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Self-Sustainable Dynamic Tariff for Real Time Pricing-Based Demand Response: A Brazilian Case Study

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ABSTRACT The operation of power systems under peak demand conditions results in higher operational costs, more instability risks and often forces an excessive use of fossil fuels. In this context, this paper proposes a self-sustainable real-time pricing (RTP) tariff that is adjusted proportionally to the aggregated demand of a group of consumers, and is based on a changing rate for each hour of the day. Therefore, demand peaks are expected to be naturally reduced by the group due to the higher tariff values imposed during these operating conditions. In addition, consumers benefit from the opportunity to reduce their bills according to the tariff and can carry out financial strategies by setting up their own consumption profile. The proposed dynamic tariff has a self-sustainable and revenue neutral nature which protects both consumers and distribution power companies from being economically affected by varying price elasticity scenarios. This is achieved by mathematically guaranteeing for such companies a revenue equal to the one they would expect with the traditional application of flat tariff. The advantages of the proposal are highlighted through numerical simulations by comparing it with the so-called Conventional Tariff and White Tariff, which are currently adopted by residential consumers in Brazil.

INDEX TERMS Demand response, real time pricing, dynamic tariff, price elasticity.

I. INTRODUCTION

Power systems must be prepared to operate under peak demand conditions, which generally present more risks for power system stability as well as higher costs with generation, transmission and distribution. In this context, many power companies are employing substantial effort to obtain peak demand reduction with demand response approaches instead of adopting solely more traditional (and invasive) strategies such as load shedding schemes [1].

Demand Response (DR) can be defined as all intentional modifications practiced by consumers in terms of their consumption patterns in response to changes in electricity tariff over time [2]. In this sense, the key idea is to apply higher tariff values for consumers when the system is overloaded and to compensate consumers that tend to reduce energy consumption during off-peak moments. Once reduction in peak demand is obtained, reinforcements with generation, distribution and transmission infrastructure are naturally avoided, specially with construction of new generation units and with transmission/distribution lines. The avoided reinforcement costs can then be reflected in price reduction of electricity for all consumers (DR program participants and non-participants) [2]. Price reduction is also obtained since the necessity of activating additional generation units during peak consumption moments can be diminished. Such additional generation units are generally much more expensive than the regularly active ones [3]. In addition, they are often based on non-renewable energy sources such as thermal power plants.

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There are basically two categories of DR programs: Incentive-Based Programs (IBP) and Price-Based Programs (PBP). In IBP, participating consumers receive participation payments usually as a bill credit or discount rate. The amount of credit or discount rate depends on the amount of load reduction they practice during critical conditions [4]–[6].

On the other hand, PBP are based on dynamic tariffs in which electricity pricing rates are not flat over time, so that tariff values vary following the actual cost of electricity [3], [7]. In literature, there are several studies revealing all possible benefits from adopting dynamic pricing, including both peak demand and resource cost reduction [3], [8]. The performance of PBP is typically measured using the concept of price elasticity, which estimates the sensitivity of consumers demand to the actual electricity tariff value [9].

Time of Use (TOU) tariff is perhaps the most basic type of PBP. It proposes that electricity prices per unit consumption should differ within different periods of the day [10]. In this sense, the tariff value during peak moments is expected to be higher than during off-peak moments. On the other hand, Real Time Pricing (RTP) is a type of PBP in which consumers are charged based on hourly fluctuating prices, where they are informed about these prices on a day-ahead or hour-ahead basis [9].

Recently, the authors in [11] proposed a dynamic tariff (DT) for uncertainty-based congestion management with the presence of stochastic parameters of flexible loads. On the other hand, the authors in [12] proposed a feeder reconfiguration method for minimizing energy cost and the DT itself. This method also encompasses lines losses when calculating the DT. An operation framework applicable for both flexible and inflexible loads is proposed in [13]. In [14], the authors use a fuzzy-logic to propose a dynamic feed-in tariff, which is designed based on electricity price, hosting capacity, ambient temperature and time of day. Meanwhile, the authors in [15] combine relaxed DT, network reconfiguration and re-profiling products to perform day-ahead congestion management. In [16], the authors propose a flexible TOU tariff for real-world thermal companies to optimize the electricity prices and their allocations to different time periods. The proposal of a distributed optimization-based dynamic tariff method for congestion management in distribution networks with high penetration of electric vehicles and heat pumps is addressed in [17]. In [18], the authors propose the use of individualized price policies combined with energy demand and electricity price to incentivize low energy users. In [19], it is proposed a robust DT method for day-ahead congestion management which is capable of dealing with forecasting errors. Finally, several promising studies covering a variety of RTP approaches developed for specific country scenarios can be found in [20]–[24].

This paper focuses on the actual Brazilian electricity market. In Brazil, Conventional Tariff (CT) is currently the most widely adopted type of tariff among residential consumers. CT is a flat type of tariff in which consumers are always charged with the same fixed energy tariff value regardless of either the hour of the day or the day type (workday, weekend, holiday). As such, consumers are not motivated to better distribute their energy use throughout different periods of the day. Consequently, this naturally contributes to some degree to the appearance of demand peaks during moments in which consumers tend to simultaneously consume more energy.

For trying to diminish such demand peaks, the Brazilian National Agency of Electrical Energy (or ANEEL, in Portuguese) proposed the so-called White Tariff (WT) [25], which is a relatively new type of TOU tariff option for Brazilian residential consumers. WT is period-dependent and day type-dependent. During weekends and holidays, White Tariff presupposes that the power system is not likely to present significant demand peaks, so it charges consumers with an off-peak tariff value. However, during workdays, White Tariff applies three different tariff values (peak, intermediate and off-peak) depending on the period of the day.

It is naturally expected that residential consumers which choose to migrate from CT to WT will tend to avoid non-essential use of energy during peak and intermediate demand moments (usually predetermined by distribution power companies as the period between 17-22h), then diminishing their consumption during these time periods. An example would be shifting the majority of their household activities (e.g. dishwashers, electric showers, pool pumps, electric vehicle chargers) to off-peak periods, in which WT is substantially cheaper than CT. Depending on the demand reduction obtained during peak and intermediate demand periods, the adoption of White Tariff may either increase or decrease bill values significantly in comparison to CT, meaning either consumers or distribution power companies become negatively impacted by its adoption [3], [29].

