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Demand Response Programs Design for EVs

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Executive Summary

The deliverable *D4.5 - Demand Response Programs Design for EVs*, aims to propose several innovative Demand Response (DR) programs focusing on Vehicle-to-Everything (V2X) end-users, fleet operators and aggregators. This deliverable is centred in three of the EV4EU project member countries: Greece, Portugal, and Slovenia. The proposed methodology includes residential electric vehicle (EV) users participating in various DR programs considering factors such as user comfort, peak power consumption minimization from the perspective of individual EVs, and of aggregators, who may also be fleet operators or parking lot/building managers. Additionally, the V2X capabilities of EVs are considered.

The methodology for the design of the DR programs reflects the reality of each country considered in this analysis and includes *i)* data processing related to the average yearly energy prices and residential charging profiles of 200 EV users for all the countries analysed. For the innovative Portuguese DR program designed, data processing of seasonal tetra-hourly energy price was implemented as well as a data processing of a yearly wind curtailment power. In the case of the innovative Slovenian DR program, data processing for two years of the voltage values was applied. For the innovative Greek DR program, data processing of monthly active power values was employed; *ii)* optimisation model for DR program considering five different objective functions such as Business as Usual (BaU) taken as the benchmark case, minimisation of energy cost, minimisation of the energy cost considering comfort level, minimisation of peak power from aggregator point of view, and minimisation of peak power from each EV point of view; *iii)* DR program optimisation model considering the V2X capabilities of the EV users; *iv)* Design of a new DR program to avoid reverse power flow using EVs in Greece, design of a new DR program to avoid wind power curtailment through EVs in Portugal, a new DR program based on tetra-hourly tariffs considering the EV profiles in Portugal, and a new DR program to avoid overvoltage by encouraging EV charging in Slovenia.

Analysing the main results, it is possible to conclude that implicit DR programs using real-time pricing are unattractive to typical users, because of the risks related with prices variation. However, for informed users, these types of tariffs can represent an opportunity mainly when the market prices are low. When the prices are high the best solution is to return to more conservative programs such as the Time-of-use (ToU). Conversely, DR programs designed to support the power system are beneficial for both EV users and operators, resulting in lower energy bills and a more balanced use of energy throughout the operational period. Each of the DR programs for the countries analysed in this report addresses real-world issues and offers attractive solutions for both the power system and EV users. These solutions include voltage control, preventing reverse power flow due to excess solar generation, and avoiding the spillage of renewable energy. Additionally, they provide business models that offer financial discounts to electric mobility users.

It is important to highlight that the new DR program based on tetra-hourly tariffs and considering the profile of EV users, specifically designed for Portugal, shows a considerable improvement in the energy bills that users would pay. Compared to cases that do not consider the EV users profiles, this new program adjusts to the needs of electric mobility users by paying particular attention to the hours when charging activity at charging stations is expected to be highest. Moreover, the new DR program based on the current ToU tariff applied in Portugal, where tariffs are deferred by -1h and +1h, validated that the -1h tariff can be interesting to EV users, resulting in improvements in energy bills, while the +1h tariff is not competitive for users.

Finally, in the DR programs applied with V2G consideration, the results demonstrated improvements in how charging and discharging energy is scheduled. This ensures competitive energy bills for users by taking advantage of discharging when energy prices are higher, without compromising the energy requirements of the users.

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Acronym

BaU	Business as Usual
BESS	Battery Energy Storage System
CPP	Critical Peak Pricing
CS	Charging Station
DR	Demand Response
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
LV	Low voltage
MV	Mid-voltage
OF	Objective Function
Pn	Nominal Power
PV	Photovoltaic system
RES	Renewable Energy Resource
RTP	Real-Time Pricing
SoC	State-of-Charge
TOC	Total Operating Cost
ToU	Time-of-Use
V2G	Vehicle-to-Grid (Bidirectional Charging)
V2X	Vehicle-to-Everything

1 Introduction

Demand response (DR) programs can be defined as adjustments in the level of electricity demand in response to fluctuations in energy prices, economic incentives within an electricity market, or the need to enhance system reliability [1]. Several studies have been focussed on how DR can help mitigate the increased peak demand and reduce the impact on the distribution system, thereby avoiding technical constraints [2]. This document proposes several innovative DR programs focusing on vehicle-to-everything (V2X) end-users, fleet operators and aggregators created considering the reality of three EV4EU countries, as detailed below:

- Greece: innovative DR program to avoid reverse power flow through electric vehicles (EVs)
- Portugal: Innovative DR program to avoid wind curtailment through EVs, new time-of-use (ToU) DR program considering EV profiles, new deferred ToU
- Slovenia: Innovative DR program implementing voltage control through EVs

1.1 Scope and objectives

The primary objective of this document is to validate the effectiveness of various DR programs specifically designed to address current issues in the power systems of the analysed countries. To achieve this aim, several optimization models for DR programs are proposed, incorporating specific data such as yearly average energy prices, monthly active power values for low voltage feeders, and yearly wind curtailment power, among others. Additionally, through notable simulation results, it was possible to demonstrate how these DR programs can enhance system reliability and improve both the energy and economic comfort of EV users.

1.2 Structure

The present document is divided into 5 sections. After the introduction section (Section 1), Section 2 provides insight into DR programs. Section 3 presents the innovative DR proposed for Greece, Portugal, and Slovenia. Section 4 details the main simulation results. Finally, Section 5 wraps ups with some overall conclusions and recommendations.

1.3 Relationship with other deliverables

The innovative DR program in Portugal, aimed at avoiding wind curtailment using electric EVs, utilized input data on wind energy curtailment. This data was processed and incorporated into *D2.2 - Control Strategies for V2X Integration in Buildings* [3]. The EV charging profiles used to create a new Time-of-Use tariff for EVs were created using the dataset processed in the *D3.3 - Apps and Tools design principles promoting EVs and V2X adoption* [4]. Downstream, several DR programs resulting from the current deliverable will be installed, configured, commissioned, operated, and monitored in the Greek, Slovenian, and Portuguese demonstrators.

2 Demand Response Programs

DR programs are initiatives designed to encourage consumers to modify their electricity usage during peak periods in response to time-based rates or other financial incentives [5]. These programs aim to balance the supply and demand of electricity, improve grid reliability, and reduce the need for additional power plants [2].

2.1 Implicit Demand Response

Implicit DR refers to the strategies and mechanisms through which the users adjust their usage patterns in response to dynamic price signals without direct intervention from utilities or third-party aggregators. Hence, implicit DR relies on consumers' voluntary reactions to price changes in the electricity market [6]. Some of the most well-known are ToU, in which the users are stimulated by different rates for electricity based on the time of day, encouraging them to shift their consumption to off-peak periods when electricity is cheaper [5]. Real-Time Pricing (RTP), in which prices fluctuate throughout the day based on real-time supply and demand conditions. The users can adjust their usage in response to these price variations [5]. Critical Peak Pricing (CPP), in which the prices are significantly increased in the periods of peak demand to encourage consumers to reduce their usage. CPP events are typically announced a day ahead [5].

2.2 Explicit Demand Response

Explicit DR involves direct intervention by utilities or third-party aggregators, where participants are called upon to reduce or shift their electricity usage during specific periods in exchange for financial incentives or other rewards [7]. This approach is more controlled and often employed during peak demand periods or grid emergencies to ensure stability and reliability. Some of the most well-known are, among others [7]: direct load control, in which utilities remotely control specific appliances (e.g., air conditioners, water heaters) during peak periods. Interruptible/Curtailable Service, where large industrial customers agree to reduce their load to a pre-determined level upon request. Demand Bidding Programs, in which the consumers offer to reduce their load at a certain price, and utilities accept bids based on their needs [7].

2.3 Electric Vehicles and Demand Response – State of the Art

EVs have emerged as a crucial component in the transition towards sustainable energy systems [8]. With the growing penetration of EVs, their interaction with the power grid has gained significant attention, particularly in the context of DR. Several research works have been focused on studying the EVs integration into the DR programs by considering vehicle-to-grid (V2G) technology for bi-directional energy flow between EVs and the power grid [9], [10]. In [10], the authors present a more detailed study by introducing a methodology for the day-ahead energy resource scheduling for smart grids, which accounts for the extensive use of distributed generation and V2G. They propose two different DR programs: i) “Trip reduce”, which allows EV users to earn profits by reducing their travel needs and minimum battery state-of-charge (SoC) requirements. ii) "Shifting reduction," which enables EV users to create a set of alternative travel periods for their anticipated trips. The EV Smart Charging is also another DR integrating EVs, in which utilities can control the timing and rate of EV charging to optimize grid performance. This can be done by delaying charging to off-peak hours or reducing charging rates during peak demand periods [11]. Several research studies have investigated the EV smart charging to improve the network reliability [12], [13]. The authors in [13] present a strategy for efficiently scheduling the EV charging within power grids. The core idea is to use an optimization algorithm to manage

EV charging in a way that balances the grid load, minimizes electricity costs, and enhances grid stability. By optimally timing and distributing the charging of EVs, the strategy aims to reduce peak demand, avoid overloading the grid, and integrate renewable energy sources more effectively. The approach seeks to benefit both the power grid operators and EV owners through improved energy management and cost savings.

2.4 Participation of Electric Vehicles in Demand Response

The incorporation of EV charging/discharging coordination into DR initiatives has gained significant attention in recent research. The emphasis primarily lies in exploring how DR programs can effectively alleviate surges in peak demand and mitigate their repercussions on the distribution grid by avoiding technical limitations [5]. Therefore, the participation of the EVs in DR programs can consider EV batteries as direct load control, where the utilities directly manage the charging of EVs to curtail load during peak periods [14], and EV users as ancillary services providers, in which services such as frequency regulation and spinning reserves can be activated by adjusting their charging rates [15], while EV owners or aggregators offer load reductions in response to price signals by implementing demand bidding program [16].

2.4.1 Time-of-Use tariff

The ToU DR program is distinguished by varying energy rates across different time segments within a 24-hour period. Typically, this entails dividing the day into three distinct periods, off-peak, peak, and super peak, based on the system's demand consumption levels. Research works have demonstrated that the ToU-based DR program collaborates by shaving the peak load of the EVs [5].

2.4.2 Real-time Pricing Tariffs

The RTP utilizes dynamic price tariffs that vary hour by hour or minute by minute, reflecting the real-time structure [16]. This program can introduce significant uncertainty and risk for EV owners, since prices can change within short intervals [17]. Many research works have examined Electric Vehicle Suply Equipments (EVSEs) in the context of these price signals [18], [19]. RTP offers a more dynamic variation, with electricity prices announced to participants on a day-ahead or an hour-ahead basis. However, compared to other DR programs, RTP generally results in the poorest economic outcomes [16].

3 Proposed Demand Response Programs

As the global energy landscape undergoes a transformative shift towards sustainability, innovative DR programs are emerging as pivotal tools in managing electricity consumption. These DR programs are not only enhancing grid stability and reliability but are also fostering a more efficient and dynamic energy ecosystem. EVs are at the forefront of innovative DR programs. With the ability to act as mobile energy storage units, EVs can provide electricity back to the grid during times of high demand by implementing V2G technology. In this section, innovative DR programs proposed for the reality of three countries of the partners involved in EV4EU project will be detailed.

3.1 Demand Response Programs for Greece: Avoiding reserve power flow through EVs

Reverse power flow, a phenomenon in which power flows from low voltage distribution grid to the medium voltage distribution grid, has become increasingly relevant due to the proliferation of renewable energy resources (RES), particularly photovoltaic (PV) installations [20]. This is particularly important in countries like Greece, which have significant solar energy potential, mainly because the Greek regulatory framework has evolved to accommodate and promote the integration of RES. Policies such as feed-in tariffs, net metering, and incentives for residential PV installations have contributed to the rise of RES systems [21]. Moreover, the intermittent nature of RES can lead to mismatches between generation and consumption, causing reverse power flow during periods of low demand and high generation. Therefore, implementing DR programs can help align consumption with generation, reducing the instants of reverse power flow. For instance, EV charging management, can absorb excess generation and release it during periods of high generation, thus minimizing reverse power flow. Moreover, in recent years, price signals based on grid tariffs (otherwise called use-of-system tariffs) have been proposed as a means for distribution system operations to motivate DR [22], [23]. Based on the challenges faced by the Greek community, a DR solution was developed to address reverse power flow by utilizing EVs. This approach, illustrated in Figure 1, aims to prevent reverse power flow by adjusting grid tariffs, in which Pn indicates the nominal power of the medium-voltage/low-voltage (MV/LV) power transformer. When reverse power flow is detected, the grid tariff is decreased to incentivize EV charging. The grid tariff is zero when the injection power reaches 50% of the transformer's nominal capacity. This approach limits losses and indirectly reduces voltage problems.

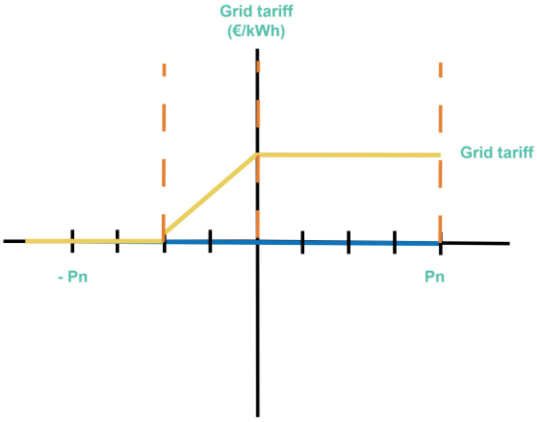


Figure 1 – Avoiding reverse power flow through EVs proposal

For this purpose,

Figure 2 illustrates how the overall strategy aims to mitigate the reverse power flow by strategically incorporating EV charging. To implement this DR program effectively, various assumptions regarding EV usage patterns must be integrated as input data. These include average daily distance travelled (km/day), energy consumption per kilometre (kWh/km), average power consumption per charging station (kW), grid tariff limits (€/kWh), power flow limits (kW). Therefore, the output information will be the discount (%) that the EV users will receive for their participation in this DR program.

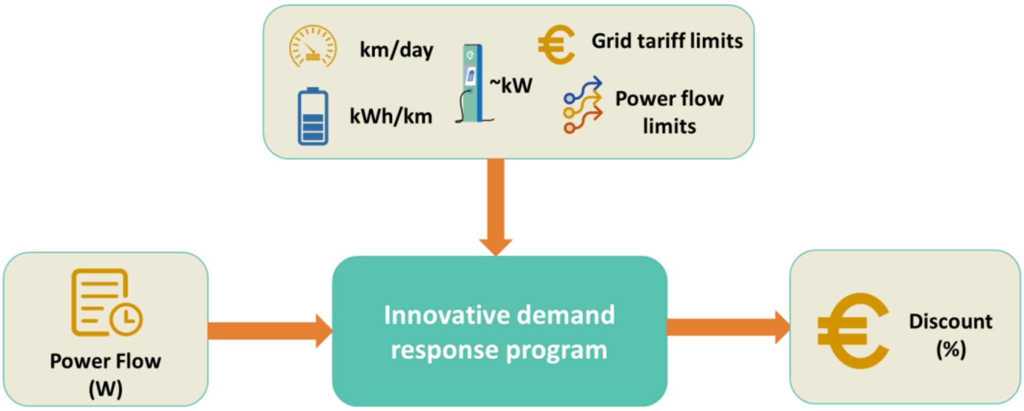


Figure 2 – Overall innovative DR program for Greece

3.2 Demand Response Programs for Portugal

3.2.1 New Time-of-Use Demand Response Program

In Portugal, ToU tariffs have emerged as a strategic tool in shaping energy consumption patterns and promoting a more sustainable approach to electricity usage. These pricing structures incentivize consumers to adjust their electricity consumption based on varying demand throughout the day, ultimately contributing to grid stability, energy efficiency, and cost optimization [24]. Under the ToU tariff system in Portugal, electricity prices fluctuate based on the time of day, with different rates applied during peak, off-peak, and shoulder periods. Typically, peak hours correspond to periods of highest electricity demand, often occurring during late afternoon and early evening, when households and businesses are most active. Off-peak hours, on the other hand, are characterized by lower electricity demand, typically occurring during late night and early morning hours, when the overall consumption is reduced. Shoulder periods bridge the gap between peak and off-peak hours, applying intermediate pricing.

Therefore, based on this tariff system, two new ToU tariffs were derived from two non-linear optimisation problems, whose objective is twofold: (*i*) to minimize the squared difference between the new tariff (ToU_t) and the average energy price ($price_t$) as shown by Formula (1), and (*ii*) to minimize the squared difference between the new tariff (ToU_t) and the average energy price ($price_t$) plus the squared difference between the new tariff (ToU_t) and the EV charging profiles ($evprofile_t$) as illustrated by Formula (2); both objective functions are subject to the constraints in Formulas (3) and (4). Hence, the optimisation process created four new tariffs based on the average price curve for Portugal without EV profile consideration in Formula (1) and considering EV profiles in Formula (2) normalized to adjust with the values of the average prices.

$$\min f = \sum_{t \in T} (nToU_t - price_t)^2 \tag{1}$$

$$\min f = \sum_{t\in T} (nToU_t - price_t)^2 + (nToU_t - evprofile_t)^2 \tag{2}$$

$$nToU_t = nToU1_t.x1_t + nToU2_t.x2_t + nToU3_t.x3_t + nToU4_t.x4_t, \qquad \forall t \tag{3}$$

$$x1_t + x2_t + x3_t + x4_t = 1, \qquad \forall t \tag{4}$$

3.2.2 Avoiding Wind Curtailment through Electric Vehicles

Portugal has made significant effort in the adoption of RES, particularly wind power, as part of its commitment to combating climate change and achieving sustainability goals, outlined in the *"Roteiro para a Neutralidade Carbónica 2050 (RNC 2050)" – Estratégia de Longo Prazo Para a Neutralidade Carbónica da Economia Portuguesa em 2050* [25]. However, one persistent challenge facing the country's renewable energy sector is the issue of wind curtailment. Wind curtailment is more frequent in Islands namely in Azores and occurs when there is excess electricity generation from wind turbines that exceeds the power demand needs [26]. In Azores this is true mainly because the high share of geothermal power that is used in the base of load diagram. Additionally, the lack of sufficient energy storage capacity exacerbates the problem, as surplus energy cannot be effectively stored for later use.

Based on the challenges faced in Azores, a DR solution was proposed to address wind curtailment by utilizing EVs. This approach, depicted in

Figure 3, aims to mitigate the impact of wind curtailment on São Miguel Island [3] by strategically incorporating EV charging. To implement this DR program effectively, various assumptions regarding EV usage patterns must be integrated as input data. These include average daily distance travelled (km/day), energy consumption per kilometre (kWh/km), total daily energy consumption (kWh/day), average power consumption per charging station (kW), feed-in tariff (€/MWh), and shared benefits (%). Feed-in tariff (€/MWh) represents an instrument for promoting RES encouraging the green energy production by guaranteeing a fixed payment to producers for the electricity they generate and feed into the grid. The shared benefit is settled to incentivize EV users to participate in the DR program by offering them a percentage of the mandatory feed-in tariff paid to the producers. Therefore, the output information will be the number of EVs needed to avoid the energy curtailment and the price to share with the EV users for their participation in this DR program.

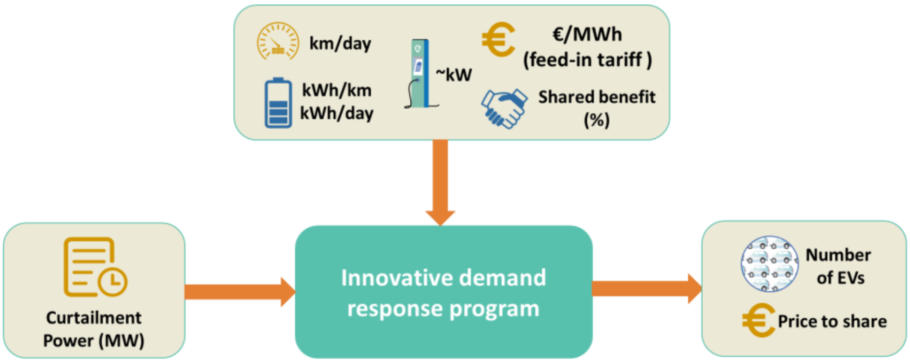


Figure 3 – Avoiding wind curtailment through EVs

3.3 Demand Response Programs for Slovenia: Voltage control in the distribution network through Electric Vehicles

Voltage control in the distribution network aims to maintain the voltage between the established boundaries. In LV grids the voltage can change ±0.1 p.u. (per unit). This phenomenon can have various causes and significant implications for both the distribution infrastructure and the end-users [27]. Related to the usage of EVs in this context, V2X can significantly help mitigate voltage constraints issues in the distribution network through optimizing the time and rate at which EVs are charged/discharged [28]. For instance, when the voltage is high due to high levels of production, the charge of the EVs should increase and in periods when the voltage is low, the EVs should reduce the charging power or even discharge energy to support the grid [28].

