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Techno-economic analysis of vehicle-to-grid technology: Efficient integration of electric vehicles into the grid in Portugal

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ABSTRACT

The aim of this work was to create an original numerical model for conducting an economic analysis of Vehicle-to-Grid (V2G) services. This model enables the computation of potential economic earnings for a certain user providing V2G services to the grid operator, considering Portugal's electricity market and the country's increasing adoption of Electric Vehicles (EVs). The model incorporates various parameters in its calculations, including battery degradation, distance traveled, charging frequency, number of V2G charge-discharge cycles, electricity purchase and sale prices or the cost of new batteries. These factors contribute to robust values that facilitate a detailed analysis closely aligned with the realities of different citizens, since no study found in the literature has addressed the economics of V2G technology in this sense. To test this model, we created four hypothetical EV users with distinct characteristics, aiming to understand the scenarios where providing this energy storage service is most beneficial from the EV user perspective. We considered and compared three scenarios for the selling price of electricity back to the grid (0,50 €/kWh, 0,30 €/kWh, and 0,20 €/kWh) and performed a sensitivity analysis. The goal is that by the time each user needs to replace their battery due to degradation, they will have generated sufficient income from the V2G service to not only cover the cost of a new battery (10,000 €) but also make a profit. This takes into account the future development of energy storage and the anticipated decline in prices. Results suggest that the V2G service can be highly beneficial when electricity sale prices are high (0,50 €/kWh) for users with very low car usage (profits of 624 € per month and 1547 € in total after the costs of a new battery), but the same doesn't happen when the prices for selling electricity to the grid drop to 0,30 or 0,20 €/kWh. This service can be advantageous too for users who use their cars intensively, even if the electricity selling price is low (0,20 €/kWh), as it allows for savings on the purchase of a new battery (savings between 300 € - 1100 € on the cost of a new battery).

1. Introduction

Governments and agencies worldwide have established ambitious objectives for the electrification and decarbonization of the transportation sector, viewing it as a key strategy to attain the much sought-after sustainability and energy security [1,2]. The production of electricity from fossil fuels has become a significant concern for communities worldwide due to its substantial carbon footprint and the impact of other detrimental pollutants on the environment. The escalating global demand has led to an excessive consumption of fossil fuels in electricity generation [3]. Electricity production is an energy-intensive process that has contributed significantly to increasing the concentration of greenhouse gases (GHG) [4] in the atmosphere including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) or chlorofluorocarbons (CFCs), leading to increased global warming. That said, a large part of current efforts focus on promoting EVs [5] for the decarbonization of transport [6,7], which can use renewable electrical energy to move [8], thus avoiding harmful emissions into the environment associated with vehicles with internal combustion engines, which burn fossil fuels such as gasoline or diesel [9].

Among some others [10], Portugal is one of the European countries that has invested the most in recent years in creating dynamics that encourages the adoption of EVs. Some interesting proposals were drawn

Abbreviations: Cd, Drag coefficient; CH_4, Methane; CO_2, Carbon dioxide; CFCs, Chlorofluorocarbons; DSO, Distribution system operator; EDP, Energias de Portugal; EVs, Electric vehicles; FCS, Fast charging stations; kW, Kilowatt; kWh, Kilowatt hour; MOBI.E, Electric Mobility Network Management Entity (Portugal); N_2O, Nitrous oxide; OCC, Optimal coordinated charging; RLP, Robust linear programming; V2G, Vehicle-to-grid; VAT, Value added tax; VPPs, Virtual power plants.

