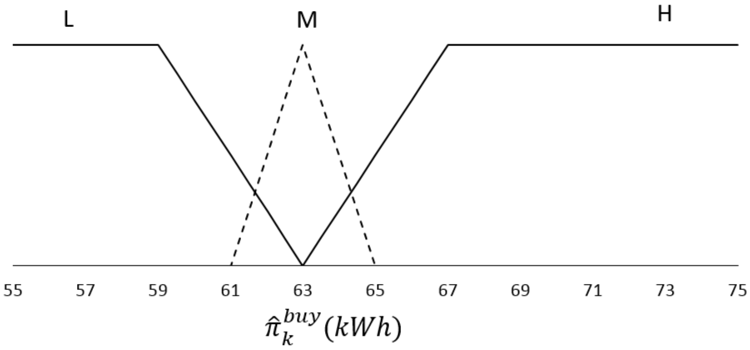

Figure 2. Membership functions for $\hat{\pi}_k^{buy}$.

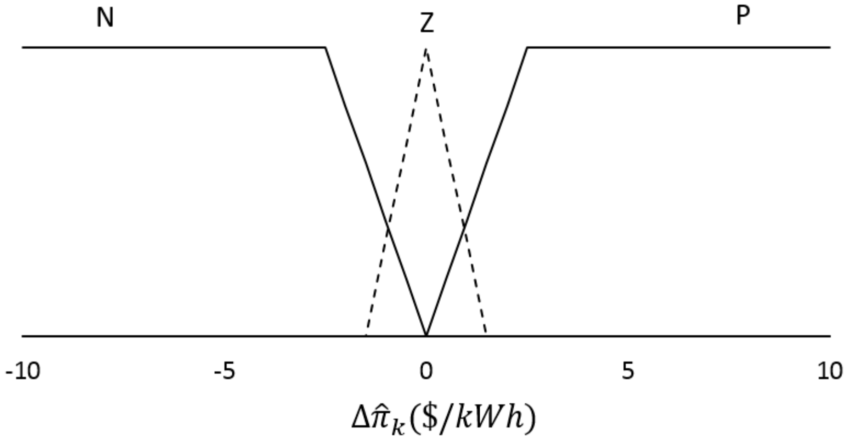

Figure 3. Membership functions for $\Delta\hat{\pi}_k$.

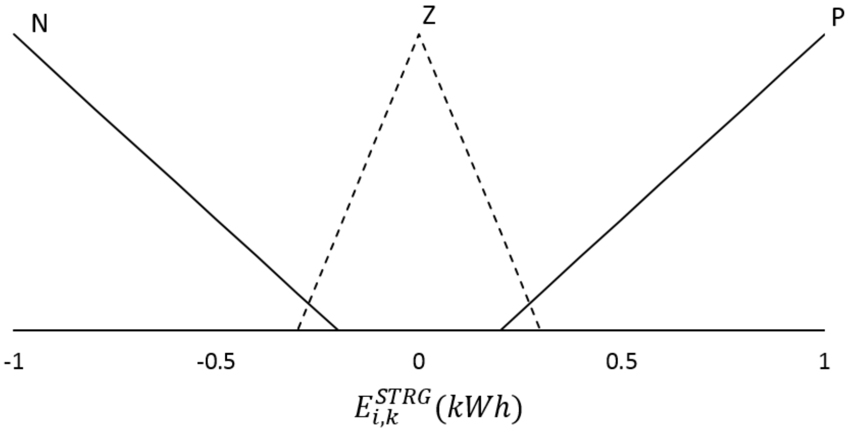

Figure 4. Membership functions for $E_{i,k}^{STRG}$.

The ranges were defined by trial and error, observing the regular behavior of the variables through repetitive simulations. The shape of the fuzzy functions was also defined by trial and error, observing the behavior of the variables through repetitive simulations.