Based on the challenges related to voltage control in distribution network in Slovenia, a DR program was developed to address this issue by utilizing EVs. This approach, presented in Figure 4, aims to encourage the EVs to change their behaviour based on the price variation associated with minimum and maximum limitations for the voltage. The main idea of this DR program is to provide price signals to encourage EV charging even (by reducing the tariff during overvoltage) or to incentivize stopping EV charging or discharging (by increasing the tariff during undervoltage). A differentiation is made in the positive and negative price signals to avoid high penalties when the voltage is low.

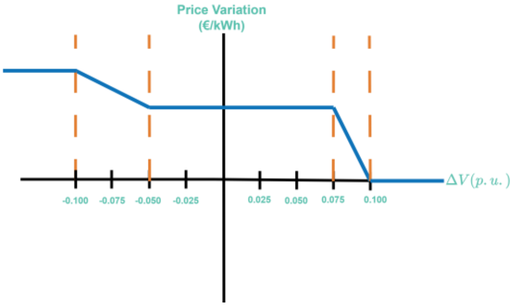


Figure 4 – Avoiding overvoltage in the distribution network through EVs proposal

Moreover, it is important to notice that new grid tariff regulation will be implemented in Slovenia, soon. The main aim of this regulation is to promote short and long-term storage strategies and electricity exports considering the ambitious targets for RES defined by Slovenian government [29]. The new price strategies will result in the definition of new DR programs, such as the ones proposed in the present document. This is where EVs come into play as a battery energy storage system (BESS) due to V2G technology.

To substantiate the assumptions outlined in the study, over- and under-voltages were also observed at the Slovenian Phase I demonstrator site, where initial measurements of the system were collected and analysed. As one of the steps to ensure a more stable energy grid, a new tariff system will come into force in Slovenia at the beginning of October 2024, which has been postponed by one year. The changes brought about by the new tariff system will apply to all users, both households and business customers. They represent an economic, legal and technological challenge, but also a social challenge. The main features of the new tariff system are calculations based on 15-minute values, the introduction of two seasons, a higher one between November and February and a lower one between March and October, five-time blocks, and the distinction between agreed and excess billing power [30]. There will be five-time blocks, whereby three different time blocks can occur on a single day. The most expensive time block will be time block 1, which will only occur in the high season, while the cheapest use of the electricity grid will be in time block 5, which will only occur in the low season [30]. The time blocks that will come into effect from 1 October 2024 are shown in Table 1.

Table 1: Time distribution of time blocks by seasons, periods and hours

			Time block				
	Period		1	2	3	4	5
Season	High	Workday	7h00-14h00 16h00-20h00	6h00-7h00 14h00-16h00 20h00-22h00	0h00-6h00 22h00-24h00		
		Holiday		7h00-14h00 16h00-20h00	6h00-7h00 14h00-16h00 20h00-22h00	0h00-6h00 22h00-24h00	
	Low	Workday		7h00-14h00 16h00-20h00	6h00-7h00 14h00-16h00 20h00-22h00	0h00-6h00 22h00-24h00	
		Holiday			7h00-14h00 16h00-20h00	6h00-7h00 14h00-16h00 20h00-22h00	0h00-6h00 22h00-24h00
			Hour of the day				

Billing will continue to be based on the separation of consumed power and energy. The tariff items will differ depending on the time block. Tariff rates will be highest when the grid is utilised at peak times and lowest when this is not the case [30].

4 Simulation Results

This section presents the simulation results to illustrate some key features of the proposed DR programs. Subsection 4.1 presents the assumptions and main results of the RTP DR program for Greece, Portugal, and Slovenia. RTP have been selected to test the different objective functions that the users can use. In that case, RTP allows higher variations in the proposed strategies to take advantage of lower prices. Price signals based on the identification of reverse power flows, that will be tested in Greece, are presented in subsection 4.2. Subsection 4.3 illustrates the main results and assumptions of the innovative ToU DR program for Portugal. Finally, the main results and assumptions of the price signals for voltage control, for Slovenia, are presented in subsection 4.4.

4.1 Real-Time Pricing Demand Response program for Greece, Portugal and Slovenia

4.1.1 Model assumptions for Real-time Pricing Demand Response program

For the RTP DR program were considered five objectives function (OFs) that represent the non-participation of the EV users in any DR program, typically a BaU method (OF1), the participation of the EV users in an implicit DR program by minimising the energy bill (OF2), the participation of the EV users in an implicit DR program by minimizing the energy bill and considering the EV comfort level (OF3), the participation of the EV users in an DR program by minimizing the peak power from an aggregator point of view (OF4), and the participation of the EV users in an DR program by minimizing the peak power from each EV point of view (OF5). The five OFs consider technical constraints about the EV operation and system operation. More detailed information can be found in [5]. For the simulations were considered typical energy price curves in the electricity spot market following the reality of each country, where the Greek energy curve was obtained from [31], from [32] was obtained the Portuguese energy curve, and the Slovenian energy curve was collected from [33]. On the other hand, for each country case, we considered an EV population of 200 residential users. Table 2 shows the details about the EV users' participation by DR program (OF).

Table 2: Objective Functions related to participation and non-participation in DR program

Scenarios	DR program
1	OF1 – EVs do not participate in any DR (BaU)
2	OF2 – EVs participate in an implicit DR program by minimizing the energy bill
3	OF3 – EVs participate in an implicit DR program by minimizing the energy bill, while considering the EV user comfort level
4	OF4 – EVs participate in an DR program by minimizing the peak power from the aggregator point of view
5	OF5 – EVs participate in an DR program by minimizing the peak power from each EV point of view

4.1.2 Main results for Real-Time Pricing Demand Response in Greece

The main results for the RTP DR in Greece are shown in Figure 5 – Figure 9. It important to highlight that for this and the following cases, the optimisation horizon considered was five days (workdays) considering 1 hour resolution, nevertheless, for simplicity, the results are illustrated for the third operation day. Hence, in Figure 5, the peak of EV power consumption (1.14MW) can be observed at 20h00, which coincides with the period when energy price is highest, this is because the EV users charge their batteries at the earliest opportunity. Due to their nonparticipation in an DR program throughout the day, the EV users incur a total cost of 262.63€ for this operation day with 3.08MWh of energy scheduled for this day. Moreover, for the five days considered into the simulation, the total energy scheduled was 19.45MWh with a total cost of 1404.84€.

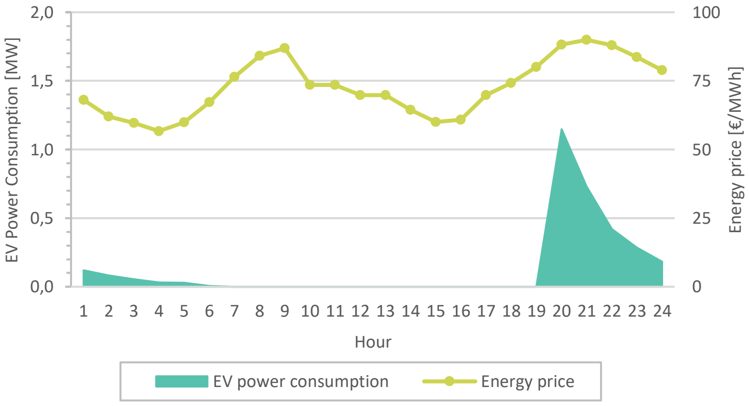


Figure 5 – EVs do not participate in any DR (BaU), Greek Case

In the case of the EV users decide to participate in the RTP DR program aimed at minimizing energy costs, a significant improvement can be observed. The EV peak power consumption (1.14MW) is concentrated during an hour when prices is lower (4h00), as can be observed in Figure 6. Moreover, the daily energy scheduled was 3.09MWh and participating EV users incur a total daily cost of 189€, 28% cheaper compared to the case in which they do not participate in any DR program. Similarly, EV users participating in the RTP DR program, aiming to minimize energy costs while maintaining energy comfort levels, experience peak consumption (1.14 MW) also at 4h00. In this case, the total daily energy scheduled was 3.09MWh, while the daily cost remains 189€, as the DR program allows them to achieve their desired comfort level without sacrificing economic benefits.

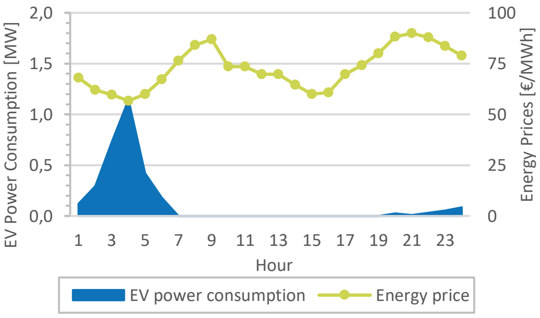


Figure 6 – EVs participate in RTP DR, Greek Case

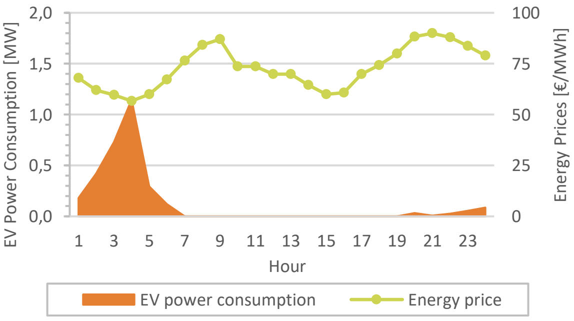


Figure 7 – EVs participate in RTP DR considering comfort level, Greek Case

In the context of the DR program to collaborate with the power system (Figure 8 and Figure 9), when EV users participate to minimise peak power consumption from the aggregator's perspective, the peak power is not concentrated in a single hour. Instead, the EV peak consumption (0.74MW) is distributed over three hours (3h00–4h00), which aids the distribution network, as illustrated in Figure 8, in this case, 3.09MWh was the daily energy scheduled and the EV users incur in a total daily cost of 190.72€, 27% cheaper than the users that non participate in any DR program. From the EV user's perspective, it can be observed that peak consumption minimization is achieved while still meeting the EVs' requirements. This results in a peak consumption of 0.71 MW concentrated at 5h00, as shown in Figure 9. In this case, EV users had an energy scheduled of 3.08MWh incurring a total daily cost of 190.72€, which is 27% cheaper than when do not participate in any DR program. It is important to notice that the primary objective of the users is to reduce the energy cost, and the peak is included in the problem as a secondary objective to avoid penalizing the costs to a significant extent. Each user can parameterize the importance of the secondary objective to have impact in the costs.

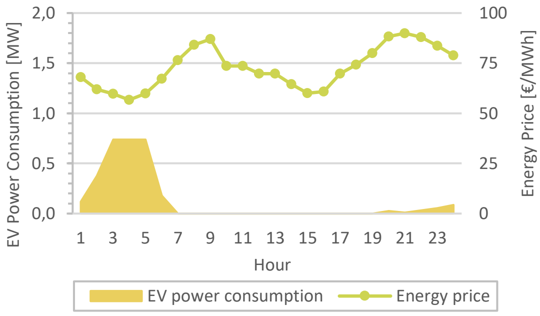


Figure 8 – EVs participate in RTP DR minimisation of peak power from the aggregator point of view, Greek Case

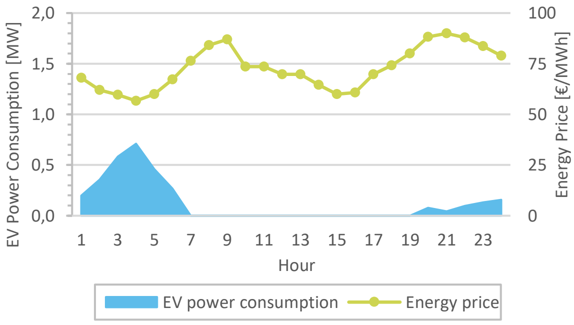


Figure 9 – EVs participate in RTP DR minimisation of peak power from each EV point of view, Greek Case

Table 3 provides a summary of the energy scheduled and the corresponding energy bills for EVs over the five days analysed in the simulation. In the BaU scenario (OF1), more energy is scheduled (19.45MWh) towards the end of the optimization horizon, resulting in a higher energy bill (1404.84 €) for EV users. Conversely, under the proposed DR programs, the same amount of energy is scheduled (16.76MWh), 14% less than the non-participant case. This reduction is due to the EV smart charging management, leading to lower energy bills compared to the non-participating scenario. Even in the case of power limitations, the total energy scheduled is maintained to 16.76MWh, but by analysing a day of operation (Figure 8 and Figure 9) the peak of EV power consumption is limited under the 1MWh, indicating that this DR programs avoids abrupt power changes that could lead to peaks, even if cheaper prices are available, as the main goal is to collaborate with the power system. In terms of economic benefits, the OF3 program is particularly cost-effective since the primary goal is to minimize the energy bill, yielding a 30% discount for participants in this DR program, while the power limitation DR programs represent a higher energy bill, 3.9% more than OF3 for the overall optimisation horizon, nevertheless 27% cheaper than the non-participant case.

Table 3: Summary of the energy scheduled, and cost related to the five days of simulation, Greek case

DR program	Energy (MWh)	Cost (€)
OF1	19.45	1404.84
OF2	16.76	981.20
OF3	16.76	988.21
OF4	16.76	1020.79
OF5	16.76	1020.79

4.1.3 Main results for Real-Time Pricing Demand Response in Portugal

The main results for the RTP DR in Portugal are illustrated in Figure 10 – Figure 14. Similar with the Greek case, in the Portuguese context, for EV users not participating in any DR program, a peak consumption of 1.14 MW is observed at 19h00 coinciding with the highest energy prices for this operation day. This is because these users prioritize recharging their batteries at the earliest convenience. As a result of their nonparticipation in any DR program throughout the day, these EV users incur a total cost of 216.73€, with a total energy scheduled for this day of 3.08MWh. In this case, for the five days considered into the simulation, the total energy scheduled was 19.54MWh with a total cost of 1282.89€.

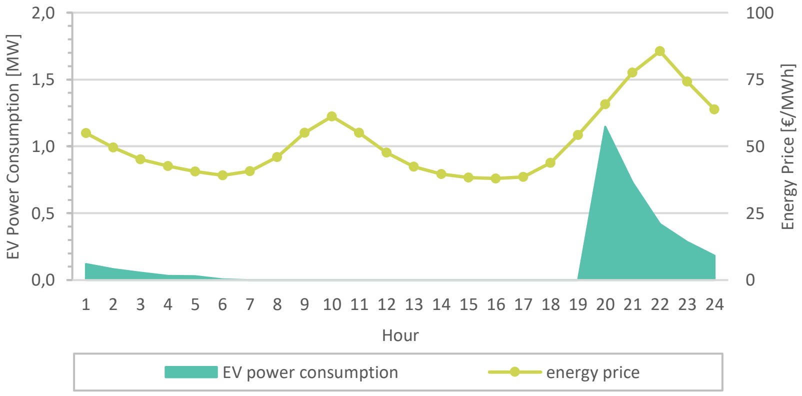


Figure 10 – EVs do not participate in any DR (BaU), Portuguese Case

On the other hand, in cases where EVs participate in the DR program with the objective of minimising energy costs while also considering their comfort level, very similar results can be observed, as shown in Figure 11 and Figure 12. In both cases, the peak power consumption of the EVs occurs at 6h00, taking advantage of the lower energy prices. Additionally, the EVs manage to reduce their energy bills by 37.60%, with a total operating cost of 135.30€ for that day, consuming a total daily energy of 3.09MWh in both cases. In the Portuguese cases where peak power is minimized, the curves show that the peak power of the EVs does not exceed 1MW, as illustrated in Figure 13 and Figure 14. From the aggregator's perspective, consumption is distributed over several hours, successfully limiting power and benefiting the system operator (see Figure 13). Moreover, the EVs manage to reduce their energy bills by 36.60%, with a total operating cost of 136.90€ for that day and with a total energy of 3.09MWh scheduled. From the EV users' perspective, the system's power remains limited (see Figure 14), but the EVs benefit from a concentrated charging period (0.71 MW) at the time when energy prices are lowest (6h00), so, in this case the EVs manage to reduce their energy bills by 32.80%, with a total operating cost of 145.81€ for that day, demanding a total energy of 3.08MWh.

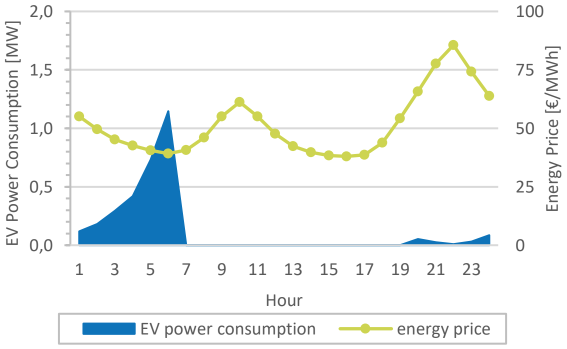


Figure 11 – EVs participate in RTP DR, Portuguese Case

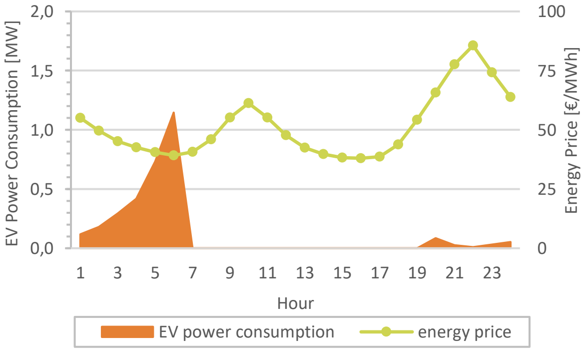


Figure 12 – EVs participate in RTP DR considering comfort level, Portuguese Case

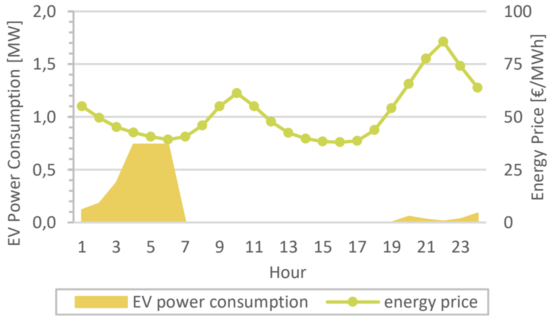


Figure 13 – EVs participate in RTP DR minimisation of peak power from aggregator point of view, Portuguese Case

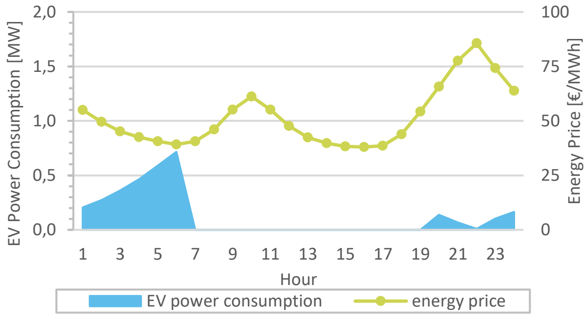


Figure 14 – EVs participate in RTP DR minimisation of peak power from each EV point of view, Portuguese Case

Table 4 provides a summary of the energy scheduled and the corresponding energy bills for EVs over the five days analysed in the Portuguese simulation case. In the BaU scenario (OF1), more energy is scheduled (19.54MWh) towards the end of the optimization horizon, resulting in a higher energy bill (1282.89€) for EV users. Conversely, under the proposed DR programs, the same amount of energy is scheduled (16.76MWh), 14% less than the non-participant case. This reduction is due to the EV smart charging management, leading to lower energy bills compared to the non-participating scenario. Specifically, in the Portuguese case, the RTP DR program is particularly cost-effective when the primary goal is to minimize the energy bill (OF3), yielding 43% discount for participants in this DR program. DR programs focusing on power limitations (OF4 and OF5), like in Greek case, results are slightly more expensive than the OF3, by 2.7% and 7.12%, respectively.