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Nomenclature

$A_{CcostsRoad}$ Annual costs for charging the EV due to road environment
$AvN_{Days/month}$ Average number of days per month of the year
AvN_{Kmday} Average number of km's each user travels per day
Bad_{Road} Annual degradation of the battery by road environment cycles
Bad_{V2G} Annual degradation of the battery by V2G cycles
B_c Battery capacity in kWh
Bmd_{Road} Monthly degradation of the battery by road environment cycles
Bmd_{V2G} Monthly degradation of the battery by V2G cycles
$C_{CostsRoad}$ Monthly charging costs for charging the EV due to road environment cycles
$C_{CostsV2G}$ Monthly charging costs for charging the EV due to V2G cycles
C_{bat} Number of battery cycles
C_{nb} Cost of a new battery
EV_R EV range
FR_{Road} Frequency of recharging the EV in road environment
M_{rV2G} Gross monthly revenue by V2G service
$NA_{profitV2G}$ User's net annual profit only from providing the V2G service to the grid
NC_{Road} Number of charging cycles in road environment per month
NC_{V2G} Number of V2G cycles per month
$N_{Km/month}$ Number of km's each user travels per month
$NM_{profitV2G}$ Net monthly profit only from providing the V2G service to the grid
NP_{V2G} Total net profit from V2G service after the expenses of purchasing a new battery
$N_{days/year}$ Number of days during a year
$N_{months/year}$ Number of months during a year
PP_{ele} Purchase price of electricity to charge the EV
PS_{ele} Selling price of electricity to the grid
P_{Tbat} Total gross profit generated from V2G service at the time of battery replacement
P_{Tyears} User's total net profit after T_{years}
TA_{Ccosts} Total annual charging costs
TM_{Ccosts} Total monthly charging costs
T_{bat} Number of years it would take for the battery needs to be replaced
T_{months} Number of months of V2G service to obtain income to buy a new battery
$Total_{Bad}$ Total annual degradation of the battery
$Total_{NAprofitV2G}$ Total net annual profit from V2G service after expenses in road environment
$Total_{NMprofitV2G}$ Total net monthly profit from V2G service after expenses in road environment
T_{years} Number of years of V2G service to obtain income to buy a new battery
U_{Bcap} Useful capacity of the battery

up by the Portuguese government such as purchase subsidies [11] with a 4000 € incentive for the acquisition or leasing of an electric, light passenger vehicle, whose value may not exceed 62,500 €, with VAT, until the limit of 1300 vehicles or 5,200,000 €, through the Environment Fund [12], ensuring benefits for the users of these vehicles, proceeding with the development of infrastructures and creating local incentives. In the case of the Portuguese market, the adoption of electric vehicles has increased strongly from year to year, making the EV share in Portugal at around 20 % of the total vehicle sales [13]. In 2023, the total number of EVs in Portugal (battery electric vehicles and plug-in hybrid electric vehicles) is 228,140 units. To observe this enormous growth in the adoption of EVs, in 2020 the total number of these vehicles registered in Portugal was 64,756 units and in 2022 it was 146,778 units [14]. Predictive data [15] indicates that the number of EVs purchased per year in Portugal will continue to rise strongly with 45,670 EVs being purchased during 2025; 51,770 during 2026; 58,810 in 2027 and 66,920 in 2028. The number of charging stations in Portugal - in the year 2024 - stands at 7760, a very high number and obviously set to grow in the coming years.