6. Simulation

A study case is presented with residential customers. Some proportion of them will have a ESS and PV, while others will be normal customers with uncontrollable demand. For the simulation, a feeder with 100 customers will be considered. The sun radiation profile and the overall demand of the 100 customers are shown in Figure 5, respectively. For the construction of the feeder power profile, data of actual customers in Santiago, Chile are considered. With the availability of smart meters, it was possible to obtain 362 actual 15-min power profiles. In order to effectively present the information of the 362 power profiles, a k-means clustering analysis was considered, leading to six main clusters shown in Figures 6–12.

In Table 2, the simulation parameters are shown.

Table 2. Simulation parameters.

Period Days	C_D **$**	π_E **$/kWh**	N	α_1	**DSS kW**	**DSS kWh**	**DPS kWp**
30	25,000	50	100	1	1	10	3

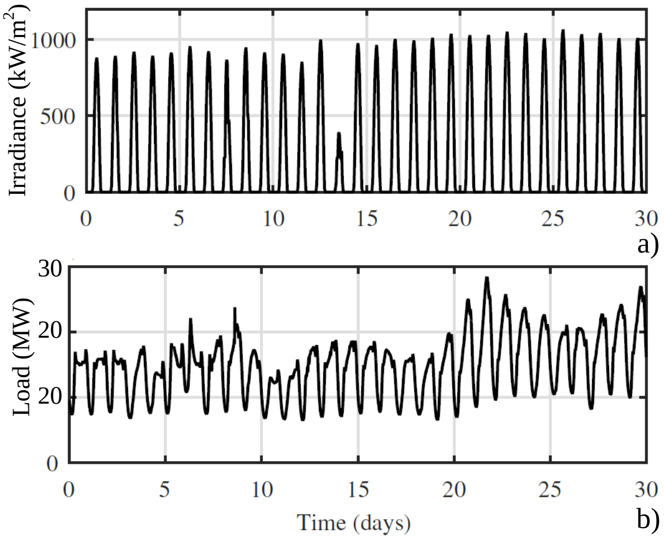

Figure 5. 30-day, hourly solar irradiance (**a**) and load (**b**) time series.

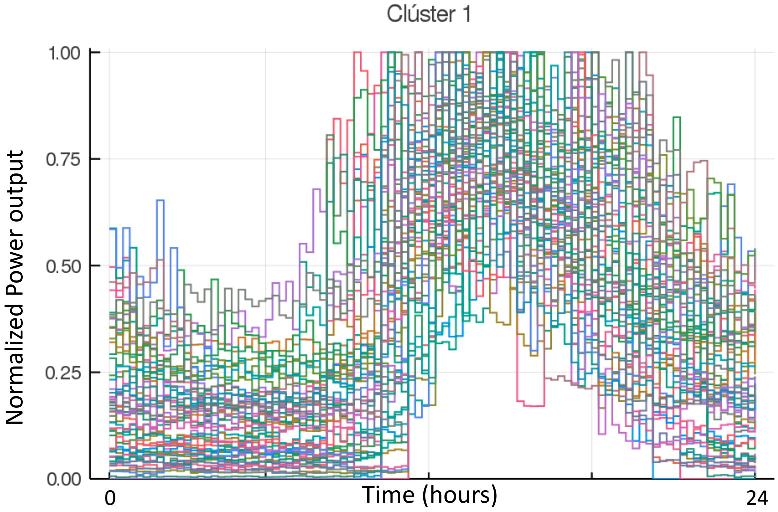

Figure 6. Data of 362 actual distribution customers from Santiago, Chile. Cluster 1.