Table 4: Summary of the energy scheduled, and cost related to the five days of simulation, Portuguese case

DR program	Energy (MWh)	Cost (€)
OF1	19.54	1282.89
OF2	16.76	725.80
OF3	16.76	726.02
OF4	16.76	745.70
OF5	16.76	781.60

4.1.4 Main results for Real-Time Pricing Demand Response in Slovenia

For the case of Slovenia, the results can be observed in Figure 15 – Figure 19. For the Slovenian case in which EV users do not participate in any DR program, like the Greek and Portuguese cases, the peak consumption of EVs (1.14MW) is concentrated at the hour when energy prices are highest (20h00), resulting in a total energy cost of 386.40€. For Slovenia, for the five days considered into the simulation the total energy scheduled was 19.54MWh with a total cost of 2067.44€.

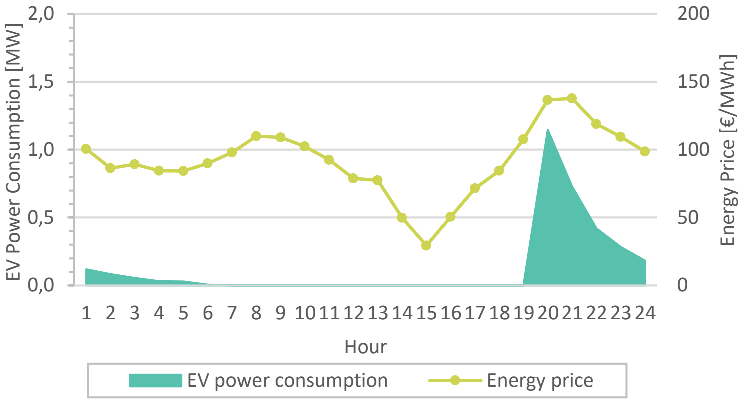


Figure 15 – EVs do not participate in any DR (BaU), Slovenian Case

In cases where EVs decide to participate in DR programs, minimizing charging costs and considering their comfort level, it can be observed that the highest power consumption by the EVs is managed to occur during the hours when prices are lowest (1h00–6h00), as shown in Figure 16 and Figure 17. In the case of Slovenia, there is a subtle variation in energy prices between 2h00 – 5h00, which impacts the EV charging management with the aim of minimizing charging costs. This is observed in Figure 16, which shows the DR that minimizes the total cost of energy, with the largest amount of consumption (1.14MW) by the EVs scheduled to occur at 5h00. For this case, the EV users would incur a total cost of 271.93 EUR, achieving a 29.70% reduction in their energy bill for that day, with a total energy scheduled for this day of 10.78MWh. In the case in which users' comfort is considered (Figure 17), to meet users' energy requirements more quickly, a greater amount of power consumption (0.73MW) is programmed to occur at 2h00. For this case, the EV users would incur a total cost of 275.71 EUR, achieving a 28.70% reduction in their energy bill, with a total energy consumed of 10.81MWh for that day. In the case of Slovenia, the minimization of peak power from both the aggregator's and users' perspectives keep the peak EV consumption below 1 MW, demonstrating a clear improvement in collaboration with the operator (Figure 18). In this scenario, users would pay a total bill of 273.04 EUR for that day, achieving a 30% discount, while consuming a total energy of 10.78MWh. From the EV users' perspective, the peak consumption also remains below 1 MW, specifically 0.78 MW at 5h00 when the energy price is lowest. In this case, users would incur a total cost of 278.05 EUR, obtaining a 28% discount, with a total energy scheduled for this day of 10.98MWh.

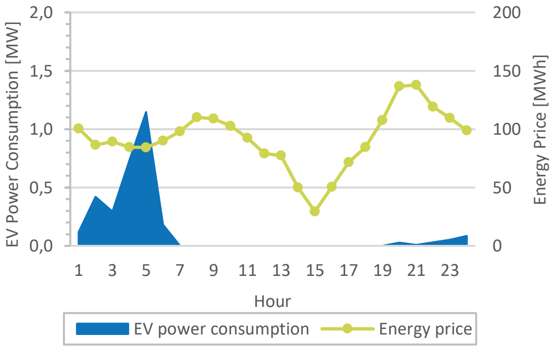


Figure 16 – EVs participate in RTP DR, Slovenian Case

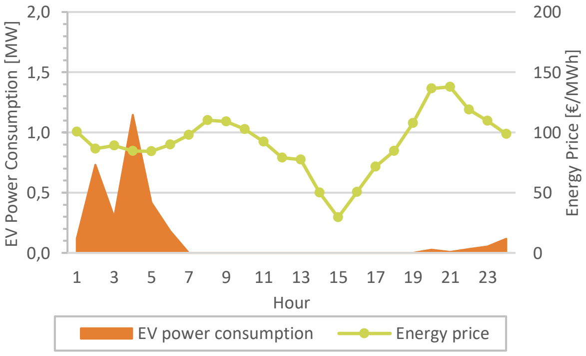


Figure 17 – EVs participate in RTP DR considering comfort level, Slovenian Case

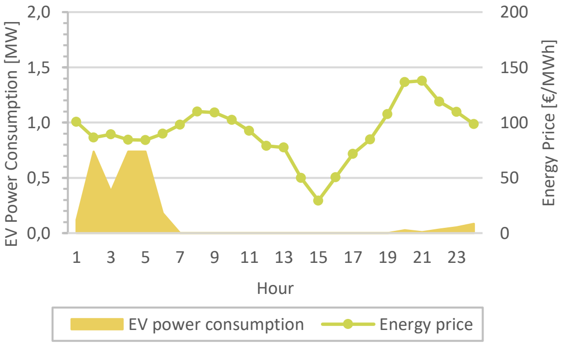


Figure 18 – EVs participate in ToU DR minimisation of peak power from aggregator point of view, Slovenian Case

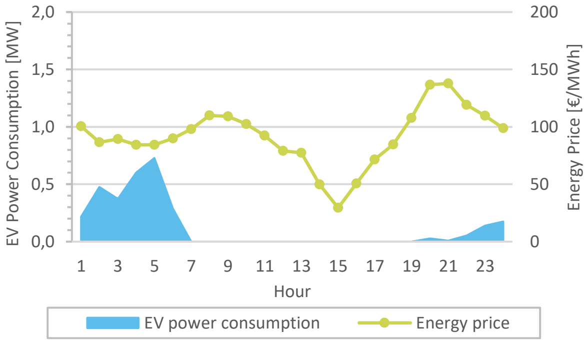


Figure 19 – EVs participate in ToU DR minimisation of peak power from each EV point of view, Slovenian Case

Table 5 summarizes the energy scheduled and the corresponding energy bills for EVs over the five days analysed in the Slovenian simulation case. In the BaU scenario (OF1), more energy is scheduled (19.54MWh) towards the end of the optimization horizon, resulting in a higher energy bill (2067.44 EUR) for EV users. Conversely, under the proposed DR programs, the same amount of energy is scheduled (16.76MWh), 14% less than the non-participant case, because of the EV smart charging management, thus leading to lower energy bills compared to the non-participating scenario. Specifically, in the Slovenian case, the RTP DR program is particularly cost-effective when the primary goal is to minimize the energy bill (OF3), yielding 38% discount for participants in this DR program. DR programs focusing on power limitations (OF4 and OF5), like in Greek and Portuguese case, are slightly more expensive than the OF3, by 1.36% and 3.49%, respectively.

Table 5: Summary of the energy scheduled, and cost related to the five days of simulation, Slovenian case

DR program	Energy (MWh)	Cost (€)
OF1	19.54	2067.44
OF2	16.76	1268.05
OF3	16.76	1269.88
OF4	16.76	1285.50
OF5	16.76	1313.78

A summary of the cost reduction percentage for each of the countries analysed in each DR program compared with the non-participant DR, considering the overall optimisation horizon, is shown in Table 6. As can be observed, there is a significant reduction in the energy bill for all cases, even when the system's peak power needs to be minimized (OF4 and OF5). It is also noticeable that the most beneficial scenario for Greek users is the one where the total energy cost is minimized (OF2), as this results in the highest discount for them, while for Portuguese and Slovenian cases both minimising DR programs without and with user comfort consideration are equally beneficial for them. When users participate in a DR program, such as OF5, the discount decreases for all three cases analysed. However, this reflects the impact of participating in a DR program that requires limiting the system's power.

Table 6: Cost reduction for each country (%)

DR program	Greece	Portugal	Slovenia
OF2	0.30	0.43	0.38
OF3	0.29	0.43	0.38
OF4	0.27	0.41	0.37
OF5	0.27	0.39	0.36

4.1.5 Main results for Real-Time Pricing Demand Response in Greece considering Vehicle-to-Grid

To validate the participation of EV users in a DR program that considers V2G functionality under RTP DR, the case of Greece is used for analysis, as shown in Figure 20– Figure 21. For this case, we analysed OF1, where no EV users participate in a DR program and an additional OF6, in which EVs participate in a DR program by minimizing the energy bill, while EVs can discharge the energy stored in their batteries. Due to the V2G option, it is necessary to include the costs associated with battery degradation in each OFs. Moreover, the operational constrains related to the EVs consider the technical components about the discharging process. Further details on the mathematical model for DR with V2G functionality can be found in [5]. Figure 20 shows the case where EVs do not participate in any DR program. In this case, the peak EV consumption (1.14MW) occurs at 20h00, hour in which the energy price is also the highest during this day. It is important to notice that even in the BaU strategy, when the V2G is activated, it is assumed that the EVs can use the V2X technology to satisfy the requirements of other EVs. This is why, some discharge can be observed in the Figure 20.

Regarding the V2G functionality, Figure 21 shows that after the EV power consumption is scheduled, the RTP DR program takes advantage of higher prices, during hours 21h00 and 22h00 to execute EV discharge. In this case the total EV discharging energy, at the end of the day, was 0.32MW. On the other hand, the total cost that EV users had to pay this day was 262.63 EUR, for a total energy consumption for this day of 3.08MWh.

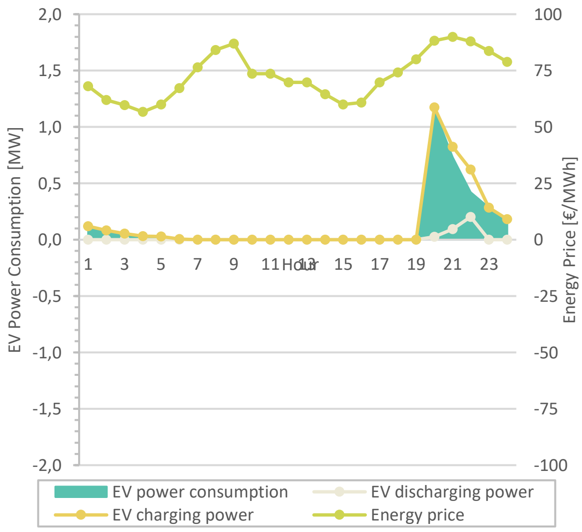


Figure 20 – EVs do not participate in any DR (BaU) considering V2G, Greece Case

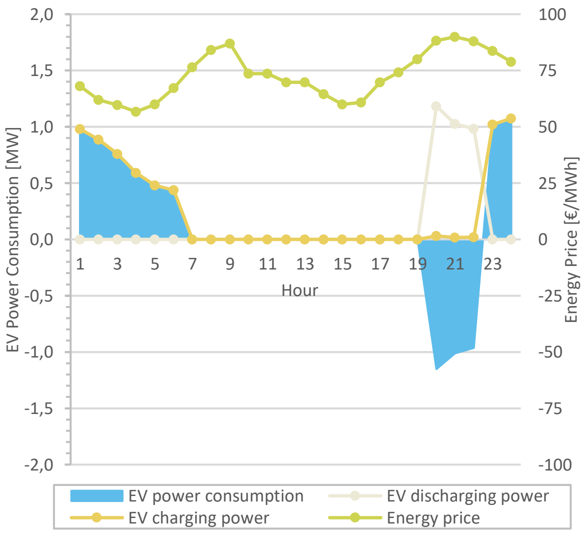


Figure 21 – EVs participate in RTP DR considering V2G, Greece Case

The participation of the EV users in a RTP DR for Greece by minimising energy cost and considering V2G is illustrated in Figure 20. In this scenario, the participation of EVs in the RTP DR program ensures better performance by optimizing EV charging power during low-price periods (1h00–7h00), as illustrated in Figure 21. Specifically, with V2G technology, the RTP DR program prioritizes EV charging, resulting in high consumption (0.98 MW) at 1h00, as it is necessary to charge the EVs before initiating discharge. Consequently, during higher-priced hours, the RTP DR with V2G increases EV discharging (with a peak discharging power of 1.15 MW) to maximize benefits. As a result, the total daily cost for EV users is 151.58 EUR, with a total energy consumption of 3.10MWh for this day. Compared to the participation of EV users in an RTP DR program without V2G consideration, the implementation of V2G in this case further enhances economic benefits. Specifically, the energy bills of EV users were reduced by an additional 14.28% (the case without V2G resulted in a total cost of 189 EUR), leading to a total reduction of 42.28%.

Table 7 summarizes the total energy consumption and cost over the five-day optimization period. It is evident that in the BaU scenario, more energy (19.54 MWh) is scheduled due to the lack of smart EV charging management, resulting in a total cost of 1404.84 EUR, which is 47% more expensive than the OF6 scenario. In the OF6 scenario, the energy discharge scheduled over the five days amounts to 16.07 MWh, achieving a total cost of 674.44 EUR.

Table 7: Summary of the energy scheduled, and cost related to the five days of simulation, Greek case considering V2G

DR program	Energy Charge (MWh)	Energy Discharge (MWh)	Total energy (MWh)	Cost (€)
OF1	21.11	1.57	19.54	1404.84
OF6	29.56	16.07	13.49	674,44

4.2 Application of Demand Response programs for Greece

4.2.1 Model assumptions for avoiding reverse power flow through Electric Vehicles

To analyse the performance of Greek DR program, i.e., avoiding reverse power flow through EVs, we processed a proprietary dataset with measurements from a specific MV/LV substation along with its 7 underlying LV feeders in May 2024, covering 21 days in total, with a data rate of 1 minute. The location of this substation is close to the Greek Demo region of the EV4EU project [34]. Regarding the input data used, the typical distance travelled in the Athens metropolitan area was set to 50km/day [35], while the average energy consumption per kilometer was set to 0.2kWh/km, representing an energy requirement of 10kWh/day, with an average power consumption per charging station of 5kW. The grid tariff considered was 0.1132€/kWh with a lower limit of 0€/kWh. It is noteworthy that the dataset for May 2024 did not show any instances of reverse power flow. To validate the proposed DR program, the lower limit for power flow was set at the minimum value observed across the dataset, considering all three phases. This minimum value was 14.78 kW in phase C, recorded on the seventh day of the 21 days analysed, as illustrated in Figure 22. The upper limit for power flow is 40kW.

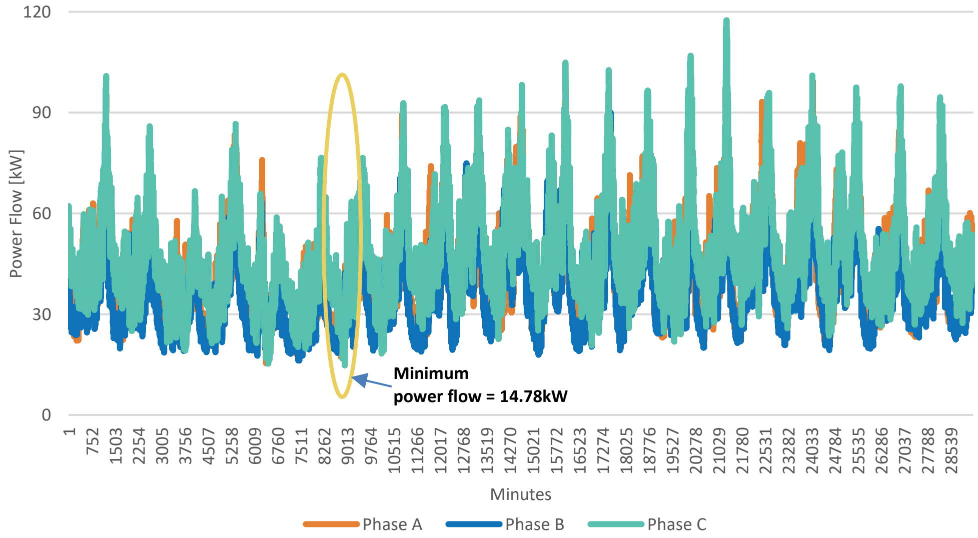


Figure 22 – Power Flow data for three phases, May 2024

4.2.2 Main results for avoiding reverse power flow through Electric Vehicles

The main results of this case are presented in Figure 23 – Figure 26. For the sake of simplicity, the results discussed pertain to a single day (the seventh day in this case study). Hence, Figures present data related to the power flow in phase C, the price signal offered to EV users to pay to participate in this DR program, and the grid tariff limit (0.1132€/kWh). For comparison of the price signals offered to the EV users, Figure 23 illustrates a baseline case considering a minimum power flow 0kW, as can be seen, the price signal decreases proportionally with the power flow, nevertheless, it never achieves the 0€/kWh. These prices change through the day due to the inclination of the curve defined by the limits of the power flow and grid tariff, as shown by Figure 1. For this baseline case, within hours 9h00–11h00 there is the most inclined price reduction, in which the price signals offered to the EV users are 0.0644€ by minute, 0.0474€ by minute, and 0.0418€ by minute. Conversely, Figure 30 presents the results for a scenario with a minimum power flow value of 14.78 kW for phase C. As observed, the price signal decreases as the power flow decreases and approaches the established minimum limit, eventually reaching 0€/kWh, for this case the price signals offered to the EV users are 0.0358€ by minute, 0.008€ by minute, and 0€ by minute. Additionally, the figure shows that the price signals remain constant for power flows above 40 kW between 19h00 and 24h00, this behaviour occurs because the DR program incentivizes EV charging by offering discounts on price signals for low power flow values.

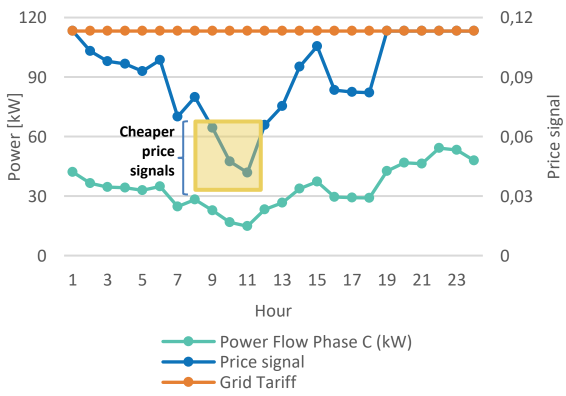


Figure 23 – Price signals without lower limit achieved, baseline case

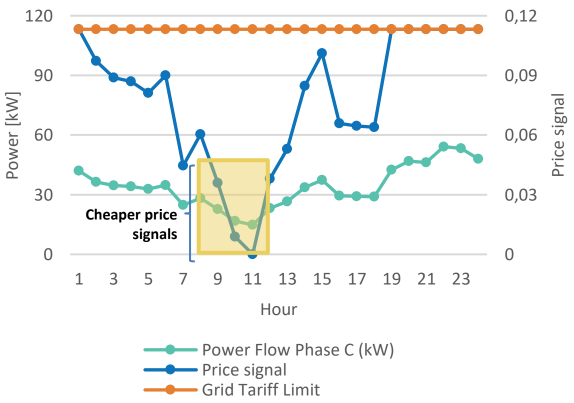


Figure 24 – Price signals with lower limit achieved

To evaluate the benefits for EV users participating in this DR program, it is necessary to analyse their usage behaviour. Given an energy requirement of 10 kWh/day and charging at 5 kW, it would take approximately 2 hours (120 minutes) to fully charge their batteries. Therefore, in the baseline case, considering the cheaper price signals, for a user arriving at 9h00 (see Figure 23) and due to the average power consumption in a charging station (CS) of 5W charging during 120 minutes, the price at 9h00 is 0.00536€, 0.00395€ at 10h00, and 0.00348€ at 11h. Therefore, this EV user must pay optimal tariffs (less than the regular tariff), for fully charge its battery, 0.73€ starting the charging at 9h00, 0.74 starting at 10h00, and 0.95€ starting at 11h00. Moreover, the grid tariff limit (0.1132€/kWh) is used as baseline to calculate the maximum value that a typical user must pay, for this case, an energy requirement of 10kWh/day, represent a maximum value of 1.132€. Therefore, due to their participation in this DR program, EV users receive 35%, 34%, and 15% discounts during the cheaper price signal hours, as illustrated in Figure 25. On the other hand, Figure 26 illustrates the benefits for EV users participating in this DR program for a minimum of 14.7 kW, as can be seen, incremented the minimum value for power flow, cheaper price signals are offered to the EV users as shown in Figure 24. Hence, in the Athens case, considering the cheaper price signals, for a user arriving at 9h00 (see Figure 24) and due to the average power consumption in a CS of 5W charging during 120 minutes, the price at 9h00 is 0.00291€, 0.00073€ at 10h00, and 0€ at 11h. Therefore, this EV user must pay 0.50€ starting the charging at 9h00, 0.51€ starting at 10h00, and 0.85€ starting at 11h00. Therefore, due to their participation in this DR program, considering the maximum value to pay, this EV user receives 56%, 55%, and 25% discounts during the cheaper price signal hours, as illustrated in Figure 26. Hence, by comparing the discounts of two cases, the case considering 14.78kW as minimum power flow represents improvement of 21% at 9h00, 21% at 10h00, and 10% at hour 11h00.