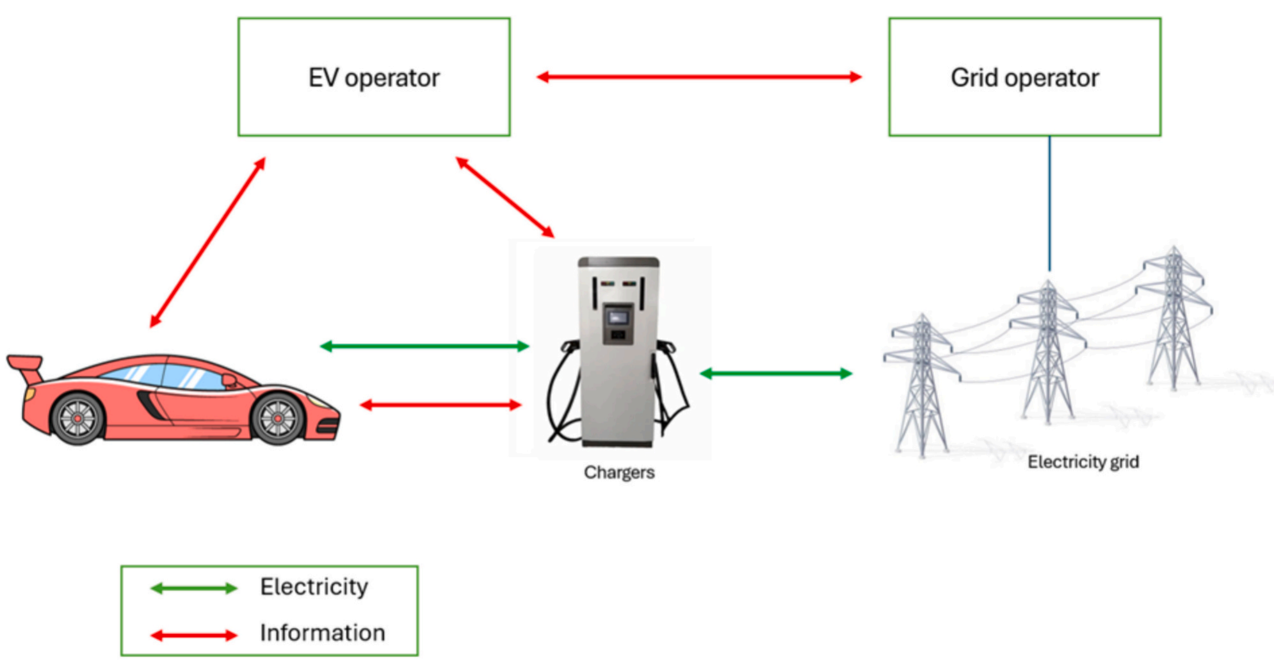

Fig. 1. - Concept of EV integration into the Portuguese grid.

The proposition of linking the electrical grid and EVs through V2G technology is gaining prominence as an emerging technology. It is seen as an effective contributor towards achieving the goals of the proposed decarbonization [16]. Specifically, V2G technology, with the incorporation of a bidirectional charging station, allows an EV to be connected to the electrical grid serving as an energy storage system, allowing electricity to flow in both directions between the vehicle and the grid [17], as seen in Fig. 1. EVs can potentially act as distributed energy storage devices to provide a service to the grid (V2G) for the benefit of the electrical energy system [18]. V2G is a technology that uses EVs batteries to support the grid [19]. The main reason for this idea is the notion of magnitude of EV batteries, which are underutilized and can be used to provide a range of services beyond just powering the EV powertrain [20], like frequency and voltage regulation, congestion mitigation or renewable energy storage [21,22].

This is a highly valuable alternative to electrical grids, as these capabilities of the huge batteries present inside EVs can be used to balance the system [23] at times of peak consumption and at times of less demand. EVs with V2G capabilities can charge/discharge cost-effectively [24,25] – charging when power prices are low and there is plenty of electricity on the grid and discharging (selling the electricity stored in the car) when costs of electricity are high and the grid is under pressure [26]. Parked EVs (when not running – almost 97 % of the time) [16,27] can thus function as a backup energy source for the grid [28]. Through the V2G interface, grid operators can maintain stable voltages and frequencies [29] in a short period of time, thus ensuring a reliable energy supply [30]. The predicted penetration of renewable generation of energy in Portugal will amount to 77 % in 2050, so this could be an amazing solution for the country [31].

Likewise, as Fig. 2 shows, EV owners can also earn monetary income based on providing that same service to the grid in a market environment [32]. However, during this process the vehicles suffer the extra battery degradation incurred by V2G operation [33,34]. As such, it is also essential to investigate the economic viability of this situation [35], understanding in which cases this service could be profitable for different types of EV users, even taking into account the additional wear and tear that will be caused to the car batteries. Despite its potential, to date, V2G technology has not yet been implemented on a sufficiently large and competitive commercial scale [17].

Considering various factors like components description, electrical and electronics analysis, operational costs and investments, carbon reductions or even grid operators profits, numerous studies in recent years have explored V2G technology and its potential benefits. However, the existing literature still lacks detailed analysis and calculations of potential revenues that specific real-life EV users could earn by offering this service to the grid, based on actual electricity market data from a specific country.