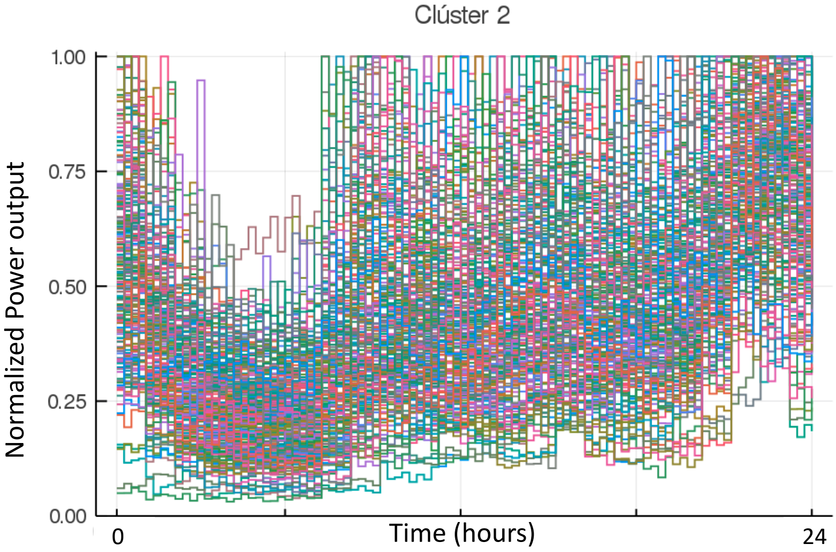

Figure 7. Data of 362 actual distribution customers from Santiago, Chile. Cluster 2.

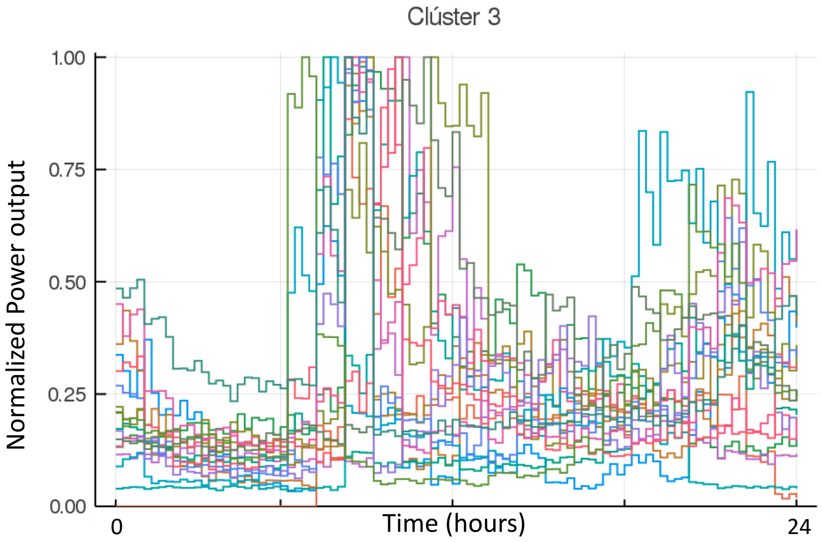

Figure 8. Data of 362 actual distribution customers from Santiago, Chile. Cluster 3.

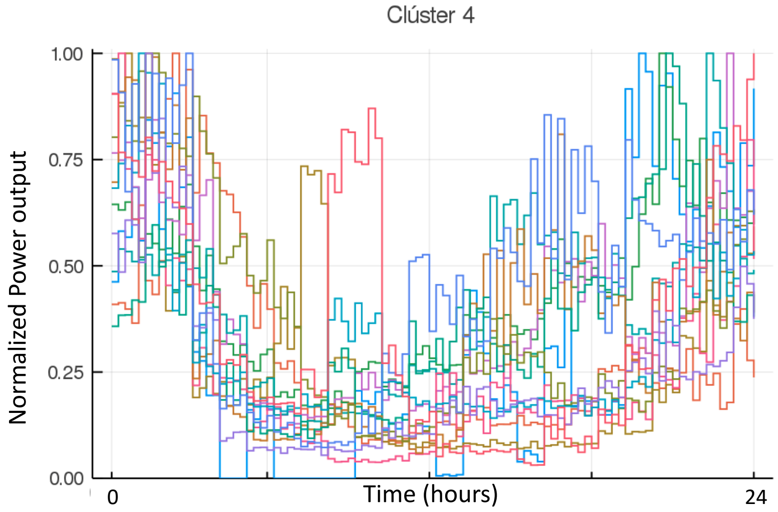

Figure 9. Data of 362 actual distribution customers from Santiago, Chile. Cluster 4.