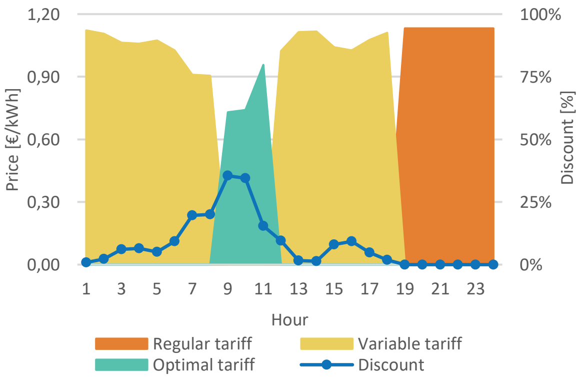


Figure 25 – Tariff to pay and discount, baseline case

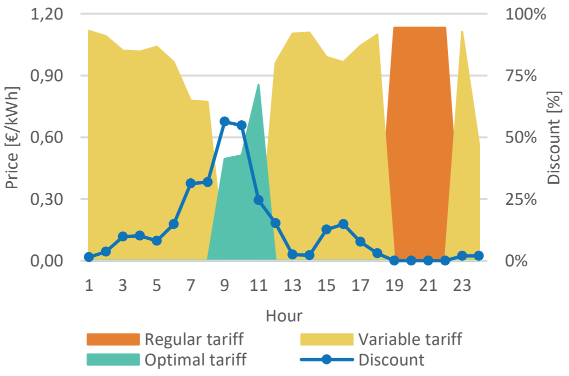


Figure 26 – Tariff to pay and discount, with lower limit achieved, 50km

4.3 Application of Demand Response Programs for Portugal

4.3.1 Model assumptions for new Time-of-Use tariffs

To create the new ToU tariff through the mathematical model proposed in subsection 3.2.1 New Time-of-Use Demand Response Program for the case without EV profiles, expression (1) used the average energy prices for each season based on historical data from [32]. As a result, four new ToU tariff curves were obtained for each season, as shown in Figure 27 (a)–(b). These new ToU tariff curves feature four price levels (representing a tetra-hourly tariff) that align with the typical average curves used.

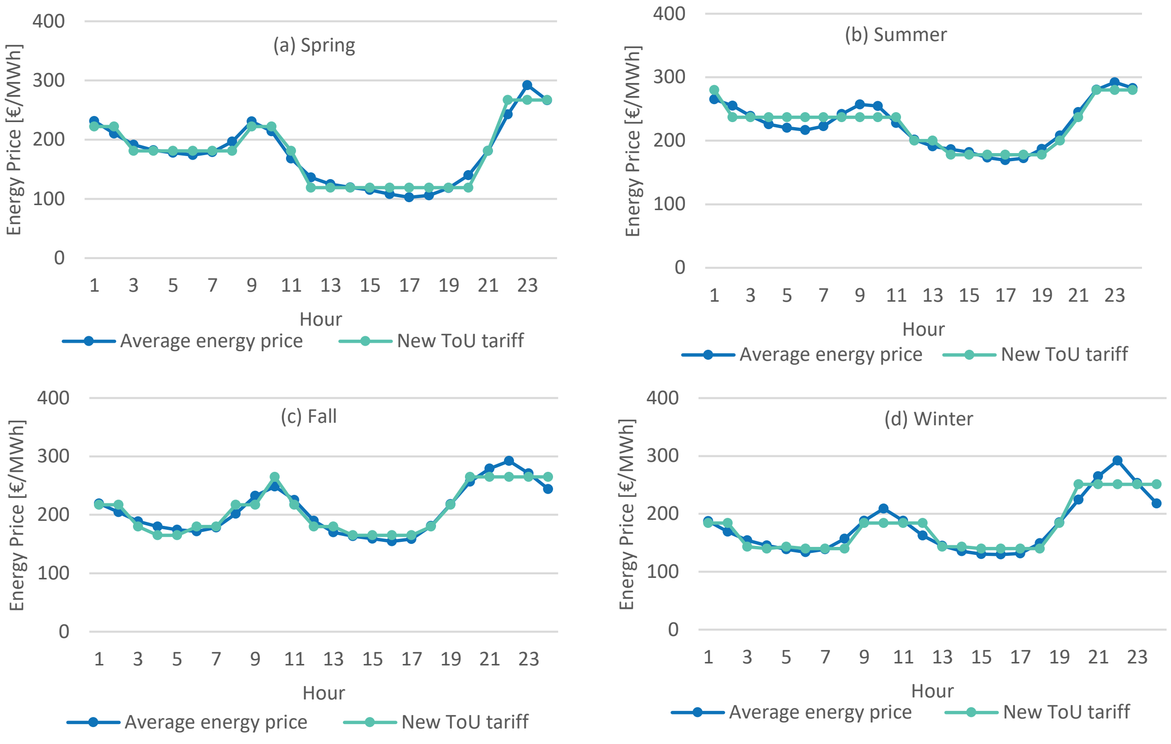


Figure 27 – Energy price comparison for the four seasons without EV profiles consideration

On the other hand, for the case of expression (2), the EV charging profiles were obtained using clustering methods on the *Greek dataset*, an updated version of the data provided by the PPC partners and reviewed in Deliverable 3.3 [4]. This dataset contains real information collected from public EV chargers across Greece, including 657 EVSEs and approximately 100,000 charging sessions from June 24, 2021, to September 30, 2023. The original charging event format (1 row of the dataset, 1 EVSE transaction) was incompatible with the temporal analysis needed for this deliverable. Therefore, after preprocessing the dataset (cleaning outliers, addressing missing data, and normalizing the data), it was necessary to convert the data into a time-series format. Once the data was transformed and grouped by season, the K-means clustering algorithm with the Dynamic Time Warping distance metric [36] was employed on each group to obtain several clusters. The EV profiles presented in Figure 28 were selected based on the resulting clusters; they aim to represent the most typical behaviour for each season. It is important to highlight that the EV profile data was normalized to align with the price values, where the peak value is 0.2922 €/MWh, as shown by Figure 28. Consequently, for each season, the highest EV charging rate is also 0.2922 without units, is only a factor and indicating that the CS are operating at their maximum power capacity for the EV, in which is possible to validate that for Spring, Autumn and Winter seasons are the most EV charging events into the CS. The new tariffs created for each season demonstrate an attenuation of the ToU tariff when the consumption profile of the cars remains stable, as seen during the hours of 11h00–13h00 in spring, 11h00 and 12h00 in Autumn, and 21h00–23h00 in summer. However, when there is a sudden change in the consumption profile of the cars, the energy tariff also changes with a certain volatility, as observed at 16h00 in autumn and 9h00 in winter.

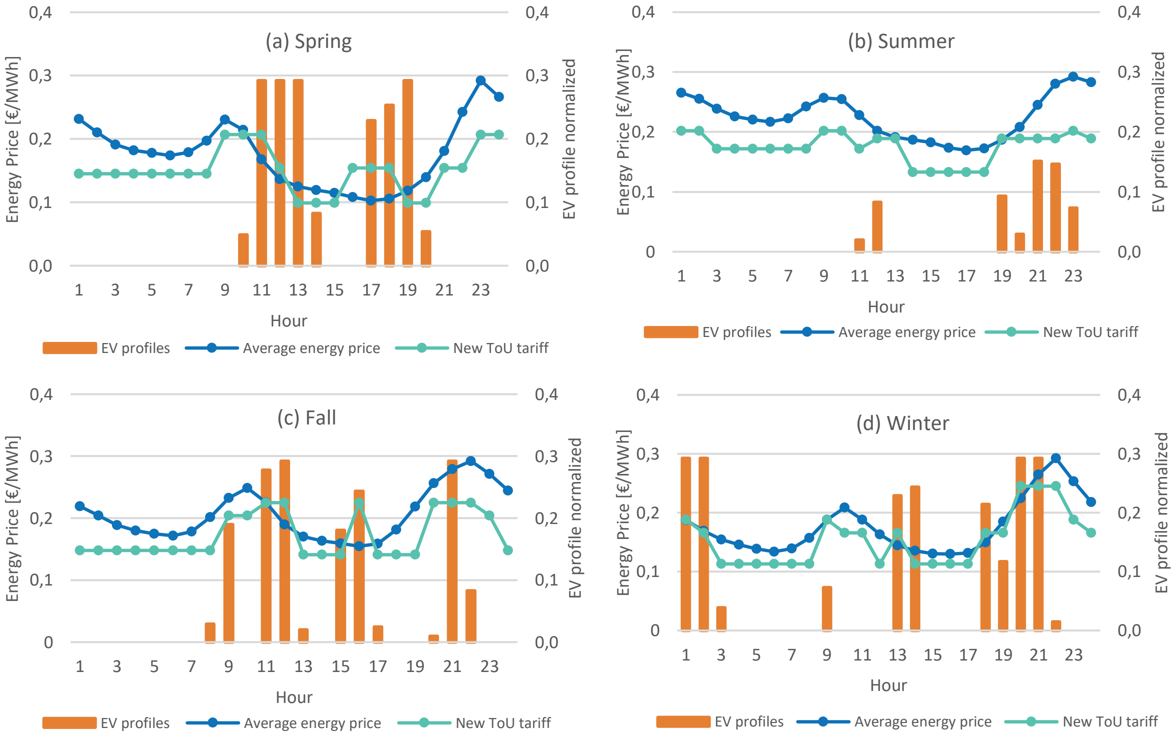


Figure 28 – Energy price comparison for the four seasons considering the EV profiles

The details associated with the new tariffs, for both cases with and without EV profiles, obtained and the hours during which they are activated, applying the model described in Section 3.2.1, can be analysed in Table 8 – Table 11.

Table 8: New ToU tariff for Portugal – Spring

Tariff type	No EV profiles		With EV profiles	
	Time Intervals	Electricity Price (€/MWh)	Time Intervals	Electricity Price (€/MWh)
Off – Peak	12h – 20h	119	13h – 15h; 19h – 20h	99
Partial – Peak	3h – 8h; 21h	181	1h – 8h	145
Peak	1h – 2h; 9h – 10h	222	12h; 16h – 18h;21h – 22h	154
Super Peak	22h – 24h	267	9h – 11h; 23h – 24h	207

Table 9: New ToU tariff for Portugal – Summer

Tariff type	No EV profiles		With EV profiles	
	Time Intervals	Electricity Price (€/MWh)	Time Intervals	Electricity Price (€/MWh)
Off – Peak	12h – 20h	178	14h – 18h	133
Partial – Peak	3h – 8h; 21h	200	3h – 8h; 11h	172
Peak	1h – 2h; 9h – 10h	237	12h – 13h; 19h – 22h; 24h	189
Super Peak	22h – 24h	280	1h – 2h; 9h – 10h; 23h	202

Table 10: New ToU tariff for Portugal – Autumn

Tariff type	No EV profiles		With EV profiles	
	Time Intervals	Electricity Price (€/MWh)	Time Intervals	Electricity Price (€/MWh)
Off – Peak	12h – 20h	165	13h – 15h; 17h – 19h;	141
Partial – Peak	3h – 8h; 21h	180	1h – 8h; 24h	148
Peak	1h – 2h; 9h – 10h	217	9h – 10h; 23h	204
Super Peak	22h – 24h	265	11h – 12h; 16h; 20h – 22h	225

Table 11: New ToU tariff for Portugal with no EV profiles – Winter

Tariff type	No EV profiles		With EV profiles	
	Time Intervals	Electricity Price (€/MWh)	Time Intervals	Electricity Price (€/MWh)
Off – Peak	12h – 20h	140	3h – 8h; 12h; 14h – 17h;	113
Partial – Peak	3h – 8h; 21h	143	2h; 10h – 11h; 13h; 14h – 17h	166
Peak	1h – 2h; 9h – 10h	184	1h; 9h; 23h	188
Super Peak	22h – 24h	251	20h – 22h	245

For the analyse of the performance of the New ToU DR program was considered also the five OFs evaluated for the case of the RTP DR program, that represent the non-participation of the EV users in any DR program (BaU) method (OF1), the participation of the EV users in an implicit DR program by minimising the energy bill (OF2), the participation of the EV users in an implicit DR program by minimizing the energy bill and considering the EV comfort level (OF3), the participation of the EV users in DR program by minimizing the peak power from an aggregator point of view (OF4), and the participation of the EV users in a DR program by minimizing the peak power from each EV point of view (OF5). Moreover, to analyse the impact of each ToU DR program applied, the 200 residential EV user's population was classified aiming to 20% of the total users participate or not in the DR program offered, i.e., was created five groups of EV users, this to follow a more realistic scenario. Table 12 shown the details about the percentage of EV users' participation by Objective Functions participation.

Table 12: Percentage of EV users' participation by Objective Functions participation

Scenarios	DR
1	OF1 – 20% of EVs do not participate in any DR (BaU)
2	OF2 - 20% of EVs participate in a DR program by minimizing the energy bill
3	OF3 - 20% of EVs participate in a DR program by minimizing the energy bill and considering the EV user comfort level
4	OF4 – 20% of EVs participate in a DR program by minimizing the peak power from aggregator point of view
5	OF5 - 20% of EVs participate in a DR program by minimizing the peak power from each EV point of view

4.3.2 Main results for New Time-of-Use Demand Response Program for Portugal

The results about the Autumn season, for the New ToU DR with no EV profiles, are shown in Figure 29 – Figure 33, similar results were observed for the other three seasons. In the case of OF1, under the New ToU tetra-hourly tariff without any EV profiles created for Portugal, the peak EV consumption (0.24 MW) occurs at 20h00 during the super peak tariff period. The highest power energy consumption, reaching 0.64 MWh, is also observed during the super peak tariff period, specifically between 20h00 – 24h00. Due to their lack of participation in any DR program during this operational day, these 40 EVs users incurred a total cost of 179.00€ for consuming 0.68 MWh of energy. Moreover, over the five simulated days of operation, this group demanded a total of 4.08 MWh of energy.

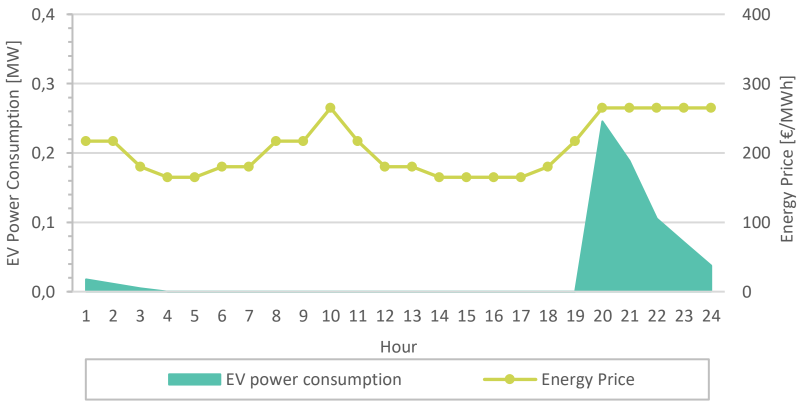


Figure 29 – 20% of EVs not participating in any DR (BaU), Autumn season

For EV users participating in ToU DR programs, results are shown Figure 30 – Figure 33. Those in the cost-minimizing DR program achieved a total cost of 156€, 13% cheaper than non-participants. Comparing with the non-participating group, during the super peak tariffs (23h00 – 24h00) the energy consumption is 0.11MW, with the peak EV consumption (0.23MW) at 5h00 the off-peak tariff. For users who chose to participate in the DR program and considering their comfort level, see Figure 31, the total consumption during the hours with the off-peak and partial peak tariffs was 0.47MW, with a total daily energy consumption of 0.58 MWh, incurring in a cost for this day of 104.34€, which is 42% cheaper than for users who did not participate in any DR program. In this case, it is important to note that the DR program takes advantage of the off-peak tariff at 4h00 to reach the required energy level as quickly as possible, balancing economic cost with the comfort provided to the user. For these two groups of EVs the total energy consumption for the five days of operation simulated were 4.06 MWh and 3.10 MWh, respectively.

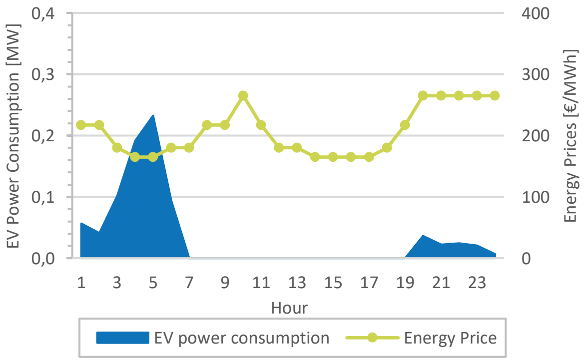


Figure 30 – 20% of EVs participate in ToU DR, Autumn season

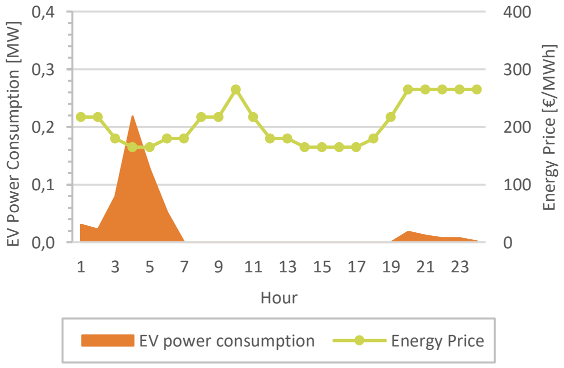


Figure 31 – 20% of EVs participate in ToU DR considering comfort level, Autumn season

In the case of users who decided to participate in DR programs, the results can be analysed in Figure 32 – Figure 33. In the scenario where power is limited from the aggregator's perspective, less energy is managed, totalling 0.33MWh during the off-peak and partial tariffs, resulting in a total daily consumption of 0.37 MWh, with an energy cost of 65.76€, 63.27% cheaper than the OF1. Conversely, from the users' perspective, a total of 0.63MWh was scheduled at a cost of 114.3€, 36.15% cheaper than the OF1. These results highlight the performance of these DR programs, which, when focused on the system, minimize power but still meet the users' required energy levels. For these two groups of EVs the total energy consumption for the five days of operation simulated were 2.31 MWh and 3.85 MWh, respectively.