1.1. Literature review

Lei et al. [36] explored the optimal charging and discharging plan for EVs from the perspective of a distribution system operator (DSO). They also developed an optimal day-ahead bidding strategy for the DSO in the spot market. The study considers varying charging demands among different EV users and introduces two contract models for V2G interactions based on the Guangdong province electricity market. The results demonstrate that the DSO can increase marginal revenue not only through the optimal day-ahead bidding strategy but also by efficiently scheduling EVs' charging and discharging. Additionally, EV users can reduce their charging costs by utilizing low electricity price periods and generate extra revenue by exporting power to the grid during peak price periods.

Meiye Wang and Michael T. Craig [37] conducted a study to assess the net revenues of a fleet of V2G-enabled EVs in California up to 2030. They achieved this by co-simulating optimization models for V2G interactions and power system operations. Their findings revealed that V2G-enabled EVs generate an average of $32 to $48 more in annual net revenues compared to smart-charging EVs.

Lotfi et al. [25] proposed a robust optimal coordinated charging (OCC) model, which utilizes robust linear programming (RLP) for an EV aggregator operating in a unidirectional V2G setup. The model aims to optimize the aggregator's income by participating in ancillary services markets. Comparing their approach to existing deterministic models, they demonstrated that their OCC model increases the aggregator's revenues and minimizes deviations between predicted and realized revenues.

Mosammam et al. [38] conducted research to enhance the economic energy management of a plug-in hybrid vehicle. Their study aimed to maximize revenue by leveraging V2G interactions during peak hours while also minimizing battery aging. Specifically, they focused on the Mitsubishi Outlander in New York City. By analyzing charging and V2G schedules, rates, and ambient temperatures, they investigated their impact on lithium-ion battery aging using machine learning techniques. The study found that by optimizing the selection of charging and V2G timing, rates, and temperature, it's possible to achieve an income of $1043 and limit battery aging to 7.2 % within one year.

Li et al. [39] investigated the carbon reduction and economic potential of V2G technology in Guangdong Province. They used a long-term power model based on the region's EV inventory. The study projected power consumption, carbon reduction, and economic gains for EVs across four carbon reduction scenarios, which were aligned with transportation trends. The findings indicate that V2G application could reduce carbon emissions by 1471 to 2873 million metric tons of CO_2, while also mitigating peak-valley load disparities by 7.6 %. The study emphasizes that large-scale V2G integration not only promotes green energy but also enhances grid efficiency, offering economic advantages for multiple stakeholders.

The research by *Nagel* et al. [40] analyzes the potential benefits of bi-

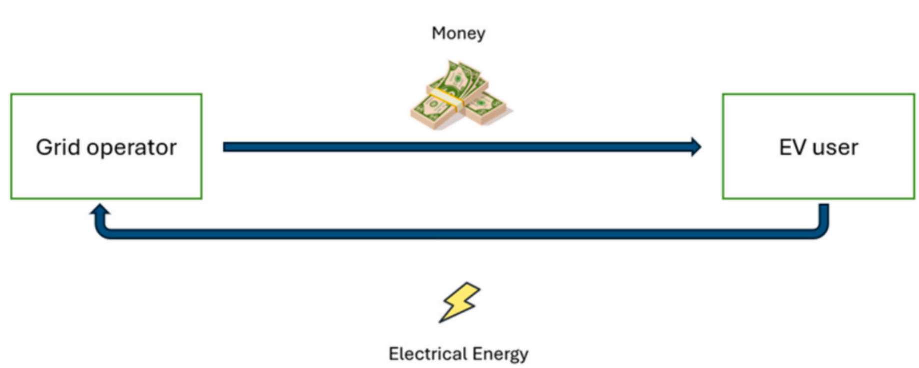

Fig. 2. - V2G business interface between the user and the grid.

directional charging for EVs and its implications for the energy sector. The study focuses on two market regions: Norway and Denmark. Key findings indicate that large-scale V2G adoption can significantly impact prices in the analyzed regions. V2G technology helps reduce price volatility, lower peak and valley electricity prices, mitigate renewable energy curtailment, and decrease overall energy system operation costs. Additionally, it's said that the spread between charging and discharging prices is highest in cases of small-scale adoption and in regions with limited inherent power system flexibility.