Apart from possible economical impacts for consumers and distribution power companies, the adoption of WT also has a second fundamental issue: due to its static behavior, it may not reflect the actual operating condition of the power system. This happens, for instance, if significant demand peaks do not occur during the predetermined intermediate and peak periods defined by WT, i.e., if demand curves are relatively flatter during the time period between 17-22h.

In order to cope with the above mentioned issues, it is proposed in this paper a dynamic self-sustainable RTP type of tariff whose dynamic behavior comes from the fact that its values during each hour of the day are adjusted proportionally to the aggregated demand of a group of consumers. Therefore, demand peaks are expected to be naturally reduced by the group due to the higher tariff values practiced during these peak periods. As in WT, consumers may produce significant bill savings by choosing to consume energy during time periods in which it is cheaper. The proposed DT has a revenue neutral nature which comes from the fact it is guaranteed to provide for distribution power companies the same revenue they would expect with the traditional application of CT. In other words, it does not prejudice neither utilities or consumers from an economical perspective. On the other hand, the self-sustainable nature of the proposed DT comes from the fact it is passively indexed to CT. Therefore, if an increase in electricity cost is requested by the National System Operator (due to national water or fuel scarcity, for instance), power companies are not required to develop specific strategies to determine new values for the proposed tariff. Instead, they just have to adjust their CT value (which is already a common practice for such companies), and the DT will adjust its values accordingly. The revenue neutral and self-sustainable nature of the proposed methodology constitutes its main advantage compared to WT and is also what differentiates it from the dynamic tariff schemes previously proposed in literature, such as the ones in [11]–[23], [36]. In summary, the proposed dynamic tariff represents a safer economic model, and protects both consumers and distribution power companies from being economically affected by varying price elasticity scenarios. The simulation results highlight its effectiveness and a comparison with traditionally applied dynamic tariffs is also presented.

The paper is structured as follows. In Section II we briefly describe the fundamental aspects regarding Conventional Tariff and White Tariff. In Section III, the proposed self-sustainable Dynamic Tariff is presented. Section IV presents the validation of the proposed DT thorough numerical simulations. In section V, we address the conclusions of the paper.

II. CONVENTIONAL TARIFF AND WHITE TARIFF

The aggregated demand of a group of consumers may vary significantly throughout hours of the day and also depending on the day type (workday, holiday or weekend) [26]. In this context, power systems must be prepared to operate under peak demand conditions, which generally present higher costs with generation, transmission and distribution. In the specific case of Brazil, additional non-renewable energy sources such as thermal generation are also required during peak consumption moments, being these sources significantly more polluting and expensive than renewable energy sources such as hydroelectric power plants.

Figure 1 shows the aggregated power demand data set for a group of actual residential consumers located in Ipiranga, Paraná, Brazil. Such data set illustrates a typical workday consumption profile for residential consumers in Brazil, which are most commonly charged based on CT.

With CT, consumers are charged with a fixed energy tariff value ρ_{CONV}, regardless of either the hour of the day or the day type. This naturally makes groups of consumers to collectively produce demand peaks, such as the one presented in Figure 1, where an excessive amount of energy is consumed during a short time period. In this sense, it is clearly shown in Figure 1 that the peak in demanded power occurs between 17-24h.

Many strategies exist for trying to reduce consumption during peak periods. In this regard, the key idea of PBP-based demand response approaches is to apply higher tariff values for consumers when the system is overloaded and to compensate consumers that tend to reduce energy consumption during off-peak moments. With this, consumers that choose to participate in these programs are naturally expected to reduce their consumption during peak periods, intentionally migrating energy use to hours of lower power system demand.

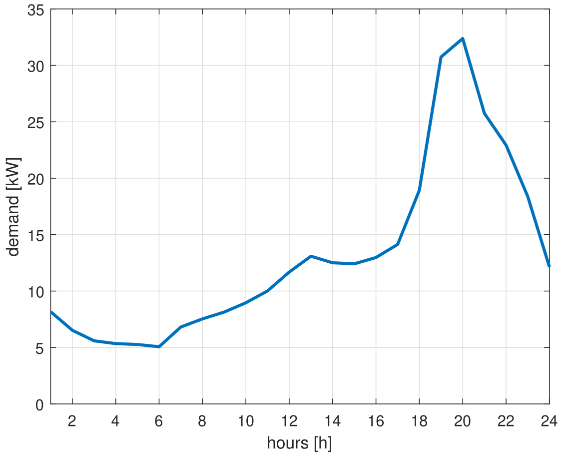

FIGURE 1. Aggregated load demand during a workday for a group of 95 actual consumers located in Ipiranga, Paraná, Brazil.

TABLE 1. Conventional Tariff (taxes included) [28].

	time interval	ρ_{CONV} [$\$/kWh$]
Conventional	0-24h	0.79878

Within the Brazilian interconnected power system, which encompasses all 5 regions of the country, since 2020 residential consumers have become allowed to migrate from CT to WT. With WT, consumers are charged based on three different (yet static) energy tariff values.

In order to clearly differentiate between these two types of tariffs (CT and WT), both of them are formally presented in the following subsections of this paper. The fundamental idea of WT is to reduce peak consumption. Nonetheless, as will be shown, depending on the price elasticity scenario, WT may negatively impact consumers and distribution power companies from an economical perspective.

A. CONVENTIONAL TARIFF

Consumers under CT regime are continuously charged based on the same fixed energy tariff value ρ_{CONV}. The Brazilian approximate value for ρ_{CONV} (with government taxes included) is shown in Table 1. In this paper, the symbol $ is used to actually denote Brazilian currency R$. In practice, Brazilian power companies specify a value for ρ_{CONV} which already takes into account the higher energy costs inherent to peak operation.

Generically, for a specific group of consumers absorbing a total amount of energy E_{T} from the power system during the 24 hours of a day, the total energy cost EC_{CONV} to be paid by these consumers with the adoption of CT can be calculated as follows

$$\text{EC}_{\text{CONV}} = \rho_{\text{CONV}} E_{\text{T}}. \tag{1}$$

In Brazil, distribution power companies receive as revenue only a proportional part of EC_{CONV} (around 20% of this

TABLE 2. White Tariff (taxes included) [28].

	time interval	price [$\$/kWh$]
Peak	18-21h	1.45488
Intermediate	17-18h, 21-22h	0.93679
Off-peak	22-24h, 0-17h	0.68559

value), being the remaining 80% of this value a division between government taxes, costs with generation and transmission, costs with public illumination etc.