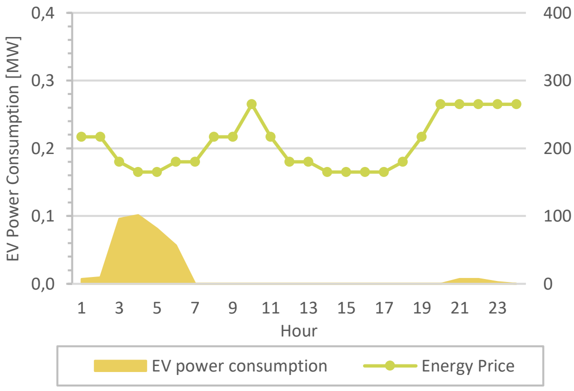


Figure 32 – 20% of EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

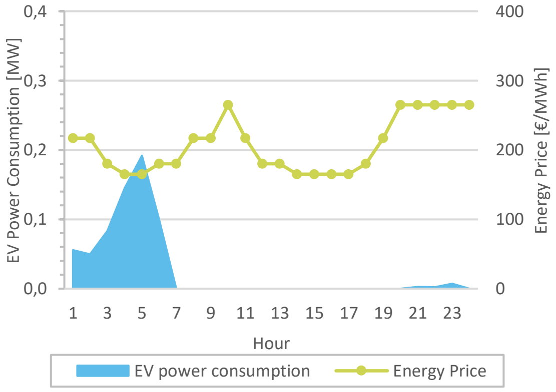


Figure 33 – 20% of EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

Table 13 illustrates a summary of the energy scheduled and cost for the four seasons for the New ToU tariff applied in Portugal considering the five operation days. As can be observed, each group of EVs consumes different levels of energy due to varying usage behaviours within each subcategory. This variation renders the comparison of economic benefits between the groups inapplicable. However, it can be validated that, for all seasons, the group participating in OF4 incurs the lowest costs under the newly proposed tariff. This confirms that the DR program, which collaborates with the energy system, ensures better costs for users

Table 13: Summary of the energy scheduled, and cost related to the five days of simulation for New ToU per season

DR program	Spring		Summer		Autumn		Winter	
	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)
OF1 (Group 1)	4.08	777.44	4.08	980.92	4.08	1027.28	4.08	953.85
OF2 (Group 2)	4.06	703.51	4.06	940.42	4.06	753.06	4.06	640.93
OF3 (Group 3)	3.10	521.04	3.10	709.05	3.10	556.41	3.10	469.10
OF4 (Group 4)	2.31	415.16	2.31	544.62	2.31	419.66	2.31	347.74
OF5 (Group 5)	3.85	666.96	3.85	893.39	3.85	698.44	3.85	581.81

Aiming to validate the performance of the DR programs attending the energy required by all 200 EVs participating in this DR program, Figure 34 – Figure 38 show the energy scheduled for the third day of each OF in the Autumn season, in each Figure is possible to observe the same energy scheduled for this operation day (same area for all), in which a total energy of 3.09MWh, in each OFs, was managed.

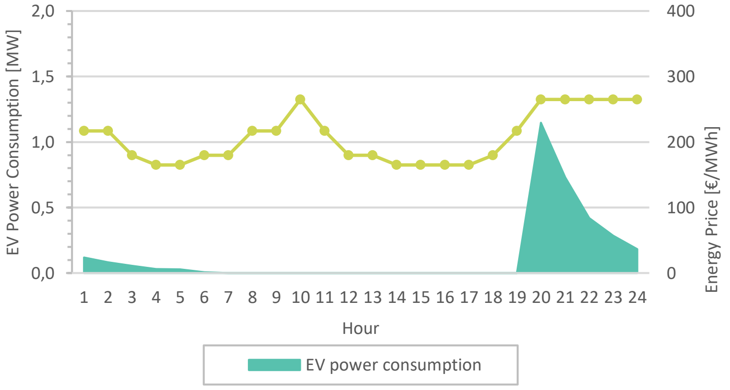


Figure 34 – All EVs do not participate in any DR (BaU), Autumn season

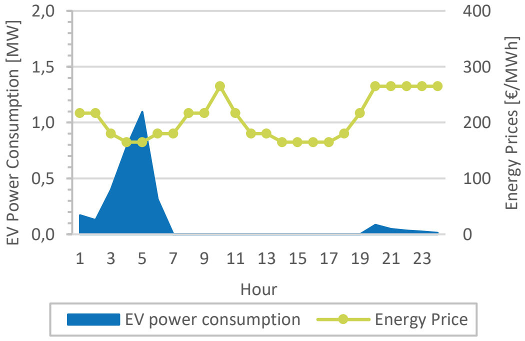


Figure 35 – All EVs participate in ToU DR, Autumn season

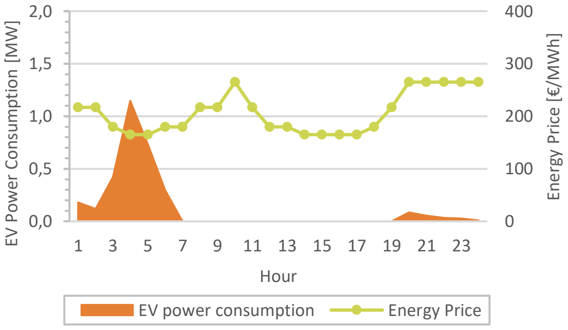


Figure 36 – All EVs participate in ToU DR considering comfort level, Autumn season

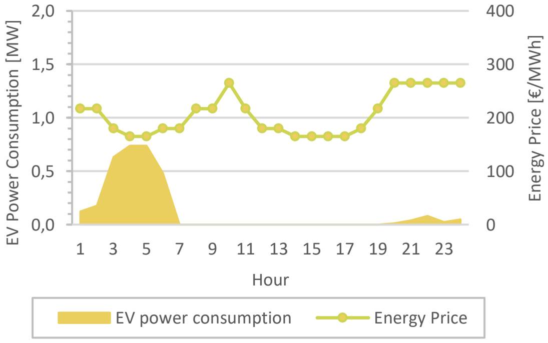


Figure 37 – All EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

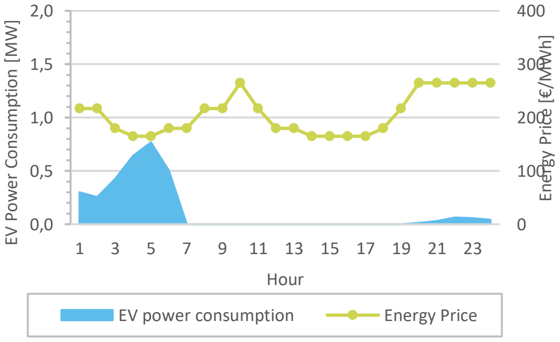


Figure 38 – All EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

4.3.3 Main results for new Time-of-Use Demand Response Program for Portugal considering Electric Vehicle profiles.

The results about the Autumn season, for the New ToU DR with EV profiles, are shown in Figure 39 – Figure 43, similar results were observed for the other three seasons and are omitted for brevity. Like the case without considering EV profiles, for this EV group, peak EV consumption (0.24 MW) in OF1 occurs at 20h00 during the peak tariff period. However, during the super peak tariff period (20h00 – 23h00), 0.53 MWh of energy was scheduled, which is 0.11 MWh less than in the scenario without EV profiles consideration. Due to their nonparticipation in any DR program during the day, these 40 EV users incur a total cost of 146.44€, which is 18% cheaper than the case without EV profiles consideration, consuming a total energy for this day equivalent to 0.68MWh. Therefore, with less energy scheduled during the super peak tariff and a reduced energy bill, it is confirmed that a new tariff considering

EV profiles is advantageous for EV users, even those not participating in any DR program. Moreover, over the five simulated days of operation, this group demanded a total of 4.08 MWh of energy.

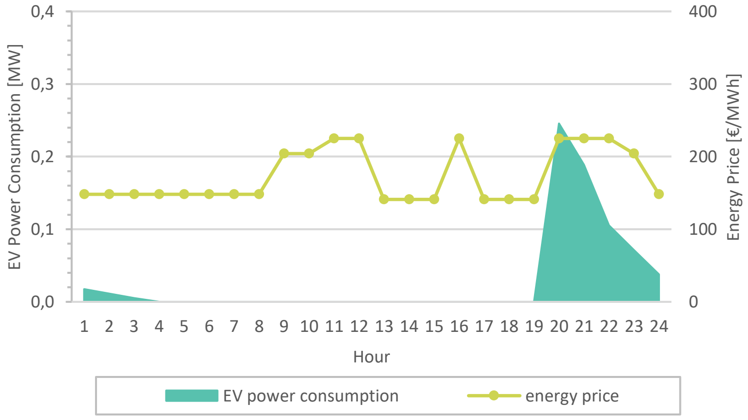


Figure 39 – 20% of EVs do not participate in any DR (BaU), Autumn season

The outcomes for EV users participating in ToU DR programs are illustrated in Figure 40 – Figure 43. Participants in the cost-minimizing DR program incurred a total cost of 128.31€, with a total energy consumption of 0.83MWh, 0.15MWh more than OF1. Nevertheless, the higher quantity of energy was scheduled at off peak tariff, with peak EV consumption (0.23 MW) occurring at 3h00 during the off-peak tariff period. For users who chose to participate in the DR program and considering their comfort level, as shown in Figure 41, the total consumption during off peak tariff hours was 0.32MWh. The total cost for this day was 87.08€. Importantly, this DR program takes advantage of the off-peak tariff at 3h00 to quickly reach the necessary energy level, balancing cost efficiency with user comfort. For these two groups of EVs the total energy consumption for the five days of operation simulated were 4.06 MWh and 3.10 MWh, respectively.

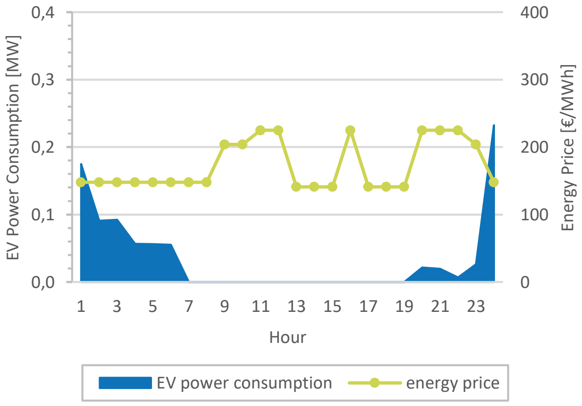


Figure 40 – 20% of EVs participate in ToU DR, Autumn season

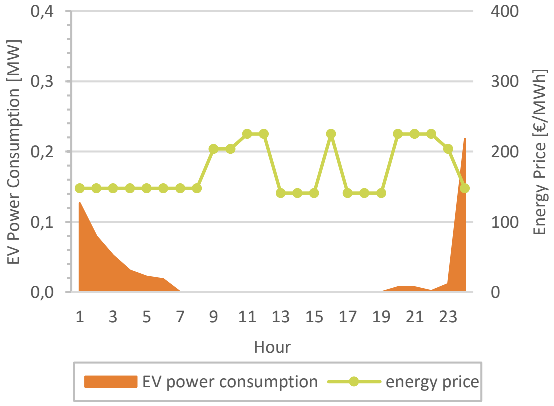


Figure 41 – 20% of EVs participate in ToU DR considering comfort level, Autumn season

For users who opted to participate in DR programs, the results can be examined in Figure 42 and Figure 43. In the scenario where power is limited from the aggregator's perspective, less energy is managed, amounting to 0.37 MWh during the off-peak tariff, resulting in an energy cost of 56.87€, with a total energy consumption of 0.38 MWh for this day. Conversely, from the users' perspective, a total of 0.64MWh was scheduled at a cost of 94.92€. These results demonstrate the effectiveness of these DR programs, which, when focused on the system, minimize power usage while still meeting the users' required energy levels. For these two groups of EVs the total energy consumption for the five days of operation simulated were 2.31 MWh and 3.85 MWh, respectively.

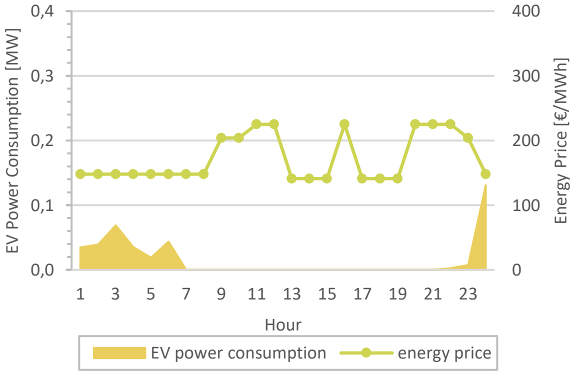


Figure 42 – 20% of EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

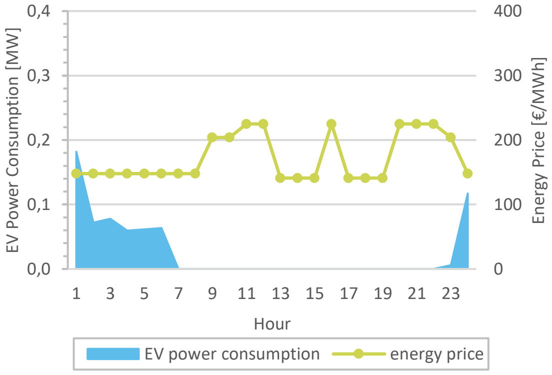


Figure 43 – 20% of EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

Table 14 illustrates a summary of the energy scheduled and cost for the four seasons for the New ToU tariff applied in Portugal considering the five operation days and EV profiles. As can be seen, each group of EVs consumes different levels of energy due to varying usage behaviours within each subcategory, for each group equal to case with EV profiles (see Table 13). This variation renders the comparison of economic benefits between the groups inapplicable. Moreover, like in case without EV profiles, it can be validated that, for all seasons, the group participating in OF4 incurs the lowest costs under the newly proposed tariff.

Table 14: Summary of the energy scheduled, and cost related to the five days of simulation for New ToU considering EV profiles

DR program	Spring		Summer		Autumn		Winter	
	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)
OF1 (Group 1)	4.08	581.52	4.08	778.91	4.08	829.96	4.08	888.66
OF2 (Group 2)	4.06	551.68	4.06	717.30	4.06	621.99	4.06	527.16
OF3 (Group 3)	3.10	413.52	3.10	543.57	3.10	467.06	3.10	382.37
OF4 (Group 4)	2.31	322.15	2.31	408.71	2.31	344.07	2.31	294.84
OF5 (Group 5)	3.85	524.25	3.85	684.14	3.85	570.54	3.85	480.16

Aiming to compare the economic benefit for each EV group participating in the new ToU DR programs without and with EV profiles, Table 15 summarizes the energy scheduled and cost for the Autumn season. As can be observed, each group have the same total energy scheduled, in which the new DR program considering the EV profiles is the more affordable for the EV users, for instance, for group 4, this DR program is 19% cheaper than the DR program without EV profiles consideration.

Table 15: Comparison of the energy scheduled, and cost related to the five days of simulation for New ToU without and with EV profiles, Autumn season

DR	Without EV profiles		With EV profiles	
	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)
OF1 (Group 1)	4.08	1027.28	4.08	829.96
OF2 (Group 2)	4.06	753.06	4.06	621.99
OF3 (Group 3)	3.10	556.41	3.10	467.06
OF4 (Group 4)	2.31	419.66	2.31	344.07
OF5 (Group 5)	3.85	698.44	3.85	570.54

Table 16 summarizes the total cost for one day of operation for each OF, considering the New ToU tariff both without and with EV profiles. These results validate the effectiveness of the new ToU tariff designed specifically for EV users, as all OF scenarios across the four seasons are more affordable, even for EV users who do not participate in any DR programs (OF1).

Table 16: Total cost for each OF with no EV profiles and with EV profiles consideration (€)

DR	Spring		Summer		Autumn		Winter	
	No EV profiles	With EV profiles	No EV pro-files	With EV profiles	No EV profiles	With EV profiles	No EV profiles	With EV profiles
OF1	127.77	96.96	162.47	130.08	178.90	146.44	168.69	157.49
OF2	143.00	110.97	191.76	146.55	155.81	128.31	133.18	110.86
OF3	92.00	74.04	129.20	101.62	104.35	87.07	88.00	72.37
OF4	64.00	50.28	82.36	63.74	65.76	56.87	54.79	43.68
OF5	104.00	84.13	147.09	111.26	114.29	94.92	95.48	75.89

Similar to the new ToU DR program without EV profiles, the performance of the DR programs attending the energy required by all 200 EVs participating in this DR program is validated by Figure 44**Figure 34** – Figure 48, in which is possible to observe the same energy scheduled for this operation day (same area for all), in which a total energy of 3.09MWh, in each OFs, was managed.

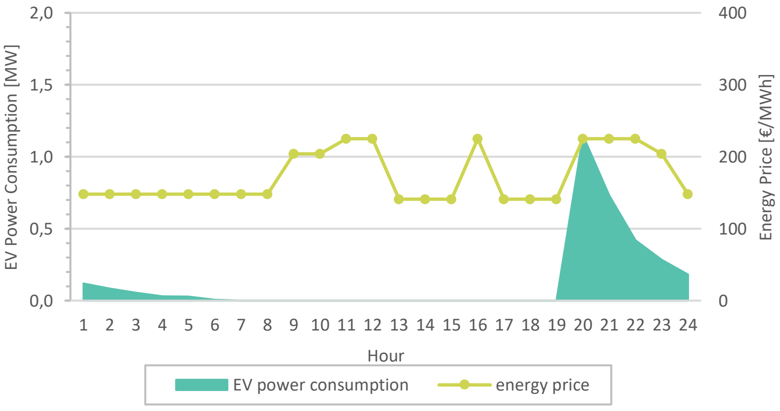


Figure 44 – All EVs do not participate in any DR (BaU), Autumn season

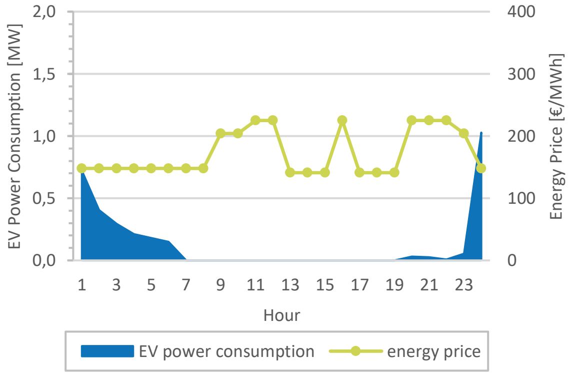


Figure 45 – All EVs participate in ToU DR, Autumn season

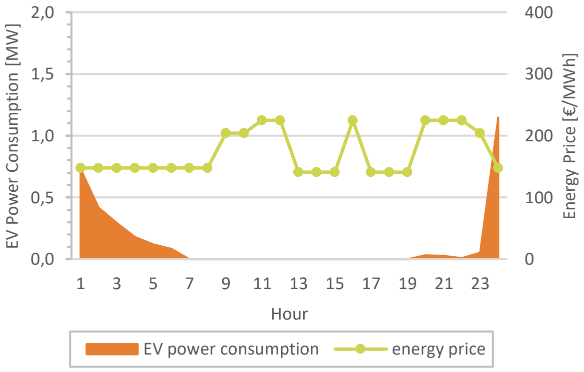


Figure 46 – All EVs participate in ToU DR considering comfort level, Autumn season

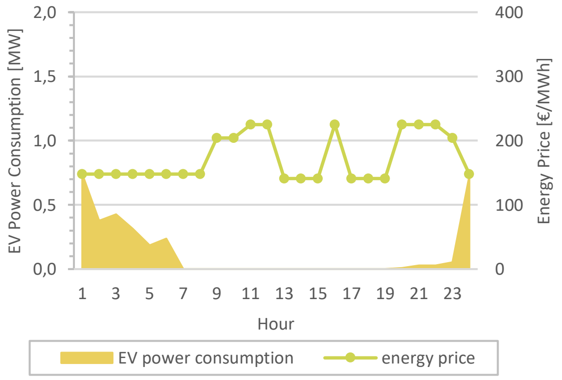


Figure 47 – All EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

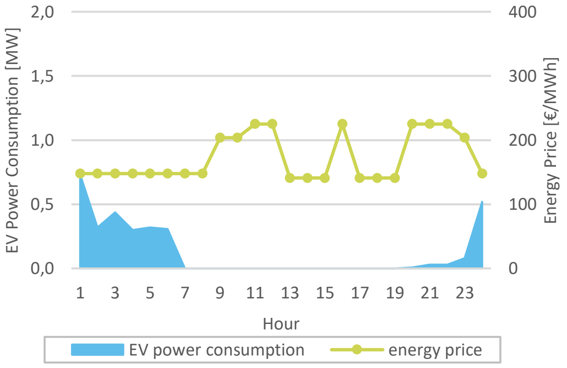


Figure 48 – All EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

Table 17 represents the total cost for each OF in the third day for the new ToU DR program without and with EV profiles, in the Autumn season. Hence, it is possible to observe that considering the EV profiles, in all cases, the price decrease.