Zheng et al. [41] explore the potential of EVs to provide V2G services from two angles: availability of time and economic feasibility. They evaluate three charging scenarios - at home, at the workplace, and at fast charging stations (FCS) - in terms of their suitability for V2G services. The findings indicate that there is ample idle time for EVs in both home-based and workplace-based charging scenarios, making it economically viable to offer V2G services in the electricity market, as per the cost-benefit analysis. However, for EVs that rely on FCS-based charging, it is improbable that users would allocate additional time for V2G operations, as these operations would extend the grid-connection time of the EVs.

Shaheen et al. [42] put forward a strategy that employs metaheuristic algorithms to orchestrate the charging and discharging operations of EVs during parking. This strategy takes advantage of V2G technology with the dual aim of decreasing the daily expenses of EV users and tackling the challenges of energy demand management in smart grids. The results derived from this proposed strategy underscore its viability in scheduling the charging and discharging activities of EVs, thereby reducing costs for EV users through the integration of V2G.

Mehdizadeh et al. [43] study estimates the blend of financial incentives and the minimum guaranteed charge required to enhance the acceptance of V2G technology among the population of Norway. The findings suggest that V2G technology is more likely to be embraced by older individuals, those who perceive the V2G system as beneficial, individuals with prior experience with EVs, and those with a high level of trust in the V2G system. The study also reveals that people expect an average reduction of 144 $ in their electricity bills (which is 72 % of the average monthly electricity bill) as compensation for investing in V2G. Furthermore, is found that they would be willing to use V2G if their EV battery maintained a minimum power level of 71 %.

Research conducted by *Niu* et al. [44] aimed to optimize the deployment and operation of V2G-enabled chargers, taking into account two charging modes: public and private chargers. Two bi-objective models were formulated to determine the optimal size of the V2G-enabled chargers and to devise charging-discharging strategies, considering uncertainties in photovoltaic energy output, EV charging demand, and household base load. These optimization problems were tested in a residential neighborhood in Shanghai, China. The results indicate that the current financial feasibility of a V2G system is dependent on additional subsidies. Therefore, the authors tell us that a fair market mechanism needs to be established to foster the healthy development of V2G applications.

Blatiak et al. [45] study quantifies the potential revenues that a commercial EV fleet operator could gain by scheduling its trips and charging using V2G technology simultaneously on a day-ahead basis. This system enables the fleet to complete its trips while capitalizing on the fluctuating energy and ancillary service prices. They propose a mathematical framework for optimal trip scheduling, formulated as a mixed-integer linear program. This framework is applied to several scenarios relevant to the current and future British electricity system. The study demonstrates that choosing an optimal journey start time can boost the revenue of commercial fleets by up to 38 % in summer and 12 % in winter. Furthermore, a single EV from the maintenance fleet could generate an additional annual revenue of up to 729 £.

A model was developed by *Geng* et al. [46] to assess the costs and profits of V2G from the vehicle's perspective. The results indicate that with the progression in battery technologies, the net present value of V2G is projected to reach around 7000 $. This highlights the potential of V2G to be cost-competitive against conventional stationary energy storage technologies. Furthermore, given the right technological advancements and usage contexts, V2G could assume a crucial role in the future electricity system, providing significant profitability.

A study by *Freeman* et al. [47] examined a five-year, hourly economic model of V2G. They modeled several scenarios for a participant who uses an EV with a 60 kWh capacity battery, such as the Tesla Model S or Chevrolet Bolt, in New York City. This modeling used pricing data from the years 2010 to 2014. The study's sensitivity analysis revealed that factors like one-way power efficiency and battery lifespan significantly impact the economics of selling electricity back to the grid. The study demonstrated that while selling electricity from vehicles to the grid can yield economic benefits, these benefits are relatively small due to the cost of additional wear on the vehicle's battery. However, the study also showed a promising trend in the potential economic benefits of this technology over the five-year period.

In this, *Rahman* et al. [48] examined the levelized cost of storage (LCOS) for V2G technology. They developed a model to estimate the available energy and associated costs for V2G applications across a range of temperatures. The base case values for the LCOS were found to be 230,88 $/MWh and 329,93 $/MWh for energy arbitrage and frequency regulation, respectively. The study identified key parameters influencing these costs, including ambient temperature, battery cycle life, daily travel distance, battery depth of discharge, battery capital cost or electricity price. This work concluded that the likely ranges for the LCOS are 158 $ - 290 $/MWh for energy arbitrage and 244 $ - 485 $/MWh for frequency regulation.