Considering that $E_i = P_i \Delta T$ (with $\Delta T = 1\text{h}$) represents the aggregated energy consumed by the group of consumers from hour $i-1$ up to hour i of the day and P_i is the corresponding averaged power demand related to this time period, the total amount of energy provided to the group of consumers reads

$$E_{\text{T}} = \sum_{i=1}^{24} E_i. \tag{2}$$

B. WHITE TARIFF

Since CT applies the same fixed tariff ρ_{CONV} for all 24 hours of the day, consumers are not motivated to better distribute their energy use throughout these hours. This contributes to the appearance of demand peaks during moments which consumers tend to simultaneously use more energy.

For trying do diminish such demand peaks, ANEEL proposed the WT, which exists since January 2018 for consumers with an average consumption above 500kWh, and since January 2019 for consumers with an average consumption above 250kWh. Since January 2020, all residential consumers have become allowed to migrate from CT to WT.

WT values are static, but period-dependent and day type-dependent. During workdays, WT applies three different tariff values depending on the hour of the day. During the time period from 18-21h, WT presupposes that the power system is operating under peak consumption levels, and it charges consumers with a ρ_{PEAK} tariff value significantly greater than ρ_{CONV}. During 17-18h and during 21-22h, WT considers an intermediate consumption operation, and it charges consumers with a tariff value ρ_{INTER} which satisfies $\rho_{\text{CONV}} < \rho_{\text{INTER}} < \rho_{\text{PEAK}}$. Finally, during 22-24h and 0-17h time periods, WT considers that the power system is operating under low consumption (off-peak) levels, and charges consumers with a lower $\rho_{\text{OFF-PEAK}}$ energy value, with $\rho_{\text{OFF-PEAK}} < \rho_{\text{CONV}}$.[1] During weekends and holidays, WT charges consumers with the off-peak tariff value $\rho_{\text{OFF-PEAK}}$, regardless of the hour of the day. The approximate tariff values regarding WT in Brazil (with taxes included) are as shown in Table 2.

For a specific group of consumers absorbing a total amount of energy E_{T} from the power system during the 24 hours of a workday, the total energy cost EC_{WT} to be paid by these consumers with the adoption of WT can be calculated as follows

$$\text{EC}_{\text{WT}} = \sum_{i=19,20,21} \rho_{\text{PEAK}} E_i + \sum_{i=18,22} \rho_{\text{INTER}} E_i + \sum_{i=1,2,\ldots,17,23,24} \rho_{\text{OFF-PEAK}} E_i \tag{3}$$

By comparing tariff values from Tables 1 and 2, one can naturally expect that residential consumers which choose to migrate from CT to WT will tend to avoid non-essential use of energy during peak and intermediate demand moments, then diminishing their consumption during these time periods. Depending on the demand reduction obtained during peak and intermediate demand periods, the adoption of WT may either increase (if $\text{EC}_{\text{WT}} > \text{EC}_{\text{CONV}}$) or decrease (if $\text{EC}_{\text{WT}} < \text{EC}_{\text{CONV}}$) bill values significantly in comparison to CT, meaning either consumers or distribution power companies may be negatively impacted by its adoption.

Apart from possible economical impacts for consumers and distribution power companies, the adoption of WT also has a second fundamental issue: it may not exactly reflect the actual operating condition of the power system. This happens, for instance, if significant demand peaks do not occur during the intermediate and peak periods defined by WT.

III. PROPOSED DYNAMIC TARIFF

Based on the information presented in Section II, it is possible to conclude that neither CT and WT completely solve the problem of reducing demand peaks without imposing possible economical losses to either consumers or distribution power companies.

In order to cope with this issue, it is proposed in this section a self-sustainable Dynamic Tariff (DT) that fundamentally solves these two problems simultaneously. The key idea is to propose a tariff that reflects the operating condition of the power system by dynamically changing its value proportionally to the actual power system demand.

In the proposed DT, the tariff value ($/kWh) corresponding to the period from hour $i-1$ up to hour i of the day is denoted by ρ^i_{DT}. Therefore, for a specific group of consumers absorbing a total amount of energy E_{T} from the power system during the 24 hours of a day, the total energy cost EC_{DT} to be paid by these consumers with the adoption of the proposed Dynamic Tariff can be calculated as follows

$$\text{EC}_{\text{DT}} = \sum_{i=1}^{24} \rho^i_{\text{DT}} E_i. \tag{4}$$

Since the idea is to dynamically change ρ^i_{DT} depending on the actual operating condition of the power system, one can enforce proportionality between ρ^i_{DT} and the actual corresponding demanded power P_i, so that

$$\rho^i_{\text{DT}} = k P_i, \tag{5}$$

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[1] In Brazil, the determination of peak, intermediate and off-peak time periods may slightly vary depending on the distribution power company. For sake of explanation, we have considered the time periods determined by COPEL [28].

where k is the proportionality constant, being its unit given by $\$/(\mathrm{kW})^2\mathrm{h}$. The insertion of this constant is responsible for making this proposed tariff dynamic.

Substitution of (5) in (4) produces

$$\mathrm{EC}_{\mathrm{DT}} = k \sum_{i=1}^{24} P_i E_i. \tag{6}$$

This paper proposes to equalize the integral revenue of the designed DT with the traditional CT in order to avoid excessive pricing as well as revenue losses due to possibly unexpected price elasticity scenarios. This is guaranteed mathematically by enforcing total costs paid by consumers to be the same between these two types of tariffs, i.e., by establishing the following relation:

$$\mathrm{EC}_{\mathrm{DT}} = \mathrm{EC}_{\mathrm{CONV}}, \tag{7}$$

or, equivalently:

$$k \sum_{i=1}^{24} P_i E_i = \rho_{\mathrm{CONV}} E_{\mathrm{T}}. \tag{8}$$

For satisfying (8) one must choose k so that:

$$k = \rho_{\mathrm{CONV}} E_{\mathrm{T}} \Big/ \left(\sum_{i=1}^{24} P_i E_i \right). \tag{9}$$

Once k has been calculated via (9), the tariff values ρ^i_{DT} corresponding to each hour of the day can be easily obtained through Equation (5). Figure 2 depicts the values obtained for ρ^i_{DT} for the demand curve shown in Figure 1 (for this curve, a $k = 0.0451\ \$/(\mathrm{kW})^2\mathrm{h}$ value has been obtained). For sake of comparison, Figure 2 also depicts the static tariff values regarding Conventional Tariff and White Tariff (see also Tables 1 and 2). Consumers benefit from the proposal since they can choose to use more energy during time periods in which it is cheaper. The power system benefit from the proposal since demand peaks are expected to be naturally reduced due to the higher tariff values during periods of peak consumption. And, finally, both consumers and distribution power companies benefit from the proposal since it guarantees $\mathrm{EC}_{\mathrm{DT}} = \mathrm{EC}_{\mathrm{CONV}}$.