Table 17: Total cost for each OF with no EV profiles and with EV profiles consideration for total population (€).

DR	Autumn	
	No EV profiles	With EV profiles
OF1	797.68	650.11
OF2	557.46	468.11
OF3	557.46	466.03
OF4	563.48	469.72
OF5	573,92	465.41

4.3.4 Main results for New Time-of-Use Demand Response Program for Portugal considering Electric Vehicles profiles and Vehicle-to-Everything.

The participation of the EV users in a DR program with V2G functionality, under the new ToU tariff, considering EV profiles in Portugal for the Autumn season, is illustrated in Figure 49 and Figure 50.
This analysis compares OF1, where no EV users participate in a DR program, with OF6. OF6 is similar to OF2 but includes EVs participating in an implicit DR program by minimizing the energy bill and allowing EVs to discharge the energy stored in their batteries. Furthermore, to analyse the impact of the two applied OFs, we consider the first two groups of EVs presented in Table 12, each comprising 40 EV participants. This analysis aims to compare these groups with the scenario lacking V2G availability, as discussed in Subsection 4.3.3. Figure 49 shows the EVs nonparticipation in any DR program, in this case the peak EV consumption (0.24 MW) occurs at 20h00 at super peak tariff. Regarding the V2G functionality, it is possible to observed that after the EV power consumption be scheduled, the ToU DR program takes advantage of higher prices, during hours 21h00 and 22h00 to execute EV discharge, in this case the total EV discharging energy, at the end of the day, was 0.11MWh. On the other hand, the total cost that EV users had to pay was 146.45€, for a total energy consumption for this day of 0.68MWh.

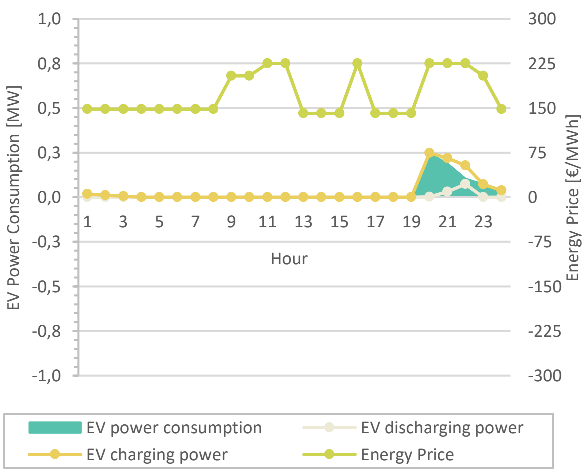


Figure 49 – EVs do not participate in any DR (BaU) considering V2G, Autumn season

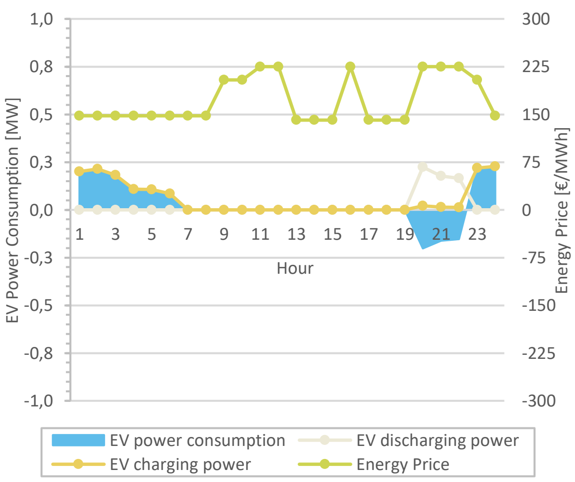


Figure 50 – EVs participating in ToU considering V2G, Autumn season

The participation of the EV users in a ToU DR considering V2G for Portugal is illustrated in Figure 50. In this scenario, the participation of EVs in the ToU DR program ensures better performance by optimizing EV charging power at the beginning of the day (1h00–7h00), as illustrated in Figure 50. Specifically, with V2G technology, the ToU DR program prioritizes EV charging, resulting in high consumption (0.20 MW) at 1h00, as it is necessary to charge the EVs before initiating discharge. Consequently, during higher-priced hours, the ToU DR with V2G increases EV discharging (with a peak discharging power of 0.22 MW) to maximize benefits. As a result, the total energy charging for this day was 1.39MWh, the total energy discharging was 0.57MWh having a total energy consumption of 0.82MWh, totalising an energy cost for this operation day of 94.20€. Compared to the participation of EV users in the new ToU DR program considering EV profiles without V2G consideration, the V2G availability offers an energy bill 26.60% cheaper than the case without V2G (total energy daily price of 128.31€ for 0.82MWh of energy consumption).
To validate the performance of these DR programs in meeting the energy requirements of all 200 participating EVs, Figure 51 and Figure 52 show the energy scheduled for the third day of operation. It is possible to observe the same energy consumption scheduled in each OF, totaling 3.09MWh (considering both charge and discharge energy), which was managed effectively.

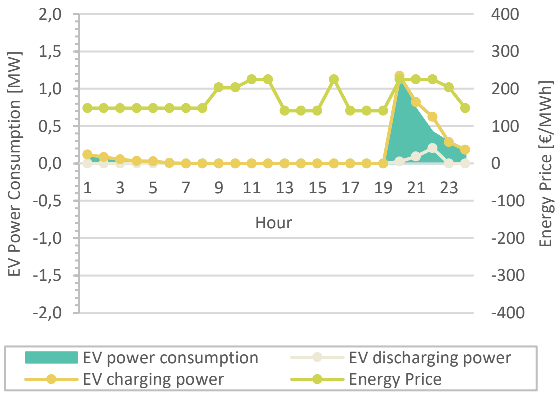


Figure 51 – EVs do not participate in any DR (BaU) considering V2G, Autumn season

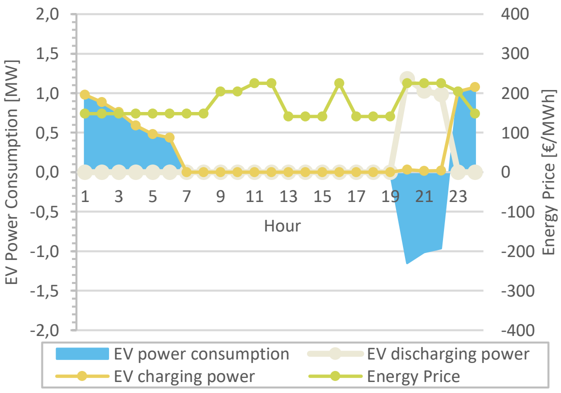


Figure 52 – EVs participating in any DR (BaU) considering V2G, Autumn season

4.3.5 Model assumptions for actual Time-of-Use Demand Response Program for Portugal

A benchmark case considering the actual ToU (winter season) implemented in Portugal is discussed below mainly because was used to create the deferred ToU tariffs. ToU tariff data was gathered from *Electricidade dos Açores’ (*EDA) current electricity price list and the daily and weekly market updates from the Portuguese energy regulatory authority, *Entidade Reguladora dos Serviços Energéticos* (ERSE) [37], these tariffs are detailed in Table 18.

Table 18: Actual ToU tariff implemented in Portugal (winter season).

Tariff type	Time Intervals	Electricity Price (€/kWh)
Off – Peak	3h – 6h	0.1255
Partial – Peak	1h – 2h; 7h – 8h; 21h – 24h	0.1363
Peak	17h – 20h	0.2315
Super Peak	9h – 16h	0.2922

For the analyse of the performance of the actual ToU DR program was considered also the five OF and the same percentage of EV users’ participation shown in Table 12.

4.3.6 Main results for Actual Time-of-Use Demand Response Program for Portugal

The main results for the actual ToU DR program, considering the winter season, are shown in Figure 53 – Figure 57. For the case of OF1, considering the actual tetra-hourly tariff in Portugal, it is noticeable an improvement even for EVs that did not choose to participate in any DR program. This is due to the inherent structure of the price curve, where the highest price occurs at times when there is not the peak EV power consumption. In this case, the peak of EV consumption (0.24MW) was concentrated at 20h00. Moreover, for this operation day, the cost for these 40 EVs was 116.26 €, for a daily total energy consumption of 0.68MWh.

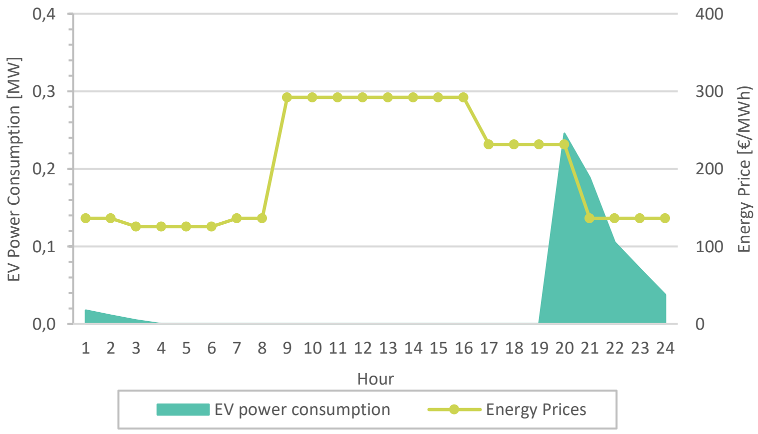


Figure 53 – 20% of EVs do not participate in any DR (BaU), winter season

For EV users in DR programs under actual ToU prices, results are shown in Figure 54 – Figure 55. Those in the cost-minimizing DR program achieved a total daily energy consumption of 0.82MWh with a total cost of 106€, 9% cheaper than non-participants. Regarding the energy consumption, for this group was scheduled a total of 0.62MWh during off-peak tariff (from 3h00 to 6h00) and partial tariffs showing that stable prices allow EV users to charge more energy at competitive rates. For users who chose to participate in the DR program and considering their comfort level, see Figure 55, the peak EV consumption (0.47MWh) occurs during at off peak tariff (from 3h00 to 6h00). The total cost that this group of EVs must pay is 73.70€, which is 37% cheaper than for users who did not participate in any DR program and consuming 0.57MWh in this operation day. In this case, it is important to note that the DR program takes advantage of the off-peak tariff at 3h00 to reach the required energy level as quickly as possible, balancing economic cost with the comfort provided to the user.

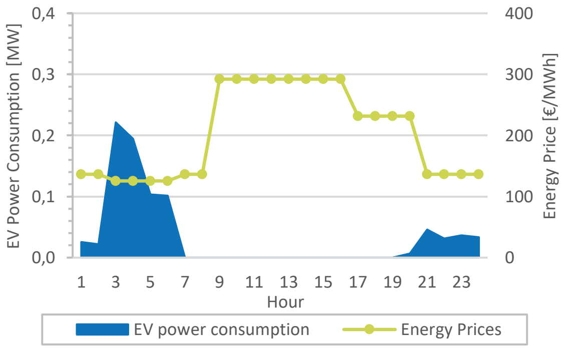


Figure 54 – 20% of EVs participate in ToU DR, winter season

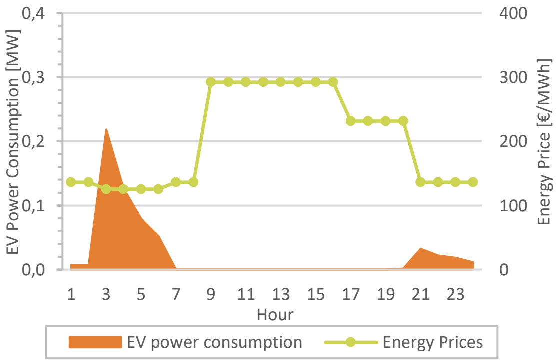


Figure 55 – 20% of EVs participate in ToU DR considering comfort level, winter season

For users who elected to participate in DR programs, the results can be analysed in Figure 56 and Figure 57. From the aggregator's perspective, where power is limited, 0.33 MW was managed during off-peak tariffs (from 3h00 to 6h00), resulting in a total energy consumption of 0.37MWh with an energy cost of 46.69 €, which is 59% lower than OF1. Conversely, from the users' perspective, a total of 0.63 MWh was scheduled at a cost of 81.54€, which is 30% less than OF1. These results underscore the efficacy of these DR programs, which, when system-focused, minimize power consumption while still fulfilling the users' required energy levels.

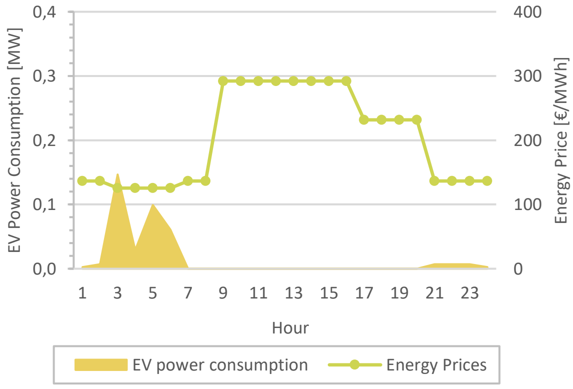


Figure 56 – 20% of EVs participate in ToU DR minimisation of peak power from aggregator point of view, winter season

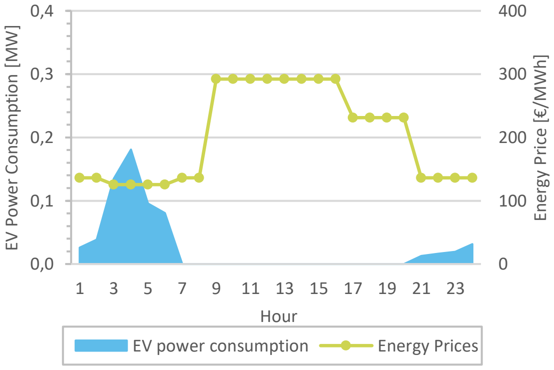


Figure 57 – 20% of EVs participate in ToU DR minimisation of peak power from each EV point of view, winter season

The performance of this DR programs attending the energy required by all 200 EVs participating is validated by Figure 58 - Figure 62, in which is possible to observe the same energy scheduled for this operation day (same area for all), in which a total energy of 3.09MWh, in each OFs, was managed.

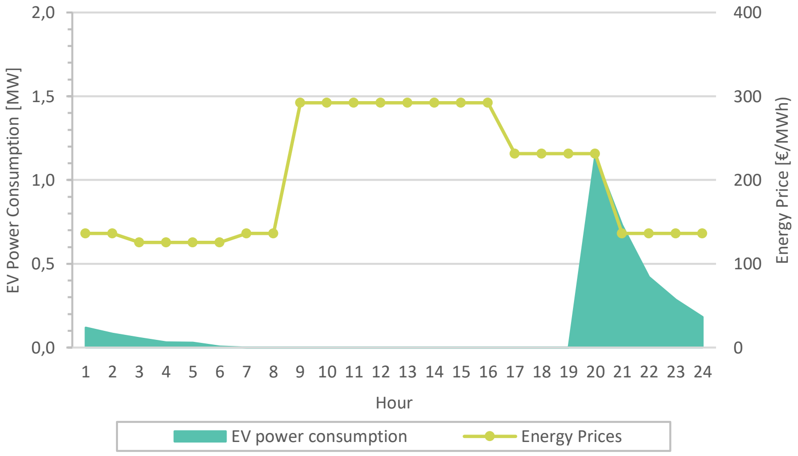


Figure 58 – All EVs do not participate in any DR (BaU), Autumn season

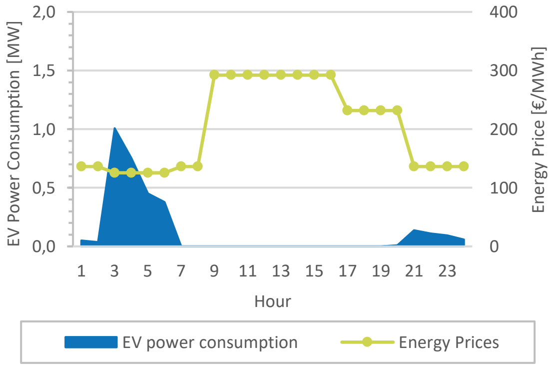


Figure 59 – All EVs participate in ToU DR, Autumn season

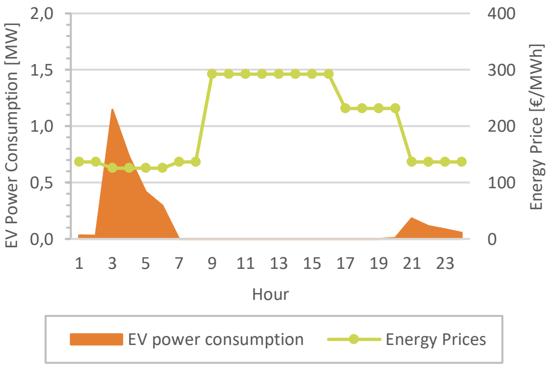


Figure 60 – All EVs participate in ToU DR considering comfort level, Autumn season

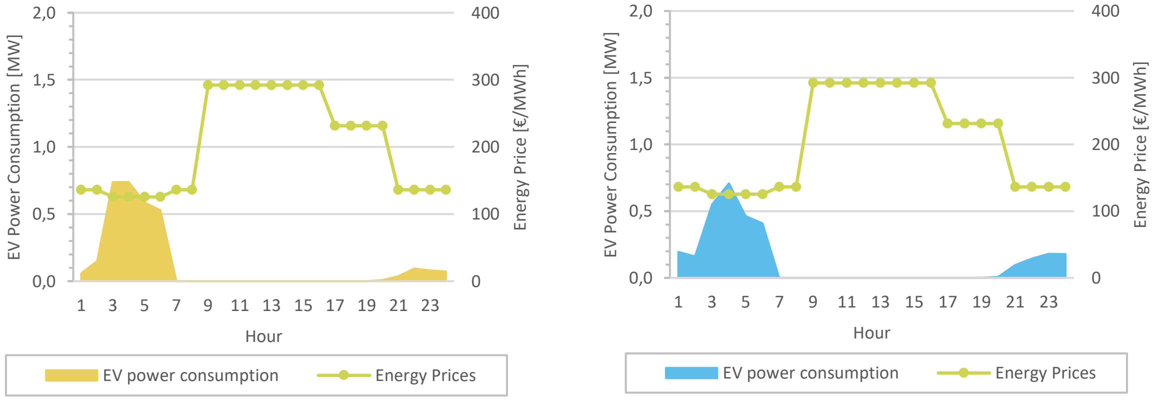


Figure 61 – All EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

Figure 62 – All EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

4.3.7 Main results for deferred in -1h Time-of-Use Demand Response Program for Portugal

With the aim to study the impact of new tariffs but similar to the implemented in nowadays in Portugal and discussed in subsection 4.3.6, the actual tetra-hourly ToU tariff was used as baseline to create a deferred ToU tariff in -1h and a deferred ToU in +1h, as shown in Table 19.

Table 19: Deferred ToU tariff (-1h and +1h) for Portugal, Winter season

Tariff type	Period	Time Intervals (-1h)	Time Intervals (+1h)	Electricity Price (€/kWh)
Tetra-Hourly	Off – Peak	2h – 5h	4h – 7h	0.1255
	Partial – Peak	1h;6h – 7h; 20h – 24h	1h – 3h; 8h – 9h; 22h – 24h	0.1363
	Peak	16h – 19h	18h – 21h	0.2315
	Super Peak	8h – 15h	10h – 17h	0.2922

The main results for the deferred ToU DR program in -1h, considering the winter season, are shown in Figure 63 – Figure 67. In the case of OF1, a significant improvement is evident when compared to the actual ToU tariff. Although peak EV consumption is also concentrated at 20h00, the difference lies in the tariff structure, which features a partial peak tariff instead of a super peak tariff**.** This results in a total daily cost of 92.76 €, which is 20% cheaper than OF1 under the actual ToU tariff. Consequently, this deferred tariff yields benefits even for users who do not participate in any DR program.