Another interesting work was formulated by *Prencipe* et al. [49] on the challenges associated with a management system that integrates car-sharing operations and V2G technology. They proposed a mixed integer linear programming formulation to optimize the management of EVs within a one-way car-sharing system that incorporates V2G. This model facilitated the determination of an optimal start-of-day distribution of EVs that maximizes the total revenue derived from system users and V2G profits via daily charging and discharging schedules for the vehicles. The authors tested the model on both a small-scale test network and a real-scale test network in Delft, Netherlands. The results suggested that the adoption of V2G technology can fully offset the daily charging costs incurred from users' trips and generate V2G profits by leveraging the unused time of EVs, without significantly impacting the demand satisfaction of the car-sharing system.

1.2. Contributions of the current work

The current work acknowledges the significant role of V2G technology in efficiently integrating more EVs into the grid. This service can contribute to the modernization and stabilization of the grid, while also being a crucial part of a greener, cleaner, and more resilient energy system. This work offers a comprehensive review of V2G technology, emphasizing the key aspects of EV grid integration and understanding how this technology and energy storage service could be beneficial and profitable for both EV owners and the grid. It also provides insights into how varying electricity and storage prices could influence the future economic viability of V2G, particularly in the context of Portuguese electricity market and EV owners.

This work addresses a significant gap in the current literature on V2G technology by developing an original economic model that puts EV users at the center stage. The model considers various factors such as battery degradation, distance traveled, frequency of charging and discharging, the number of V2G charge-discharge cycles, electricity purchase and sale prices, and the cost of new batteries for example. The model is designed for four types of EV users: “Retired”, “Worker”, “Commercial Technician”, and “Uber”. Each user type has distinct vehicle usage characteristics. The model enables the calculation of potential revenue that each user can generate by providing V2G services to the electricity grid. Importantly, it also considers the point at which each user would need to replace their vehicle battery due to wear and tear. This work, therefore, provides a valuable tool for understanding the economic implications of V2G technology for different types of real-life EV users.

This paper's key contributions include the development of a unique economic model that calculates the financial revenue a user can earn from the grid by providing V2G services, while also compensating for additional battery degradation. It also introduces four distinct types of EV owners, each with different vehicle usage characteristics, to test the model. Furthermore, this research integrates the aforementioned aspects within the context of the Portuguese electricity market. It links the growing number of EV users in Portugal and analyzes the results obtained. This analysis helps understand the scenarios in which this service could be most beneficial for different real-life EV users. The paper also projects the future of this technology, suggesting that this service could become increasingly profitable and significant in the coming years as storage prices continue to decline. This research thus provides valuable insights into the evolving landscape of EV usage and V2G services.

To date, no scientific article has tackled the subject of V2G technology within this specific context. Numerous technical analyses exist, detailing the workings of the technology and the benefits it can offer to the electrical grid. Some articles have even developed economic models to evaluate the future feasibility of the V2G service, mostly in terms of operational costs. However, none of these works have put these models to the test using potential users and varying vehicle usage profiles, let alone incorporated as many parameters into these models as our work has. Moreover, there is a noticeable absence of papers in the literature that analyze the case of the Portuguese electricity market in relation to V2G technology. Consequently, this study provides data that could enable companies, organizations, and prospective EV buyers to make informed decisions, helping them understand the circumstances under which this service could be economically advantageous. The viewpoint of electric vehicle users, and how to engage them in providing services to the grid, is a topic that is noticeably underrepresented in scientific discourse. This work aims to illuminate, publicize, and advance understanding of this issue.

2. Methodology and case study

2.1. Model presentation

To assess the economic feasibility of a potential V2G service for the electricity grid, a numerical model was created. This model estimates the potential revenue a user could earn after several years of providing V2G service. The aim is for this revenue to offset the degradation inflicted on the car battery by the V2G operations and cycles and provide a profit to the user at the same time.