A complete scheme containing all fundamental steps for implementing the proposed Dynamic Tariff in practice is shown in Figure 3. In an actual online application of this tariff, it is expected that the distribution power company can make tariff values $\rho^1_{\mathrm{DT}}, \cdots, \rho^{24}_{\mathrm{DT}}$ available for all consumers in advance (via Mobile App, for instance), so that they can be effectively prepared to respond to the power system demand. Now, since the power demand for the current day is not known before the day actually ends, these tariff values can always be calculated for the next day based on a day-ahead forecast. Day-ahead forecasting power demand is not within the scope of this paper, although the interested reader is hereby referred to [27], [30]–[32] which analyze demand forecasting techniques in detail. Instead, we here perform an offline validation of the proposed DT by considering actual demand measurements for $P_1, \cdots, P_{24}$.

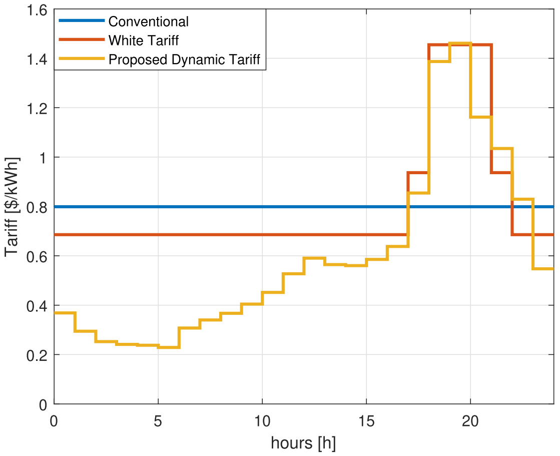

FIGURE 2. Comparison between the proposed Dynamic Tariff with Conventional Tariff and White Tariff. Dynamic Tariff is the only one which dynamically changes according to demand (see Figure 1).

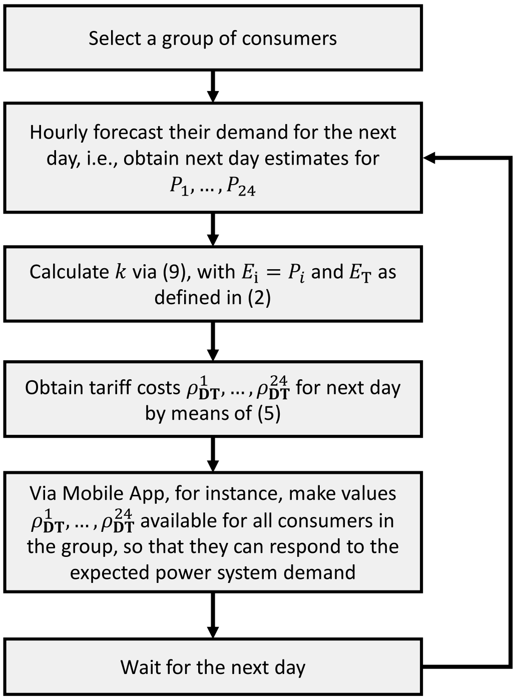

FIGURE 3. Fundamental steps for implementing the proposed Dynamic Tariff.

IV. NUMERICAL RESULTS

To validate the self-sustainable DT proposed in this paper, two case studies are considered in the following subsections. As mentioned in the previous section of this paper, we here perform an offline validation of the proposed DT by considering actual demand measurements for $P_1, \cdots, P_{24}$ instead of day-ahead forecasting these values. We also assume that the total energy E_{T} consumed by the group of consumers is always the same, regardless of the type of tariff they choose to adopt.

A. CASE STUDY 1

This first case study is based on the workday demand data set depicted in Figure 1, which corresponds to the actual behavior of a group of 95 residential consumers in response to CT.

TABLE 3. Estimated price elasticity with White Tariff.

	intermediate reduction [%]	peak reduction [%]
Case 1	10	30
Case 2	20	50
Case 3	30	70

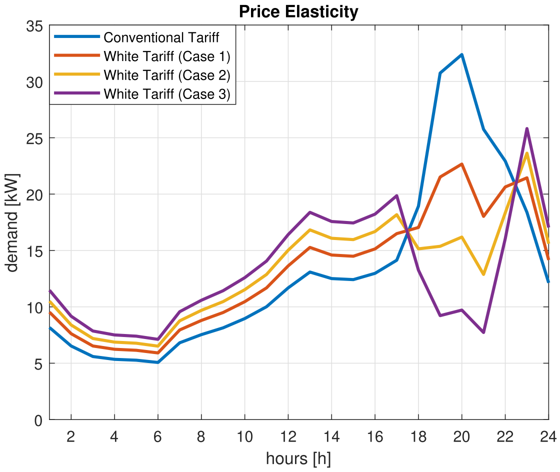

FIGURE 4. **Comparison between actual price elasticity for Conventional Tariff and estimated price elasticity scenarios for White Tariff.**

For comparison purposes, we additionally assume three scenarios that estimate how this group of consumers would change their consumption behavior if they all migrated from CT to WT. These three scenarios are explained in Table 3. Motivated by the WT values shown in Table 2, it is assumed a higher demand reduction during hours of peak consumption, and a lower demand reduction during hours of intermediate demand. The resulting estimated curves regarding each scenario for WT are depicted in Figure 4.[2] The original CT-based demand curve is also depicted in this figure for comparison. As it can be observed in the three WT scenarios shown in Figure 4, all energy reduced during peak and intermediate consumption hours has been compensated by proportional demand increases during off-peak hours, so that total amount of energy E_{T} consumed during the 24 hours of the day is exactly the same as for the Conventional Tariff-based demand curve.