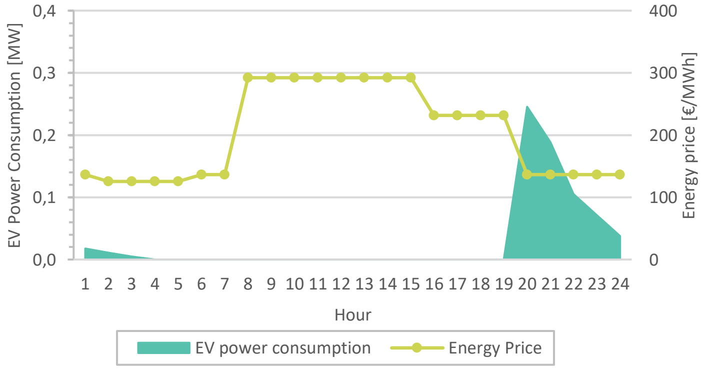


Figure 63 – 20% of EVs do not participate in any DR (BaU), -1h case

For EV users that chose to participate in DR programs under deferred ToU -1h, results are shown in Figure 64 and Figure 65. For EV users participating in a cost minimization DR program, a total daily cost of 106.63 was achieved, totalling 0.83 MWh, which is 0.15 MWh more than that of non-participants. For EV users participating in a cost minimization DR program that considers their comfort levels, a total daily cost of 73.81€ was achieved. In this scenario, the DR program capitalizes on the off-peak tariff at 2h00 to achieve the required energy level as swiftly as possible, thereby balancing economic cost with the comfort provided to the users.

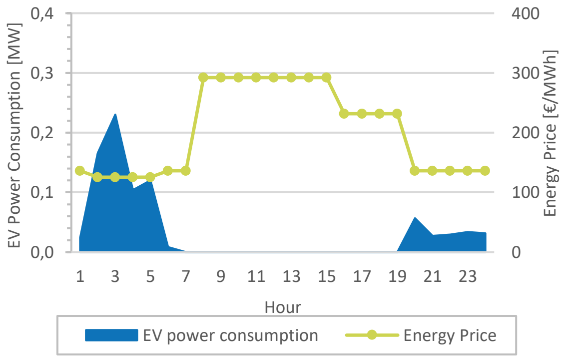


Figure 64 – 20% of EVs participate in ToU DR, -1h case

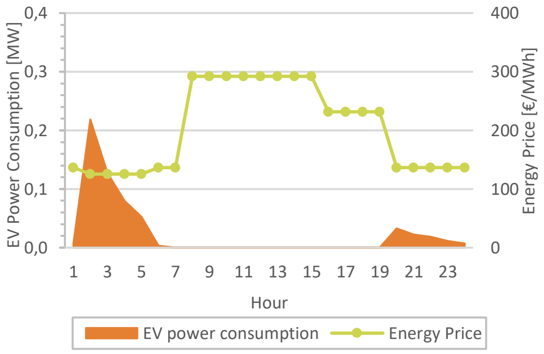


Figure 65 – 20% of EVs participate in ToU DR considering comfort level, -1h case

For EV users who chose to participate in DR programs under deferred ToU tariffs by 1 hour, the results are presented in Figure 66 and Figure 67. From the aggregator's perspective, with power limitations, 0.34 MWh was managed during off-peak tariffs, resulting in a daily total cost of 46.69€. Conversely, from the users' perspective, a total of 0.56 MWh was scheduled at a cost of 83.54€. These results underscore the efficacy of these DR programs; when system-focused, they minimize power consumption while still meeting the users' required energy levels.

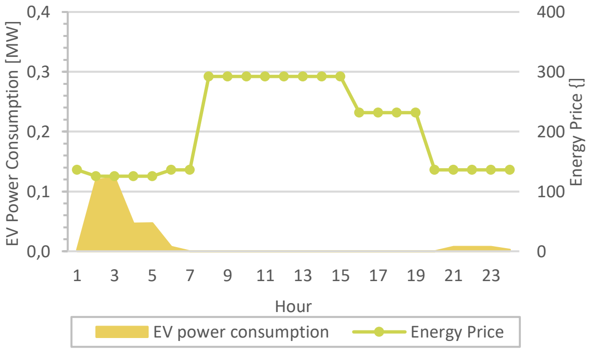


Figure 66 – 20% of EVs participate in ToU DR minimisation of peak power from aggregator point of view, -1h case

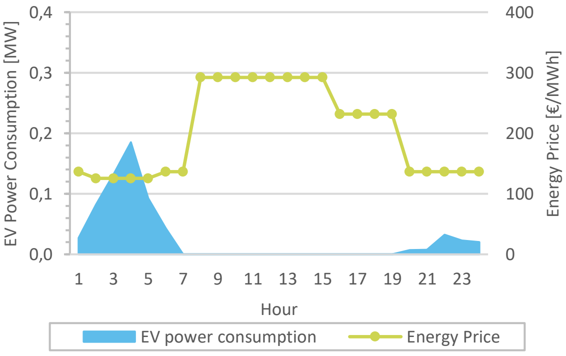


Figure 67 – 20% of EVs participate in ToU DR minimisation of peak power from each EV point of view, -1h case

The performance of this DR programs attending the energy required by all 200 EVs participating is validated by Figure 68 - Figure 72, in which is possible to observe the same energy scheduled for this operation day (same area for all), in which a total energy of 3.09MWh, in each OFs, was managed.

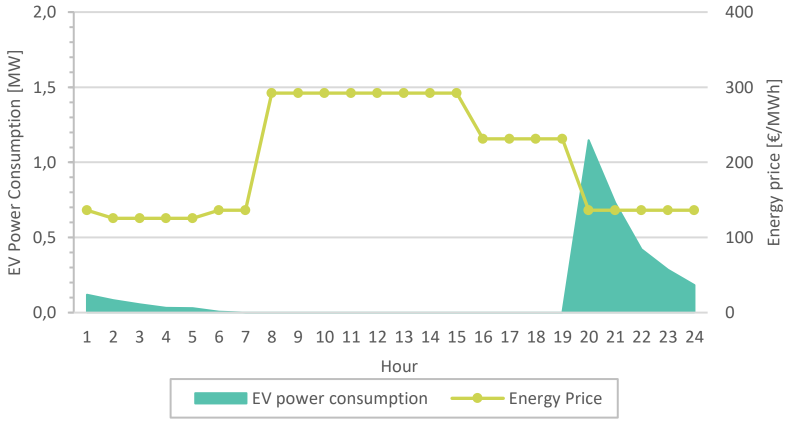


Figure 68 – All EVs do not participate in any DR (BaU), Autumn season

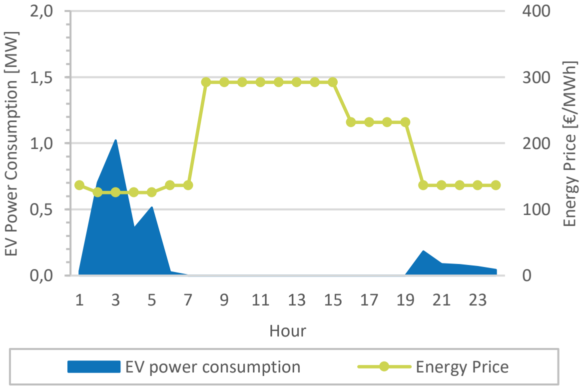


Figure 69 – All EVs participate in ToU DR, Autumn season

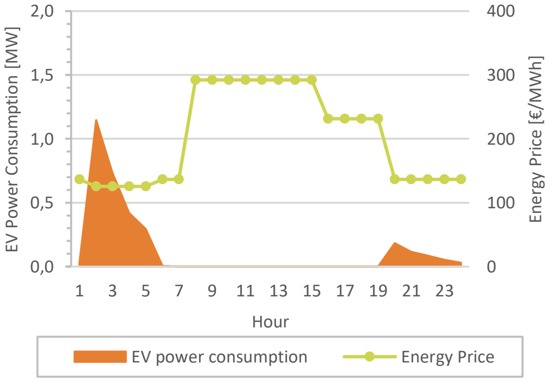


Figure 70 – All EVs participate in ToU DR considering comfort level, Autumn season

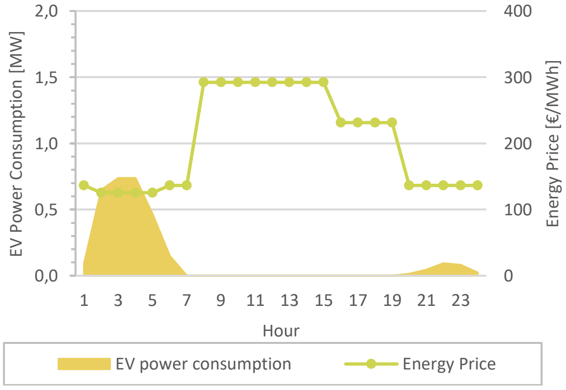


Figure 71 – All EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

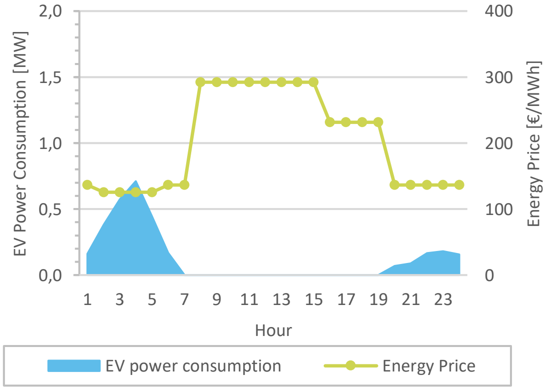


Figure 72 – All EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

4.3.8 Main results for deferred in +1h Time-of-Use Demand Response Program for Portugal

The main results for the deferred ToU DR program in +1h, considering the winter season, are shown in Figure 73 – Figure 77. This deferred tariff is less advantageous for this group of EV users, as it results in a total daily cost of 134.27€, which is 24% more expensive than the actual ToU tariff and 31% more expensive than the deferred ToU by -1 hour.

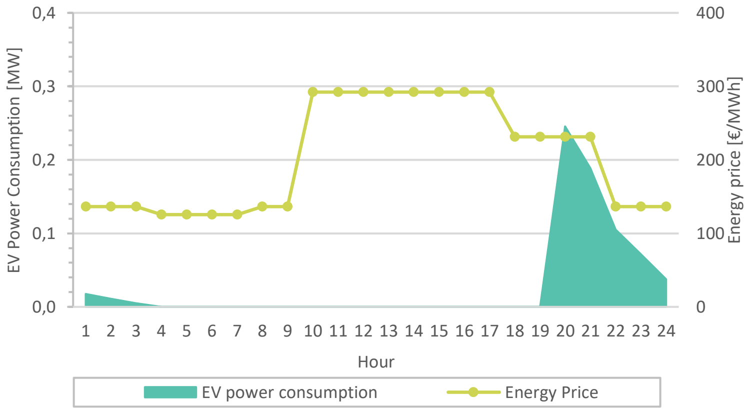


Figure 73 – 20% of EVs do not participate in any DR (BaU), -1h case

For EV users participating in cost minimization DR program the main results are illustrated by Figure 74 and Figure 75, this new deferred ToU tariff is also disadvantageous, as the total daily cost amounted to 108.57€, which is 3% higher than both the current ToU tariff and the ToU deferred by -1 hour. For EV users participating in cost minimization DR program considering their comfort level, this new deferred ToU tariff is also disadvantageous, as the total daily cost amounted to 75.01€, which is 2% higher than both the current ToU tariff and the ToU deferred by -1 hour.

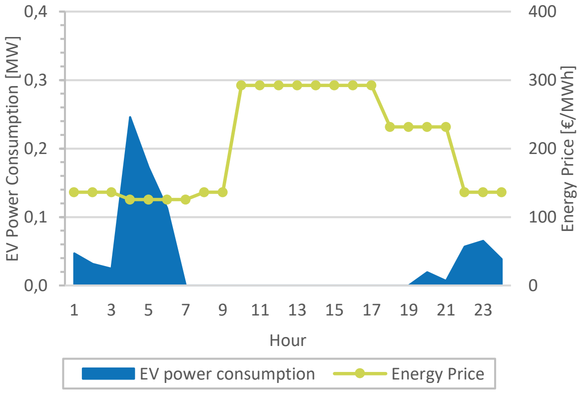


Figure 74 – 20% of EVs participate in ToU DR, -1h case

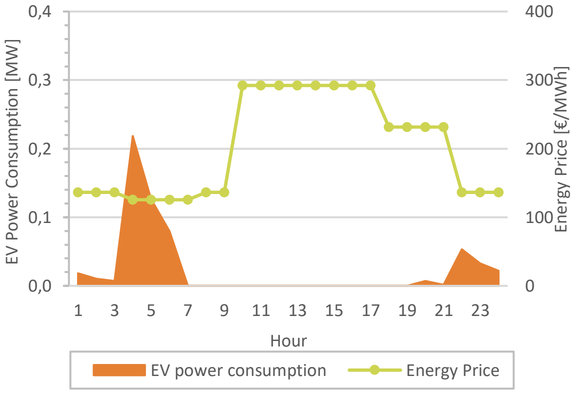
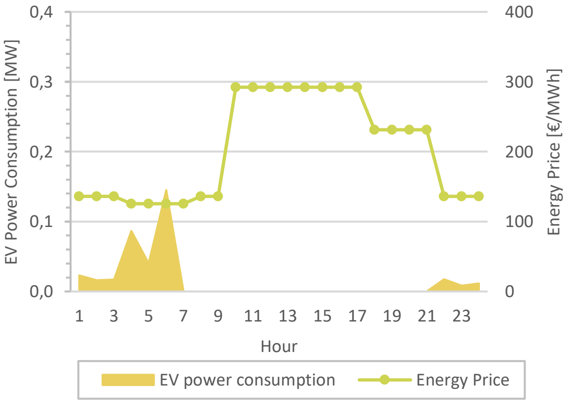


Figure 75 – 20% of EVs participate in ToU DR considering comfort level, -1h case

For EV users participating in DR programs, the primary results are illustrated in Figure 76 and Figure 77. From the aggregator's perspective, this new deferred ToU tariff is equally advantageous as both the current ToU tariff and the ToU deferred by -1 hour, with a total daily cost of 46.69 €, identical to the other scenarios. From the EV users' perspective, this new deferred ToU tariff is marginally less expensive, with a total daily cost of 81.65 €, 3% cheaper than the ToU deferred by -1 hour and identical to the actual ToU.



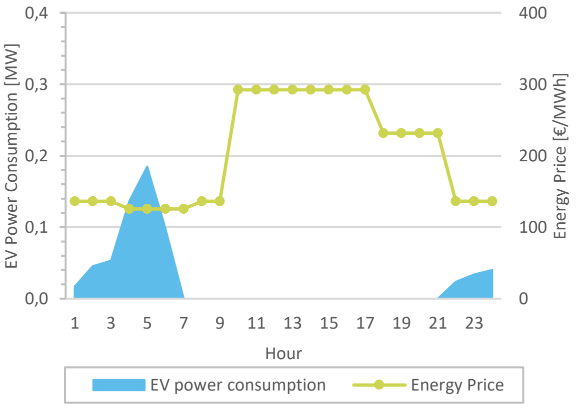


Figure 76 – 20% of EVs participate in ToU DR minimisation of peak power from aggregator point of view, -1h case

Figure 77 – 20% of EVs participate in ToU DR minimisation of peak power from each EV point of view, -1h case

The performance of this DR programs attending the energy required by all 200 EVs participating is validated by Figure 78 - Figure 82, in which is possible to observe the same energy scheduled for this operation day (same area for all), in which a total energy of 3.09MWh, in each OFs, was managed.

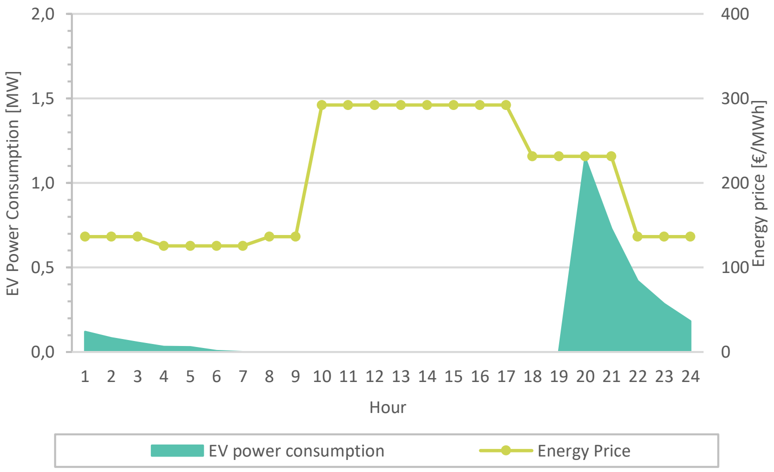
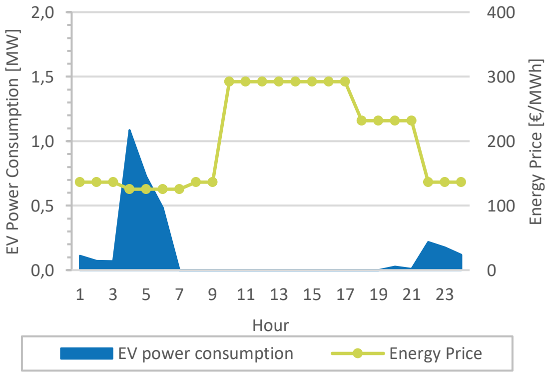


Figure 78 – All EVs do not participate in any DR (BaU), Autumn season



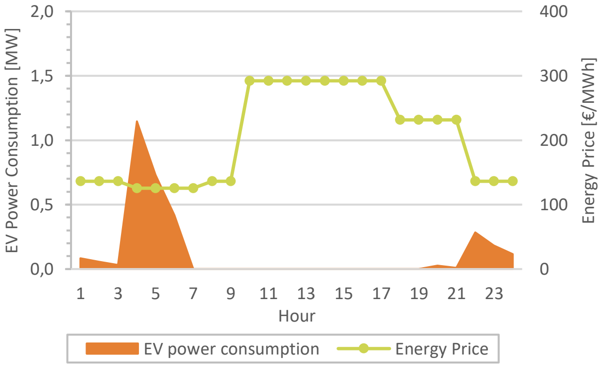


Figure 79 – All EVs participate in ToU DR, Autumn season

Figure 80 – All EVs participate in ToU DR considering comfort level, Autumn season

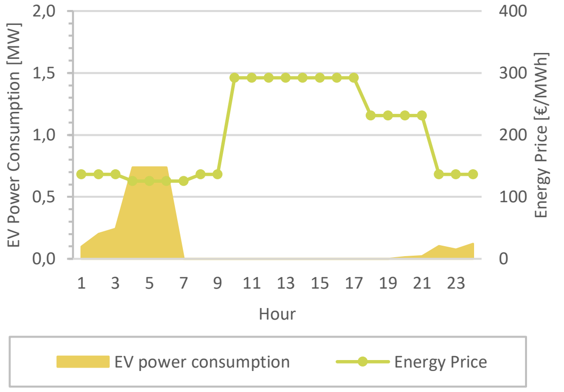


Figure 81 – All EVs participate in ToU DR minimisation of peak power from aggregator point of view, Autumn season

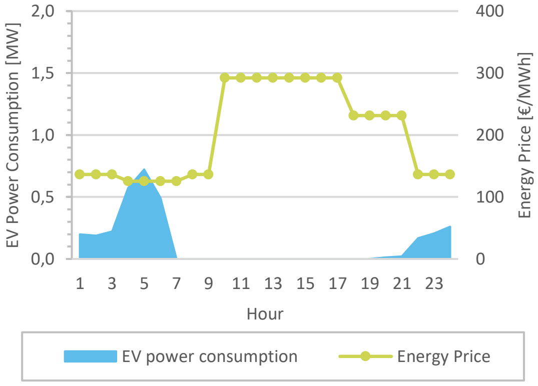


Figure 82 – All EVs participate in ToU DR minimisation of peak power from each EV point of view, Autumn season

Table 20 summarizes the total energy scheduled and the operational costs for the five days of simulation for each EV group, considering the actual ToU tariff and the ToU tariffs deferred by -1 hour and +1 hour. The results confirm that the same energy is scheduled for each subgroup, despite the consideration of different DR programs. Moreover, it is established that the ToU tariff deferred by -1 hour is more advantageous for non-participant EV users. In contrast, the ToU tariff deferred by +1 hour becomes less competitive because subgroups 1, 2, 4, and 5 experience an increase in the tariff, except for subgroup 3, where EV users encounter similar energy costs across all three scenarios.