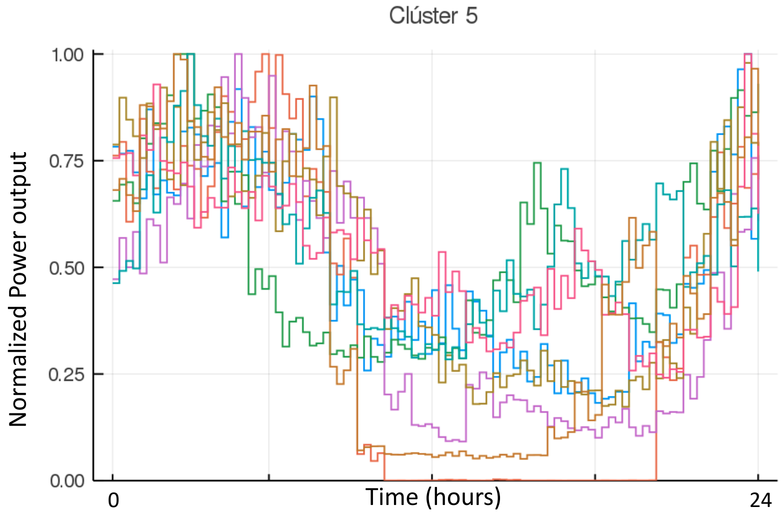

Figure 10. Data of 362 actual distribution customers from Santiago, Chile. Cluster 5.

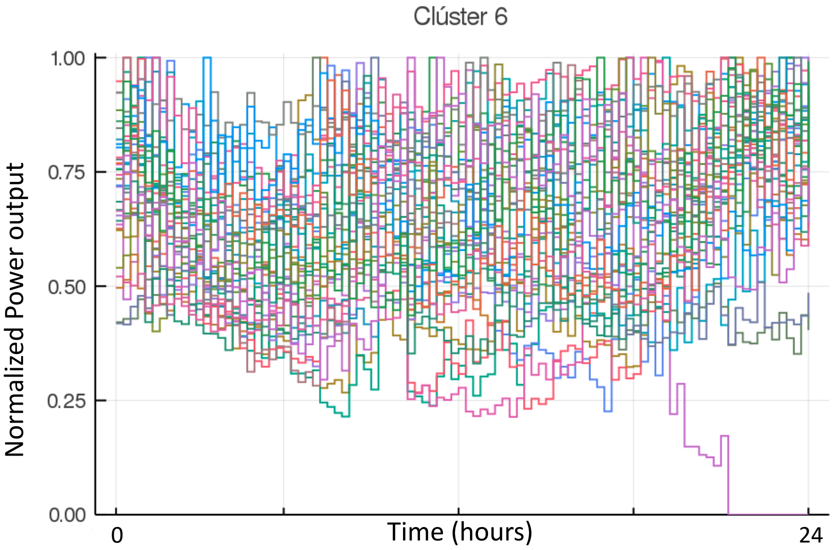

Figure 11. Data of 362 actual distribution customers from Santiago, Chile. Cluster 6.

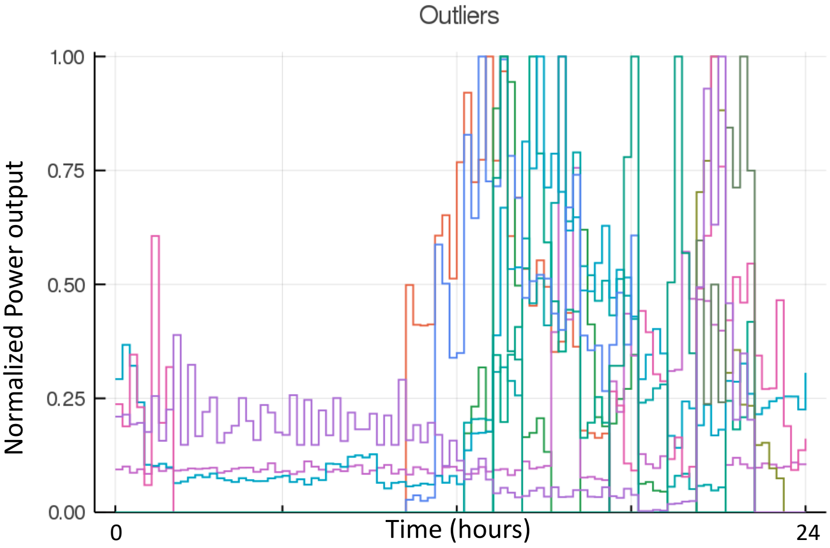

Figure 12. Data of 362 actual distribution customers from Santiago, Chile. Outlayers.