Figure 5 depicts the energy costs for the group of consumers throughout the day, corresponding to each case in Figure 4. Total costs EC_{CONV} and EC_{WT} are also shown in the legend of the figure. For Case 1 and Case 2, it is observed that the adoption of WT negatively impacts consumers since it is observed an increase in total energy costs paid by them in comparison to CT, i.e., $EC_{\mathrm{WT}} > EC_{\mathrm{CONV}}$. Meanwhile, for Case 3 the demand reduction during peak and intermediate hours has resulted in lower energy costs with WT in comparison to CT ($EC_{\mathrm{WT}} < EC_{\mathrm{CONV}}$). This provides bill savings for consumers but, from the power company point of view, this reduction represents a proportional revenue decrease of about 3.11%. For a scenario with a larger number of consumers, such a revenue decrease could negatively impact the power company in maintaining energy quality aspects.

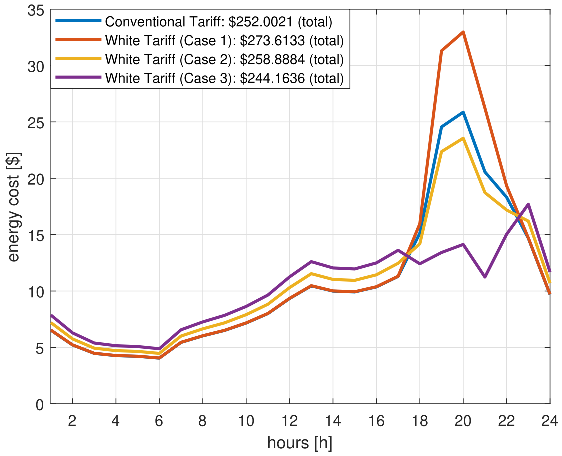

FIGURE 5. **Energy costs throughout the day, corresponding to each case in Figure 4.**

We now compare these results with three scenarios that estimate how consumers would change their consumption behavior if they all migrated from CT to the DT proposed in this paper. These three scenarios are shown in Figure 6.[3] The three curves for DT in Figure 6 have been generated by assuming that consumers would not change their consumption behavior as abruptly as with the adoption of WT (compare with Figure 4), since DT does not specifically specify periods of intermediate and peak consumption. As compared in Figure 7, instead of specifying fixed (static) tariff values for pre-specified time periods, DT more smoothly changes its tariff values throughout the day depending on each hourly associated demand. In order to achieve this expected behavior, the three curves for DT in Figure 6 have been generated by applying to the original CT-based curve a moving average with 3, 8, and 13 points for Cases 1, 2 and 3, respectively.

By analyzing Figures 6 and 7 simultaneously, it is important to observe that the dynamic behavior of the proposed approach comes from the fact that its values during each hour of the day are proportionally related to the corresponding demand (see also Equation (5)). This means that, in opposition to CT, DT tends to make consumers to reduce (increase) their use of energy during peak (off-peak) hours, then promoting for the power system a more balanced (homogeneous) distribution of energy. In addition, the proportionality constant k in DT (see Equation (9)) is set so that it guarantees for the distribution power company a revenue equal to the one expected with the traditionally adopted CT. That is, the same total costs of $252.0021 obtained with CT are also expected for the proposed DT, regardless of the price elasticity scenario,

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[2] It is also important to emphasize that one should not expect consumers to change their behavior as shown in Figure 4 within a few days. Instead, one should assume that it may take a few months (or even a few years) for consumers to consolidate such behavioral changes.

[3] As with WT, one should not expect consumers to change their behavior as shown in Figure 6 within a few days. Instead, one should assume that it may take a few months (or even a few years) for consumers to consolidate such behavioral changes.

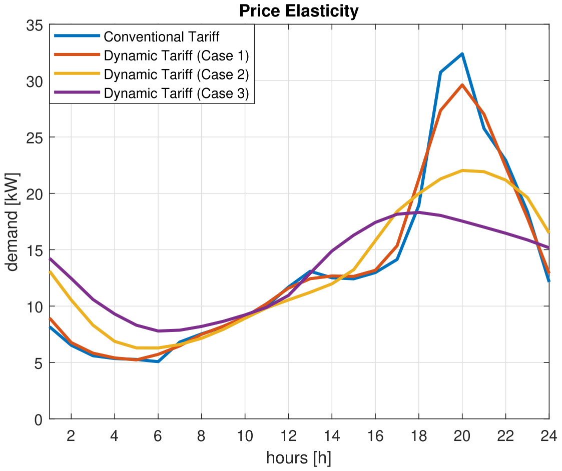

FIGURE 6. **Comparison between actual price elasticity for CT and estimated price elasticity cases for DT.**

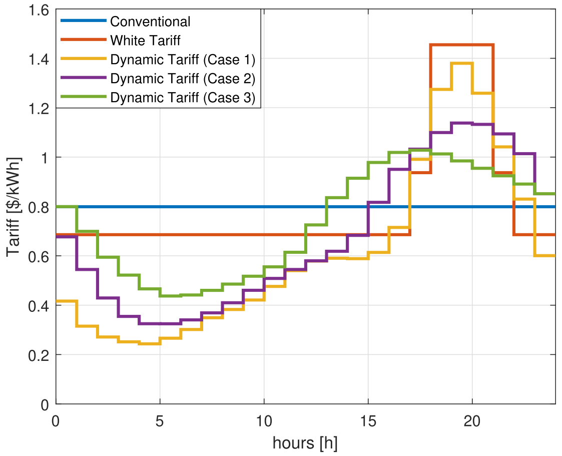

FIGURE 7. **Tariff values for the group the consumers throughout the day.**

i.e., $EC_{DT} = EC_{CONV} = \$252.0021$ for all cases in Figure 6. As a result, DT protects both consumers and power companies from being economically affected by any price elasticity scenario that may occur with a possible widespread adoption of WT (see the WT cases in Figure 5).

B. CASE STUDY 2

In this case study, we modify the workday demand data set depicted in Figure 1 in order to generate the data presented in Figure 8. Specifically, the demand data from period 10-24h in Figure 1 has been reflected to intentionally move the demand peak from 17-24h to 11-17h. The objective is to show that WT performs even poorly than the proposed DT in situations where demand peaks occur during periods which do not correspond to the intermediate and peak hours defined by WT, i.e., if demand curve presents peaks which are not within the time period from 17-22h.