To implement this model, we have conceptualized four distinct potential EV users:

1) "Retired" - An individual who only operates the vehicle for two hours over the weekend.
2) "Worker" - An individual who uses the vehicle for one hour on weekdays solely for commuting to work, and for three hours over the weekend.
3) "Commercial Technician" - An individual employed in the commercial sector who utilizes the vehicle for four hours each working day (either in the morning or afternoon), and leaves it parked at the company's premises over the weekend.
4) "Uber" - Individuals who work as Uber drivers and operate the vehicle for 16 h daily throughout the week (split into two 8-h shifts between two drivers), except on alternate Sundays. The vehicle is privately owned by another individual and is operated by two different drivers who work both shifts.

We designed these four user profiles to mimic different types of vehicle usage, enabling a thorough and varied analysis of multiple scenarios. This analysis allows us to examine a range of users, from those who use the vehicle intensively (like "Uber"), to those who rarely use the car (such as "Retired"), and even those who fall somewhere in between, like 'Worker' and 'Commercial Technician'. Importantly, the model developed in this study can be adapted to any real-life user type, making it a potentially valuable tool for the future of this technology and its widespread implementation.

The detailed characteristics of each user (number of V2G charge-discharge cycles, number of road environment charge-discharge cycles, kilometers traveled per day, hours of vehicle use, frequency of recharging, etc.) will be elaborated in detail in Tables 2 to 5 that follow.

The number of V2G cycles (NC_{V2G}) each user performs per month is determined by their individual time availability, which naturally depends on their chosen vehicle usage. This model posits that a user with more 'free' time (i.e., less frequent car usage) has more opportunities to carry out the V2G service.

In this model, it is assumed that all users possess the same EV - a Tesla Model X - and have the capability to charge it either at home or at their company's premises. The Tesla Model X was chosen because it is one of the brand's most popular models in Portugal, which has grown in terms of sales year on year. Also, for a more intuitive comparison of results between the different users created to test the model, it was decided to assign the same car to all of them. The characteristics of this vehicle are presented in Table 1 below:

For the calculations performed, an optimistic sales price of 0,50 €/kWh was chosen (contracted with the energy supplier) for the user/owner of the EV to sell the stored electricity back to the grid (it will also be calculated the more realistic prices of 0,30 €/kWh and 0,20 €/kWh, to analyze the differences and perform a sensitivity analysis), with the aim of making a great profit for providing the energy storage service and attract new users to provide this service. It was also defined that car charging by users/owners would always be carried out at night in slow charging when energy prices are lower. Based on Energias de Portugal (EDP) [51] data, an electricity cost (in Portugal) of 0,11 €/kWh was set for EV charging during the night. Despite the Tesla Model X vehicle batteries having a capacity of 100 kWh, it was decided that each user would only make 80 kWh (80 %) available for sale to the grid, to avoid depleting the battery to 0 % of its energy and thus prevent accelerating its degradation even further. For this model we consider that each time a V2G charge-discharge cycle is carried out, the battery charge available (80 kWh) is completely consumed by the grid and the same happens when the user charges the battery again, always charging it up to 100 %. In the case of road use, each user (through their use of the vehicle) always charges their vehicle to 100 %, then uses its entire range (576 km) and only then charges again. For the price of a new battery in 2023–2024, we receive information from Tesla staff directly, who told us depending on the circumstances, the price could be between 8000

Table 1
- Key features of the Tesla Model X Vehicle [50].

Tesla Model X characteristics	
Characteristics	Values
Price	103,990 euros
Range	576 km
Maximum speed	250 km/h
Capacity 0–100 km/h	3,9 seconds
Transmission	Dual engine all-wheel drive
Battery capacity	100 kWh
Battery cycles until it drops to 80 % of its capacity	1500
Cost of a new battery (2023–2024)	Between 8000 and 10,000 €
Resistance coefficient	0,24 Cd
Weight	2335 kg
Motor power	Front: 252 kW; Rear: 252 kW
Total Vehicle power	670 horsepower (~500 W)
Supercharging	250 kW

and 10,000 €. So, for these calculations we assume that a new battery always costs 10,000 €.