Simulation Scenarios

For the simulation, a base case and four scenarios are considered. The base case assumes that no active customers exist, so customers do not modify their natural behaviors, and E_k^{net} is exactly the collective behavior shown in Figure 5. In this work, an active customer will be modeled with a PV of 3 kWp installed capacity and a 1 kW@10 kWh ESS. In order to see the impact of different scenarios, four conditions will be considered: 25% active customers without PV, 50% active customers without PV, 25% active customers with PV, and 50% active customers with PV. Individual power profiles are taken from the 362 actual profiles in Figures 6–12 , and then a one-year simulation is considered, implementing the proposed tariff system. Figures 13–16 show the histograms of net demand E_k^{net} for the four scenarios, respectively.

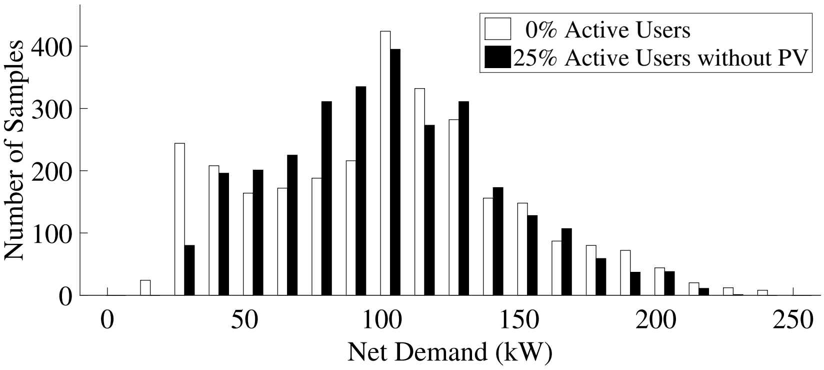

Figure 13. E_k^{net} for the 25% active customers without PV.

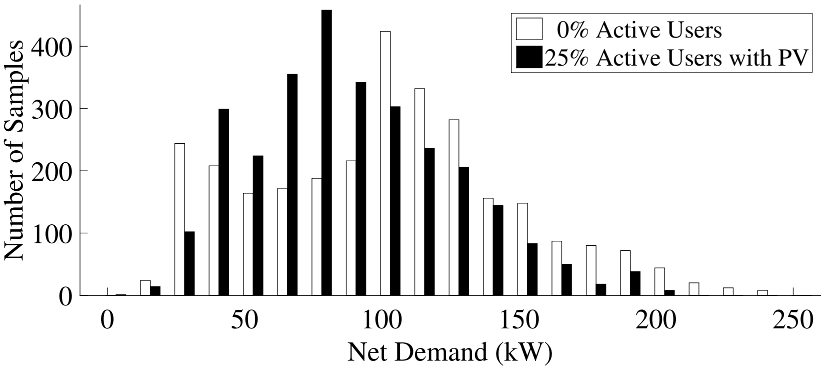

Figure 14. E_k^{net} for the 50% active customers without PV.

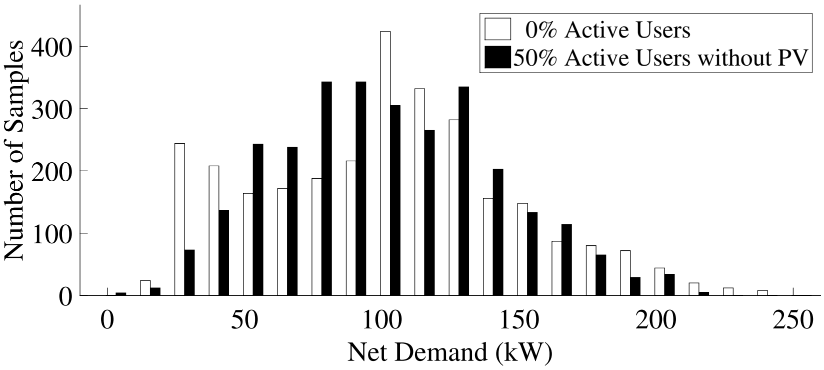

Figure 15. E_k^{net} for the 25% active customers with PV.