We here assume different scenarios that estimate how consumers would change their consumption behavior if they migrated from CT to either WT or DT. The resulting estimated curves are depicted in Figure 9. These curves have been generated following the same ideas discussed in the previous case study.

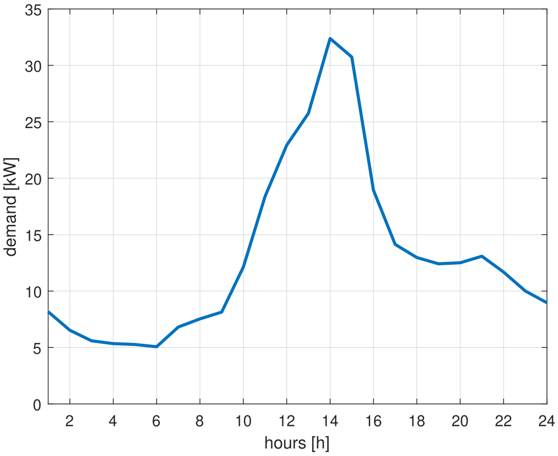

FIGURE 8. **Modified Demand with a peak between 11-16h.**

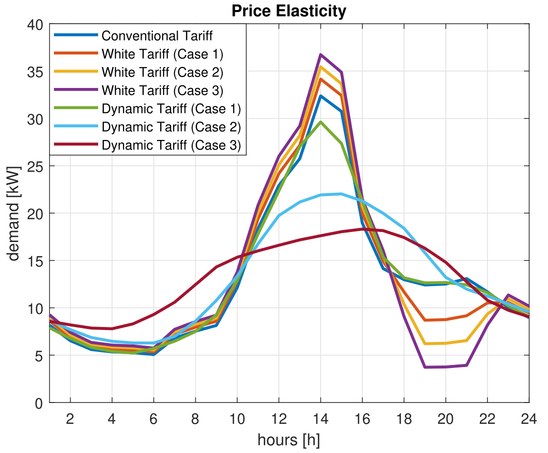

FIGURE 9. **Comparison between actual price elasticity for Conventional Tariff and estimated price elasticity scenarios for White Tariff and Dynamic Tariff.**

Figure 10 depicts the energy costs for the group of consumers throughout the day, corresponding to each case in Figure 9. Total costs EC_{CONV}, EC_{WT} and EC_{DT} are also shown in the legend of the figure. Due to its fixed pricing behavior established by Table 2, WT presents for all three cases a decrease in total energy costs paid by consumers in comparison to CT and DT. In the worst case scenario (Case 3), this represents an estimated reduction in revenue of approximately 8.97% for the power company. On the other hand, DT is expected to guarantee a revenue equal to the one expected with CT. As also shown in Figure 9, once WT presents a cheaper value during time period from 0-17h in comparison to CT, one can even expect an inconvenient demand peak increase with its adoption.

For comparison purposes, tariff values throughout the day are shown in Figure 11. As in the previous case study, the proposed DT is the only one that proportionally adapts its values to the actual power system demand (compare with Figure 9).

C. COMPARISON WITH PREVIOUSLY INTRODUCED DYNAMIC TARIFFS

As shown in the case studies presented in sections IV-A and IV-B, revenue oscillations from 8.97%

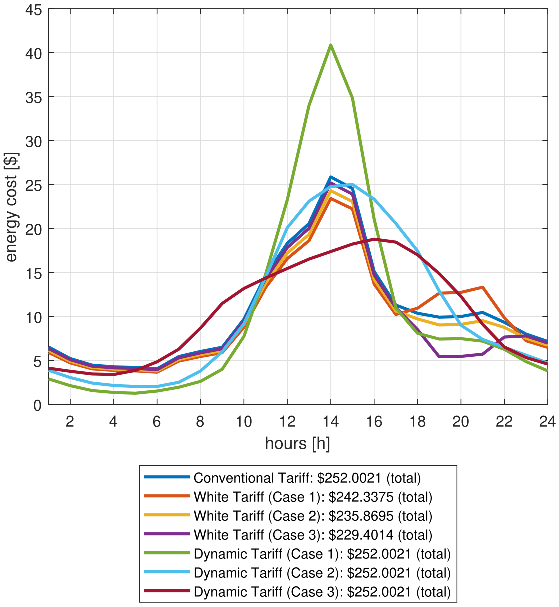

FIGURE 10. Energy costs throughout the day, corresponding to each case in Figure 9.

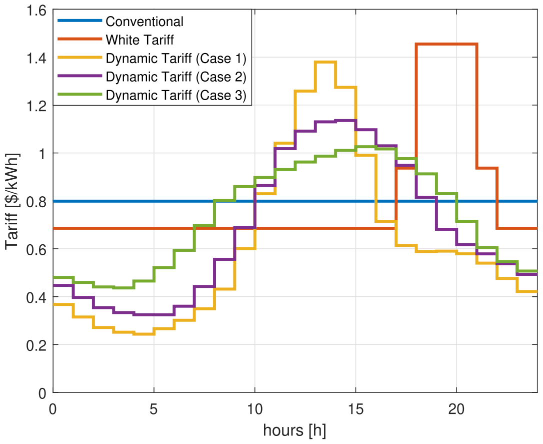

FIGURE 11. Tariff values for the group the consumers throughout the day. Dynamic Tariff values depend on the corresponding demand curve in Figure 9.

reduction to 8.58% increase may occur when switching from flat rate to WT (see Figures 5 and 10). Such oscillations are also observed when applying other types of dynamics tariffs previously proposed in literature. For instance, the authors in [33] have analyzed the impact of applying a RTP dynamic tariff in a pilot containing 1142 commercial and industrial consumers in Northern California, and concluded that consumers observed from 4% reduction to 8% increase in the bill amount. On the other hand, our proposed dynamic tariff has a revenue neutral nature which makes it to guarantee a 0% revenue oscillation w.r.t. CT. In other words, it benefits both consumers and utilities since significant reductions or increases are not expected to be observed.