Table 20: Summary of the energy scheduled, and cost related to the five days of simulation for Actual and Deferred ToU programs.

DR program	Actual ToU		Deferred ToU -1h		Deferred ToU +1h	
	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)	Energy (MWh)	Cost (€/MWh)
OF1 (Group 1)	4.08	669,74	4.08	550,34	4.08	760,07
OF2 (Group 2)	4.06	521,19	4.06	519,63	4.06	533,22
OF3 (Group 3)	3.10	395,42	3.10	394,74	3.10	401,39
OF4 (Group 4)	2.31	294,76	2.31	294,42	2.31	299,12
OF5 (Group 5)	3.85	493,63	3.85	493,63	3.85	499,16

4.3.9 Model assumptions for avoiding wind curtailment through Electric Vehincles Demand Response

To analyse the performance of the mitigation of wind curtailment through EVs proposed as DR program for Portugal, two scenarios are considered. The details of the input data, including kilometres per day, average kilowatt consumption per charging station (CS), kilowatt-hours per kilometre, kilowatt-hours per day, feed-in tariff, and the percentage of shared benefits, are presented in Table 21. For the benchmark case, data from the metropolitan area of Lisbon was used. For the Azores case, real data from the metropolitan area of Ponta Delgada was utilized. The processed data related to wind energy curtailment, for 2022, was gathered from [3], and is shown by season in Figure 83, in which is possible to observe that in the Autumn season had the highest wind curtailed energy, a total of 476.27MWh.

Table 21: Input data details for the two scenario considerations for Wind Curtailment DR program

Scenario	km/day	Average kW per CS	kWh/km	kWh/day	Feed-in tariff €/MWh	Shared Benefit (%)
Benchmark	50	5	0.165	8.25	70	50
Azores	30	5	0.165	4.95	50	50

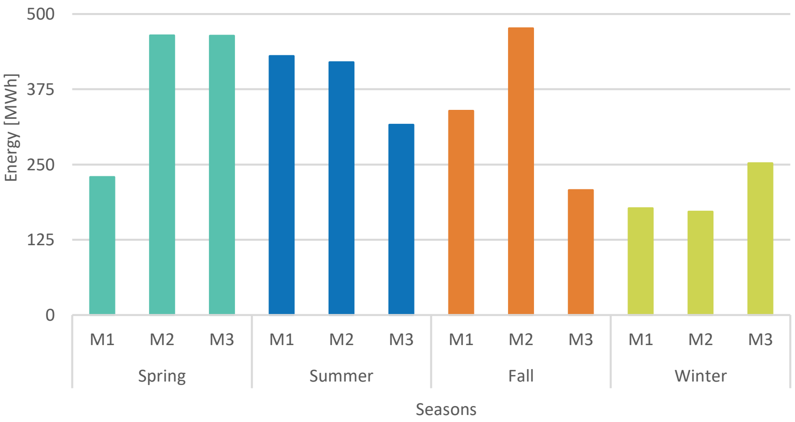


Figure 83 – Curtailment Energy by season – 2022

4.3.10 Main results for mitigating wind curtailment through Electric Vehicles Demand Response program

The main results of this case are presented Figure 84 – Figure 85, which display the number of EVs that would need to be charged during each season to avoid wind power curtailment, both for the base case and for the case of Ponta Delgada. In the benchmark case, during the Autumn season, a total of 8,094 EVs would be required, whereas in Ponta Delgada, EVs would be necessary, 45% more than the benchmark case. This discrepancy arises because, with a lower energy requirement (30 km/day) for Ponta Delgada, a significantly higher number of cars would need to participate in this DR to avoid wind curtailment.

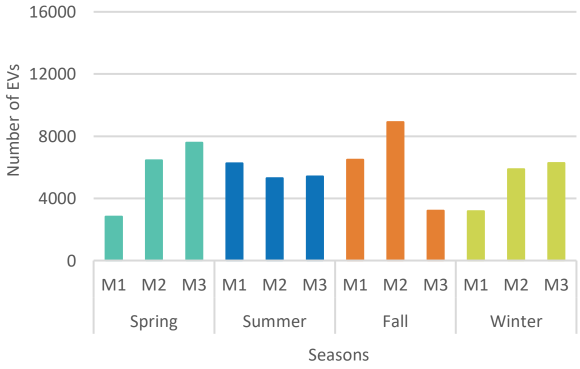


Figure 84 – Necessary Number of EVs to avoid Curtailment Energy by season, benchmark case

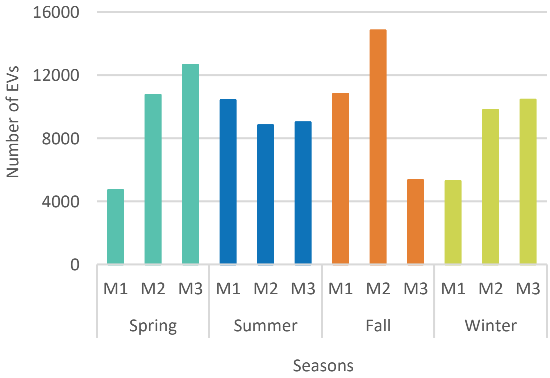


Figure 85 – Necessary Number of EVs to avoid Curtailment Energy by season, Ponta Delgada case

Regarding the economic results, Figure 86 and Figure 87 show the price to be shared between the renewable energy producer and the EVs for each season of the year. Since the feed-in tariff for the benchmark is 70€/MWh, which is 20€ more than the case of Ponta Delgada, the EVs in the benchmark received a price of 2,570.78 €, 28% more than in the case of the Azores. However, due to the higher number of EVs required to avoid power curtailment, each participant in this DR in the case of Ponta Delgada would receive a daily discount on their energy bill equivalent to 0.12 €, totalling 3.6 € per month, which is 58% less than in the benchmark, where users would receive a total of 8.7 € per month for participating in this DR.

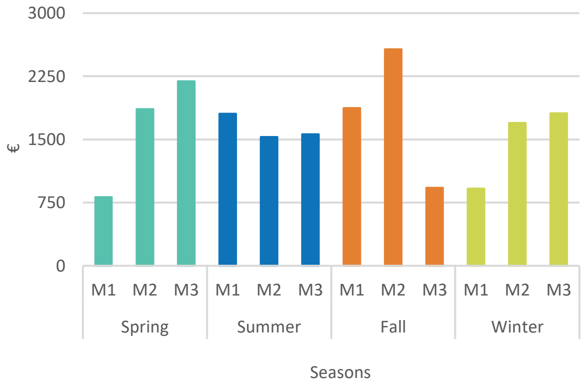


Figure 86 – Price to share with the EVs by season (€), benchmark case

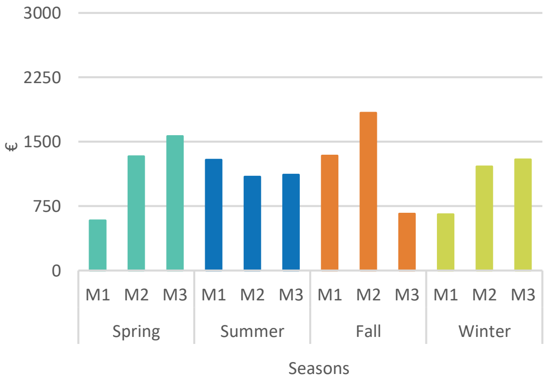


Figure 87 – Price to share with the EVs by season (€), Ponta Delgada case

It is important to emphasize that the economic benefits that EV users can receive highly depend on a directly proportional relationship between the agreements established between the parties. That is, the feed-in tariff must increase in proportion to the percentage to be shared with the EVs. On the other hand, the number of EVs participating in this DR directly impacts the marginal value that each of them will receive per day. Thus, in an island context such as Ponta Delgada, where fewer kilometres are needed to travel on a typical workday, each participant will receive a moderate economic benefit. However, they will be contributing to the use of green energy, thereby facilitating the achievement of decarbonization of the energy [34].

4.4 Application of Voltage Control Price Signal Demand Response Program for Slovenia

4.4.1 Model assumptions for voltage control in distribution network

To analyse the performance of the voltage control in distribution network EVs proposed as price signal DR program for Slovenia was processed a confidential dataset related to measurements for a specific MV/LV substation along with its 23 underlying LV feeders for two years, 2020 – 2022. Nevertheless, aiming to validate this DR program, only one month (February of 2022), with data each 15 minute is analysed, as shown by Figure 88 and Figure 89. Regarding the input data used, for the Slovenian metropolitan area was considered 50km/day [38] as typical distance travelled, for the average energy consumption per kilometer was considered 0.2kWh/km, representing an energy requirement of 10kWh/day, with an average power consumption per charging station of 5kW. The grid tariff considered was 0.1€/kWh with a lower limit of 0€/kWh. In Slovenia, under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed ± 10 % of the nominal voltage [39]. The analyzed data (see Figure 88 and Figure 89) indicate an overvoltage in phase B on February 19th at 1h45 and an undervoltage in phase C on February 25th at 12h30.

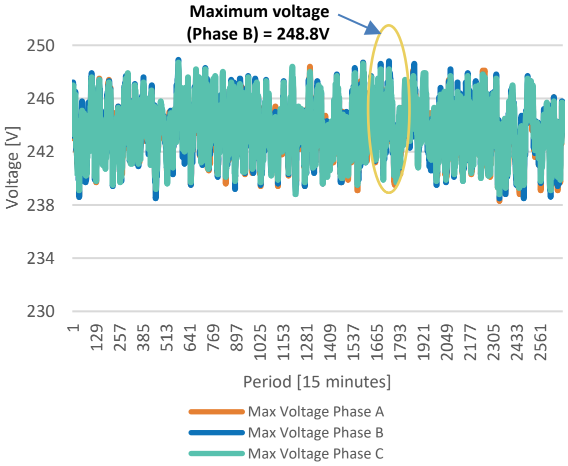


Figure 88 – Max voltage data for three phases, February 2022

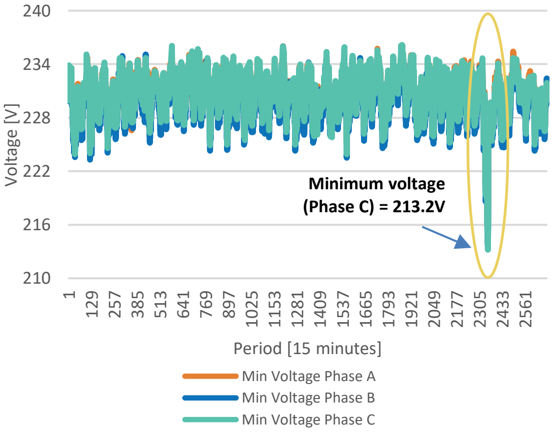


Figure 89 – Minimum voltage data for three phases, February 2022

4.4.2 Main results for voltage control in distribution network

The main results of this case are illustrated in Figure 90 – Figure 93. To make the discussion more practical, two cases will be analysed: one on February 19th due to the overvoltage in phase B, and another on February 25th due to the undervoltage in phase C. Figure 90 and Figure 91 illustrate the voltage in p.u., the price signal offered through this DR program, and the grid tariff (€0.10/kWh) for the two analysed cases. As shown in Figure 90, the price signal decreases as the voltage rises beyond the established limit (+10%), maintaining a regular level when it remains within the permitted limit. The lower prices signals offered to incentive the DR program is 0.0852€ by 15min, 0.0730€ by 15min, and 0.0921€ by 15min occurring between 1h30 and 2h00 and 0.0887€ by 15min, 0.0973€ by 15min, 0.0956€ by 15min, 0.0991€ by 15min between 3h15 and 4h00, with no additional overvoltage observed for the rest of the analysed day. On the other hand, Figure 91 illustrates how prices increase when the voltage in p.u. Autumns below the established limit (-10%), aiming to encourage EV users to cease charging. Consequently, the highest price signals are observed between 11h45 and 12h45 specifically: 0.1078€ by 15min, 0.1156€ by 15min, 0.1160€ by 15min, 0.1230€ by 15min, and 0.1095€ by 15min, with no further undervoltage occurring for the remainder of the analyzed day.

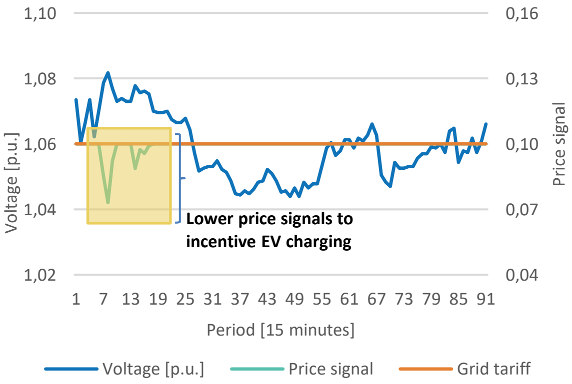


Figure 90 – Price signals in case of overvoltage, Phase B, Nineteenth day of February 2022

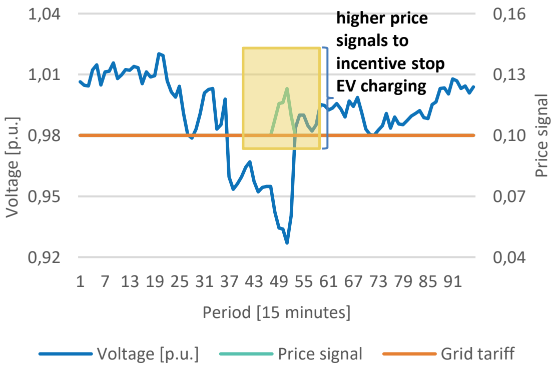


Figure 91 – Price signals in case of undervoltage, Phase C, Twenty-fifth day of February 2022

To assess the benefits for EV users participating in this DR program, it is essential to analyse their usage behaviour. Assuming an energy requirement of 10 kWh per day and a charging rate of 5 kW, it would take approximately 2 hours (or 8 intervals of 15 minutes) to fully charge their batteries. Therefore, in the overvoltage case, considering the lower price signals, for a user starting the charge at 1h45 (hour with the higher overvoltage) and due to the average power consumption in a CS of 5W charging for 120 minutes, the price at 1h30 is 0.0852€ by 15 minutes, therefore, this EV user must pay an optimal tariff (less than the regular tariff) 0.924€/kWh starting the charging at 1h30. Moreover, the grid tariff limit (0.1€/kWh) is used as baseline to calculate the "normal" value that a typical user must pay, for this case, an energy requirement of 10kWh/day, represent a maximum value of 1.0€/day. Therefore, due to their participation in this DR program, an EV user starting the charge at 1h30 receives a discount of 7.61%, as shown by Figure 92. On the other hand, conversely, Figure 93 illustrates the case of undervoltage, where it is not possible to offer lower price signals. In this scenario, the signals are increased to encourage the EV to stop or reduce charging. Thus, a user who wishes to charge at 12h30, when the undervoltage is most severe, would receive an price signal of 0.1230€ by 15 minutes starting the charging at 1h30, therefore, this EV user must pay an averse tariff (more than the regular tariff) of 1.041€/day, due to the start of EV charging at this time and the need to charge for 8 intervals, thereby receiving no discount.

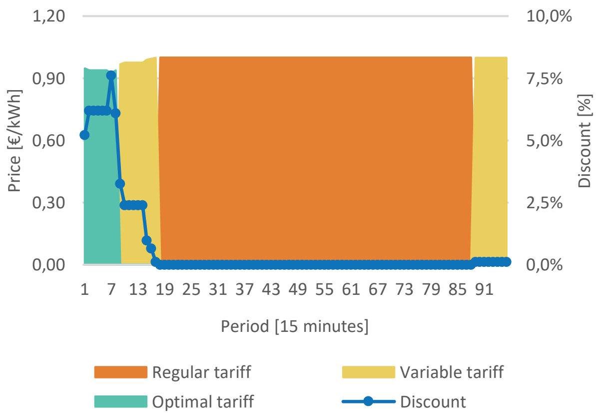


Figure 92 – Tariff to pay and discount for incentive EV charging, overvoltage case

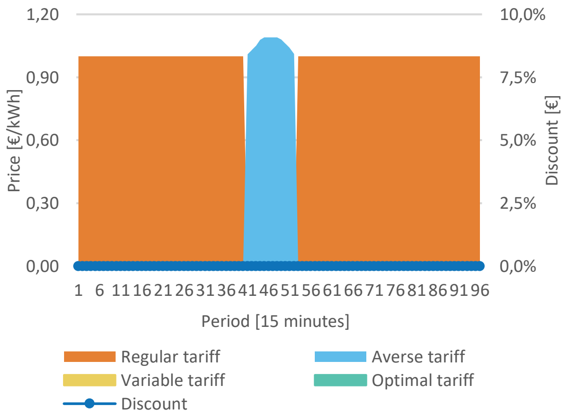


Figure 93 – Tariff to pay and discount for incentive stop EV charging, undervoltage case

5 Conclusions

This deliverable presents an analysis of various demand response (DR) programs, both implicitly and explicitly implemented, in three countries involved in the EV4EU project: Greece, Portugal, and Slovenia. Additionally, innovative DR programs designed to address real issues using electric vehicles (EVs) in each analysed country have been proposed. A key conclusion is that each new program, specifically designed to address a particular issue in each country, provides benefits to electric mobility users by offering energy bill discounts regardless of user behaviour, which varies across the different contexts analysed.

In a deeper analysis of the results, it is possible to conclude that:

- When implementing an implicit DR program based on real-time tariffs in the three countries, the best alternative for users in terms of reducing energy bills is the DR program that focuses on minimizing the cost of charging. Compared to the scenario of not participating in any program, this approach results in a 30% discount for Greece, 43% for Portugal, and 38% for Slovenia. On the other hand, when this DR program is applied in one of the analysed countries and considering vehicle-to-grid (V2G) technology, the energy bill can be further reduced by taking advantage of discharging (without compromising energy consumption). For the specific case of Greece, this results in an additional 14.28% reduction compared to the scenario that does not consider V2G. Other objective functions can also be adopted by the users increasing the comfort level (charge faster) or reducing the peak consumption. In both cases the global costs will be slightly improved, but its definition will depend on the user behaviour.
- The DR program proposed for Greece provides price signals that make it competitive for EV users to charge to avoid reverse power flow and ensures discounts, based on the regular grid tariff applied, of up to 56% for users who choose to participate in this DR program through EV charging.
- The new DR program designed for Portugal, based on tetra-hourly Time-of-Use (ToU) tariffs that consider EV user profiles, demonstrated the importance of aligning price tariffs with the charging behaviour of electric mobility users. By comparing the results of the DR program without considering EV profiles to those that do, discounts of up to 24% were achieved for users who choose to participate in this DR program. Furthermore, when this DR program is applied considering V2G, participating users receive an additional discount of 26.6% on their energy bill without compromising their energy demand.
- New deferred DR programs -1h and +1h based on the current ToU tariff applied in Portugal were analysed, concluding that the +1h deferred option is not beneficial, as it increases the energy costs for participating users in this DR program. Conversely, the -1h deferred option shows slight improvements in reducing the energy bill, albeit not exceeding 10% in this case, validating that for the effectiveness with EVs, creating a new tariff is more advantageous.
- The new DR program designed to prevent wind curtailment energy in Portugal, particularly in Ponta Delgada, in the Azores archipelago, provides insight into the number of cars required to be charged to avoid wasting this renewable energy, a total of 14,840 users, which results in a discount of 3.6€ on their monthly energy bill.

The new DR program designed to prevent overvoltage/undervoltage in Slovenia by incentivizing EV charging/cessation of EV charging offers price signals that vary based on established overvoltage and undervoltage limits (+10%) in Slovenia. Thus, users who choose to charge during an overvoltage event can receive, according to the analysed results, up to a 6.2% discount on the energy consumed during a daily to fully charge the EV battery. On the other hand, based on the analysed data, there are fewer undervoltage events, which means that, if a user needs to charge during these specific times, they may have to pay their energy bill without any discount, considering the required energy needs more than one charging session.

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