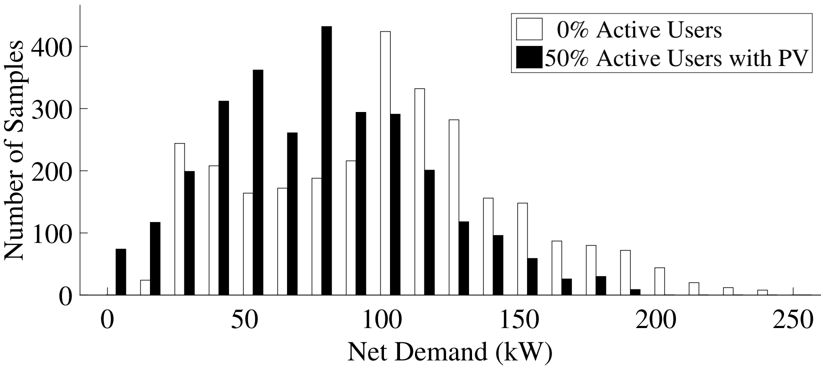

Figure 16. E_k^{net} for the 50% active customers with PV.

The E_k^{net} behavior shows the peak shaving effect of the tariff. The occurrence of peaks is reduced in all cases where active customers are present. The PV integration improves the peak shaving effect, as the load profile has diurnal peaks.

To understand how the peak shaving effect is a consequence of the tariff rule, Figure 17 shows the prices and their relationship with the net load profiles.

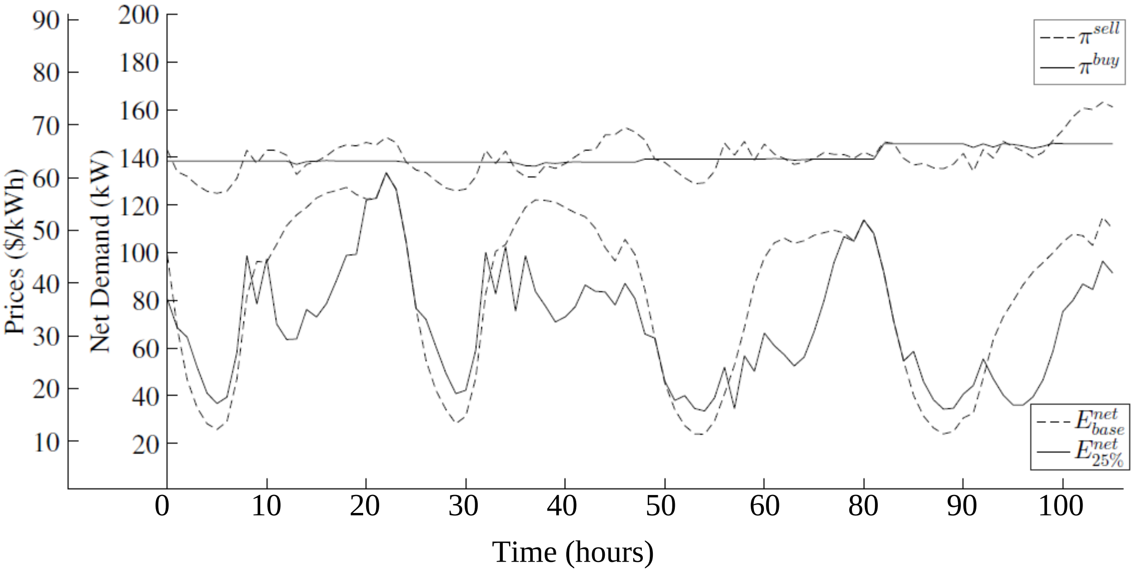

Figure 17. Prices and Net Demand for a 100-h Period with 25% of active with PV.