Now, as far as peak demand reduction is concerned, the results presented in sections IV-A and IV-B show that the proposed DT make consumers to face, on average, a peak-to-off-peak price ratio of 3.84:1, providing on average a 28.78% peak demand reduction. In comparison, [8] refers to a study which states that RTP can induce a peak demand reduction of 10–14%. Meanwhile, the authors in [34] survey 14 utilities in the USA and observed over 30% reduction in peak hour consumption in response to RTP. Further comparisons with previously proposed approaches are depicted in Table 4, which considers results produced for a total of 63 pilots included in the well-known Arcturus Database [35]. In this table, methods are categorized according to the adopted peak-to-off-peak price ratio, and also according to the presence or absence of enabling technology. As shown in this table, without enabling technology, on average, a customer facing a peak-to-off-peak price ratio of 2:1 will reduce in 5% his or her typical peak usage. As this ratio increases to 4:1, the consumer will reduce in 10% his or her typical peak usage. In contrast, the presence of enabling technology amplifies the peak reduction, with 9% and 16% reductions with 2:1 and 4:1 peak-to-off-peak price ratios, respectively. To summarize, the results provided by the proposed DT are comparable with those obtained with previously proposed methodologies, but it is still expected to provide a slightly superior peak demand reduction.

TABLE 4. Comparison with previously proposed DTs (based on [35]).

	peak-to-off-peak price ratio	peak reduction [%]
Literature	2:1	5
Literature (with enabling technology)	2:1	9
Literature	4:1	10
Literature (with enabling technology)	4:1	16
Proposed DT (average)	3.84:1	28.8%

V. CONCLUSION

It has been proposed in this paper a dynamic self-sustainable real time pricing tariff (DT) whose dynamic behavior is related to the tariff rate during each hour of the day. The tariff rate is adjusted proportionally to the aggregated demand of a group of consumers. A scheme containing fundamental steps for implementing this proposed DT has also been presented. Indeed, the proposed DT naturally reduces demand peaks by using an economical approach which presents advantages for both consumers and distribution power companies. Mathematically, this is achieved by its self-sustainable and revenue neutral nature. Numerical results highlight that demand peaks are expected to be naturally reduced due to the higher tariff values imposed during peak conditions. In addition, consumers also benefit from the proposed methodology, since they can produce significant bill savings by choosing to consume more energy during cheaper tariff periods. For both case studies analyzed, it has been shown that the proposed DT smoothly changes its values throughout the day depending on each hourly associated demand. In addition, it has shown to guarantee for the distribution power company the same $252.0021 revenue it would obtain with the traditionally adopted CT, regardless of the price elasticity scenario. In contrast, for the worst price elasticity scenario tested in case study 2, it has been shown that a widespread adoption of WT would produce a 8.97% revenue reduction. For this second case study, it is also shown that WT performs even poorly than the proposed DT if demand peaks occur during periods which do not correspond to the intermediate and peak hours pre-defined by WT, i.e., if demand curves present peaks which are not within the time period from 17-22h. In summary, DT is shown to outperform both CT and WT.

In Brazil, the same metering infrastructure already required to implement WT could be used to implement the proposed DT. Nonetheless, additional regulatory aspects should be addressed before one can indeed offer this methodology as a tariff choice for residential consumers. This constitutes a topic for future research.

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REFERENCES

[1] K. Bhattacharya, M. H. J. Bollen, J. E. Daalder, *Operation of Restructured Power Systems*. Boston, MA, USA: Springer, 2001, doi: 10.1007/978-1-4615-1465-7.

[2] M. H. Albadi and E. F. El-Saadany, "Demand response in electricity markets: An overview," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2007, pp. 1–5, doi: 10.1109/PES.2007.385728.

[3] G. Dutta and K. Mitra, "Multilayer perceptron for short-term load forecasting: From global to local approach," *J. Oper. Res. Soc.*, vol. 68, no. 10, pp. 1131–1145, 2017, doi: 10.1057/s41274-016-0149-4.

[4] A. Asadinejad, A. Rahimpour, K. Tomsovic, H. Qi, and C.-F. Chen, "Evaluation of residential customer elasticity for incentive based demand response programs," *Electr. Power Syst. Res.*, vol. 158, pp. 26–36, May 2018, doi: 10.1016/j.epsr.2017.12.017.

[5] O. Erdinc, A. Tascikaraoglu, N. G. Paterakis, and J. P. S. Catalao, "Novel incentive mechanism for end-users enrolled in DLC-based demand response programs within stochastic planning context," *IEEE Trans. Ind. Electron.*, vol. 66, no. 2, pp. 1476–1487, Feb. 2019, doi: 10.1109/TIE.2018.2811403.

[6] US Department of Energy. (2006). *Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them*. [Online]. Available: http://eetd.lbl.gov

[7] P. L. Joskow and C. D. Wolfram, "Dynamic pricing of electricity," *Amer. Econ. Rev.*, vol. 102, no. 3, pp. 381–385, 2012, doi: 10.1257/aer.102.3.381.

[8] A. Faruqui, "The ethics of dynamic pricing," in *Smart Grid*. Amsterdam, The Netherlands: Elsevier, 2012, pp. 61–83.

[9] A. K. David and Y. Z. Li, "Consumer rationality assumptions in the real-time pricing of electricity," *IEE Proc. C Gener., Transmiss. Distrib.*, vol. 139, no. 4, pp. 315–322, Jul. 1992, doi: 10.1049/ip-c.1992.0047.

[10] C. W. Gellings and J. H. Chamberlin, *Demand-side Management: Concepts and Methods*. Lilburn, GA, USA: The Fairmont Press, 1988.

[11] S. Huang, Q. Wu, L. Cheng, Z. Liu, and H. Zhao, "Uncertainty management of dynamic tariff method for congestion management in distribution networks," *IEEE Trans. Power Syst.*, vol. 31, no. 6, pp. 4340–4347, Nov. 2016, doi: 10.1109/TPWRS.2016.2517645.

[12] S. Huang, Q. Wu, L. Cheng, and Z. Liu, "Optimal reconfiguration-based dynamic tariff for congestion management and line loss reduction in distribution networks," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1295–1303, May 2016, doi: 10.1109/TSG.2015.2419080.

[13] D. T. Nguyen, H. T. Nguyen, and L. B. Le, "Dynamic pricing design for demand response integration in power distribution networks," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3457–3471, Sep. 2016, doi: 10.1109/TPWRS.2015.2510612.