In Figure 17, the prices, and energy profiles are shown for a period of four days (96 h). It can be seen that the energy profile of the base case E_{base}^{net} presents peaks that are partially shaved by the behavior of the active customers, resulting in the energy profile of the case with 25% penetration of active customers with PV. Consistent with that behavior, the price of injecting energy is high during peak periods, incentivizing the injection of energy which contributes to reducing peak demand. It is also noticeable that, in the scenarios with storage, there is valley shaving, due to the need for the storage system to "refill" during periods of low consumption prices (the rule incentives customers to consume during valley periods). In the scenarios with PV, the high production of solar is selected by the fuzzy controller to charge the storage, so the valley shaving effect is less significant in the scenarios with PV.

It can also be seen from Figure 17 that a better storage decision system could have been made, showing the optimality limitation of the fuzzy rules. For example, in the first peak at about $k = 20$, a significant peak occurs, with a rise in the injection price. However, the fuzzy rule depleted the storage before the price peak, so a further reduction in peak (and more profit from the deployed energy) could have been possible by following the tariff system closer to optimal.

In Table 3, a summary of numerical results is presented, where $\mu(.)$ represents the average value and $\sigma(.)$ the standard deviation, for net demand and the prices. It can be seen that, for example, the average net demand $\mu(E^{net})$ for the cases without PV does not significantly change. This is consistent with the fact that the amount of energy needed to satisfy demand is the same with or without the storage system since the storage system does not generate electricity. When PV is present, the average net demand decreases as the PV systems provide some of the demand. However, the storage system has an impact on the standard deviation of net demand $\sigma(E^{net})$, which decreases with the presence of the storage system, given that the storage system tends to shave the peaks and valleys of net demand. In the case of the prices, it can be seen that both averages increase as the penetration of active customers increase. A particular situation is observed for 50% penetration of active customers and PV integration; the volatility of prices increases significantly. This shows that, as the amount of energy consumed from the grid decreases with PV integration, the value of such power must increase to make up for the shortfall and reach a level to cover the costs of infrastructure C_D. These results show that the problem of covering infrastructure costs in a scenario of high penetration of PV and ESS is still complicated, even when a systematic representation of the prices is implemented.

Table 3. Summary of numerical results.

Active Users	$\mu(E^{Net})$ MWh	$\sigma(E^{Net})$ MWh	$\mu(\pi^{sell})$ \$	$\sigma(\pi^{sell})$ \$	$\mu(\pi^{buy})$ \$	$\sigma(\pi^{buy})$ \$
0%	98.3	46.5	61.2	1	61.2	2.6
25%	98.2	39.7	61.2	4.2	61.2	2.6
25% + PV	85.5	36.4	62.9	5.0	62.9	3.5
50%	98.3	39.0	61.1	4.3	61.5	2.6
50% + PV	72.7	38.2	64.8	115.1	64.8	115.0

7. Conclusions and Future Work

This work has presented a tariff system of simple implementation that guarantees recovery of the total regulated cost and send price signal tending to efficiency by incentivizing peak shaving. The proposed tariff system was implemented in a simulation to see the effects of active/passive customer scenarios, showing that the definition of prices incentivizes customers to reduce demand peaks. Although the tariff system behaves as expected, there are various aspects that need to be treated in future works.

The tariff system assumes that the energy price π_R is fixed. In general, this price may not be fixed, depending on the value of energy in the electricity market or the energy contract that may not be fixed. Future work may explore an adaptation of the rule to represent variable π_R and its impact on prices and customer behavior.

The proposed simulation does not consider the investment cost of storage and PV to assess the adequacy of customers' investment. Although the simulation shows prices and a reduction in energy cost for active customers, financial indicators are not taken into account. If financial indicators are considered, the inclusion of active customers may not be profitable for all conditions, as the investment cost of the customer must be represented. Future work is proposed to explore such a scenario.

In addition, a more accurate description of welfare maximization is left for future work in terms of maintaining the simplicity of the mathematical representation.

Similarly, the work contribution is centered on the simplicity of the approach, and a qualitative comparison was exposed in Section 3. Future work will be focused on developing a more systematic comparison metric that can numerically evaluate different tariff proposals.

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