[14] M. A. Hayat, F. Shahnia, and G. Shafiullah, "Replacing flat rate feed-in tariffs for rooftop photovoltaic systems with a dynamic one to consider technical, environmental, social, and geographical factors," *IEEE Trans. Ind. Informat.*, vol. 15, no. 7, pp. 3831–3844, Jul. 2019, doi: 10.1109/TII.2018.2887281.

[15] F. Shen, S. Huang, Q. Wu, S. Repo, Y. Xu, and J. Østergaard, "Comprehensive congestion management for distribution networks based on dynamic tariff, reconfiguration, and re-profiling product," *IEEE Trans. Smart Grids*, vol. 10, no. 5, pp. 4795–4805, Sep. 2019, doi: 10.1109/TSG.2018.2868755.

[16] X. Li, H. Yang, M. Yang, and G. Yang, "Flexible time-of-use tariff with dynamic demand using artificial bee colony with transferred memory scheme," *Swarm Evol. Comput.*, vol. 46, pp. 235–251, May 2019, doi: 10.1016/j.swevo.2019.02.006.

[17] S. Huang, Q. Wu, H. Zhao, and C. Li, "Distributed optimization-based dynamic tariff for congestion management in distribution networks," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 184–192, Jan. 2017, doi: 10.1109/TSG.2017.2735998.

[18] M. B. Rasheed, M. A. Qureshi, N. Javaid, and T. Alquthami, "Dynamic pricing mechanism with the integration of renewable energy source in smart grid," *IEEE Access*, vol. 8, pp. 16876–16892, 2020, doi: 10.1109/ACCESS.2020.2967798.

[19] F. Shen and Q. Wu, "Robust dynamic tariff method for day-ahead congestion management of distribution networks," *Int. J. Electr. Power Energy Syst.*, vol. 134, pp. 1–11, Jan. 2022, doi: 10.1016/j.ijepes.2021.107366.

[20] R. Jinsiwale and D. Divan, "Decentralized real-time pricing to achieve integrated transactive and physical grids," *IEEE Access*, vol. 7, pp. 132525–132541, 2019, doi: 10.1109/ACCESS.2019.2941424.

[21] S. S. Reka, P. Venugopal, H. H. Alhelou, P. Siano, and M. E. H. Golshan, "Real time demand response modeling for residential consumers in smart grid considering renewable energy with deep learning approach," *IEEE Access*, vol. 9, pp. 56551–56562, 2021, doi: 10.1109/ACCESS.2021.3071993.

[22] H. Liu, N. Mahmoudi, and K. Chen, "Microgrids real-time pricing based on clustering techniques," *Energies*, vol. 11, no. 6, p. 1388, May 2018, doi: 10.3390/en11061388.

[23] Z. Wang, R. Paranjape, Z. Chen, and K. Zeng, "Multi-agent optimization for residential demand response under real-time pricing," *Energies*, vol. 12, no. 15, p. 2867, Jul. 2019, doi: 10.3390/en12152867.

[24] K. Christensen, Z. Ma, and B. N. Jørgensen, "Technical, economic, social and regulatory feasibility evaluation of dynamic distribution tariff designs," *Energies*, vol. 14, no. 10, p. 2860, May 2021, doi: 10.3390/en14102860.

[25] ANEEL. (2020). (in Portuguese). *Tarifa Branca*. [Online]. Available: aneel.gov.br/tarifa-branca

[26] D. S. Kirschen, "Demand-side view of electricity markets," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 520–527, May 2003, doi: 10.1109/TPWRS.2003.810692.

[27] B. Xiang, K. Li, X. Ge, F. Wang, J. Lai, and P. Dehghanian, "Smart households' available aggregated capacity day-ahead forecast model for load aggregators under incentive-based demand response program," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, Sep. 2019, pp. 1–10, doi: 10.1109/IAS.2019.8911988.

[28] COPEL. (2021). (in Portuguese). *Tarifa Branca*. [Online]. Available: https://www.copel.com/hpcweb/copel-distribuicao/taxas-tarifas/

[29] K. Costello, "An observation on real-time pricing: Why practice lags theory," *Electr. J.*, vol. 17, no. 1, pp. 21–25, Jan. 2004, doi: 10.1016/j.tej.2003.11.007.

[30] G. Dudek, "Multilayer perceptron for short-term load forecasting: From global to local approach," *Neural Comput. Appl.*, vol. 32, no. 8, pp. 3695–3707, Apr. 2020, doi: 10.1007/s00521-019-04130-y.

[31] J. R. M. Hosking, R. Natarajan, S. Ghosh, S. Subramanian, and X. Zhang, "Short-term forecasting of the daily load curve for residential electricity usage in the smart grid," *Appl. Stochastic Models Bus. Ind.*, vol. 29, no. 6, pp. 604–620, Nov. 2013, doi: 10.1002/asmb.1987.

[32] M. Jacob, C. Neves, and D. V. Greetham, *Forecasting and Assessing Risk of Individual Electricity Peaks*. Cham, Switzerland: Springer, 2020, doi: 10.1007/978-3-030-28669-9.

[33] S. Borenstein, "Wealth transfers among large customers from implementing real-time retail electricity pricing," *Energy J.*, vol. 28, no. 2, pp. 131–149, Apr. 2007.

[34] J. C. Mak and B. R. Chapman, "A survey of current real-time pricing programs," *Electr. J.*, vol. 6, no. 7, pp. 76–77, Aug. 1993.

[35] A. Faruqui, S. Sergici, and C. Warner, "Arcturus 2.0: A meta-analysis of time-varying rates for electricity," *Electr. J.*, vol. 30, no. 10, pp. 64–72, Dec. 2017, doi: 10.1016/j.tej.2017.11.003.

[36] S. Kahawala, D. De Silva, S. Sierla, D. Alahakoon, R. Nawaratne, E. Osipov, A. Jennings, and V. Vyatkin, "Robust multi-step predictor for electricity markets with real-time pricing," *Energies*, vol. 14, no. 14, p. 4378, Jul. 2021.

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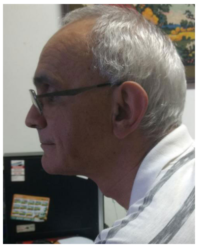

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