2.2. User characteristics

Below in Tables 2 to 5 are represented some chosen in advance (Car, B_c, C_{bat}, EV_R, NC_{V2G} and Vehicle use) and calculated characteristics of each of the four users designed for the economic feasibility study. The way to perform the calculated characteristics is based on eqs. 1, 2, 3 and 4, presented in the next part of the paper, in the section "user characteristics calculations". They are $AvN_{Days/month}$, AvN_{Kmday}, FR_{Road} and NC_{Road} (average number of days during a month; average number of kilometers each user travels per day; frequency of charging in a road environment and number of road environment cycles performed during a month respectively). The characteristics "Car", "B_c", "C_{bat}" and "EV_R" are all based on real-life data from Tesla, presented before in Table 1. The characteristics "NC_{V2G}" and "vehicle use" were chosen by the authors to be able to analyze several different user scenarios in terms of vehicle use and consequent availability of time to carry out the V2G service.

2.3. User characteristics calculations

To calculate the parameters $AvN_{Days/month}$, AvN_{Kmday}, FR_{Road} and NC_{Road}, equations Eq. 1, Eq. 2, Eq. 3, Eq. 4 were used:

$$\mathrm{AvN_{Days/month}} = \frac{\mathrm{N_{days/year}}}{\mathrm{N_{months/year}}} \quad (1)$$

where $AvN_{days/month}$ is the average number of days per month of the year, $N_{days/year}$ is the number of days during a year (always considered 365 days) and $N_{months/year}$ is the number of months during a year. Then, to calculate the average number of km's each user travels per day:

$$\mathrm{AvN_{Kmday}} = \frac{\mathrm{N_{Km/month}}}{\mathrm{AvN_{days/month}}} \quad (2)$$

where AvN_{Kmday} is the average number of kilometers each user travels per day and $N_{Km/month}$ is the number of kilometers each user travels per month. To know the frequency of each user to recharge their EV due to road environment use, we can use the following equation:

$$\mathrm{FR_{Road}} = \frac{\mathrm{EV_R}}{\mathrm{AvN_{Kmday}}} \quad (3)$$

where FR_{Road} is the frequency (in days) of recharging the EV from each user based on the utilization of the car in road environment and EV_R is the EV range.

Table 2
- "Retired" user characteristics.

Retired	
Characteristics	Values
Car	Tesla Model X
B_c	100 kWh (of which only 80 kWh are sold)
C_{bat}	1500 cycles
EV_R	576 km
NC_{V2G}	20 cycles - 5 times a week on weekdays
Vehicle use	0 h per day during the five working days of the week; two hours over the entire weekend (8 days a month)
AvN_{Kmday}	15 km each Saturday and 15 km each Sunday (Average of 3,94 km's per day of the month)
$N_{Km/month}$	120 km
FR_{Road}	146 (needs to recharge the EV only due to road environment use from 146 to 146 days)
NC_{Road}	0,2083 cycles
PS_{ele}	0,50 €/kWh
PP_{ele}	0,11 €/kWh

Table 3
- "Worker" user characteristics.

Worker	
Characteristics	Values
Car	Tesla Model X
B_c	100 kWh (of which only 80 kWh are sold)
C_{bat}	1500 cycles
EV_R	576 km
NC_{V2G}	10 cycles - twice a week on weekdays; once every two weekends
Vehicle use	One hour per day for the five working days of the week; three hours all weekend (31 days per month)
AvN_{Kmday}	5 km's each working day of the week; 20 km's over the weekend (average of 5,91 km's per day of the month)
$N_{Km/month}$	180 km's
FR_{Road}	97,33 (needs to recharge the EV only due to road environment use from 97,33 to 97,33 days)
NC_{Road}	0,3125 cycles
PS_{ele}	0,50 €/kWh
PP_{ele}	0,11 €/kWh

Table 4
- "Commercial technician" user characteristics.

Commercial technician	
Characteristics	Values
Car	Tesla Model X
B_c	100 kWh (of which only 80 kWh are sold)
C_{bat}	1500 cycles
EV_R	576 km's
NC_{V2G}	5 cycles - once a week on Friday; once in a weekend to be defined
Vehicle use	Four hours a day during the five working days of the week; zero hours all weekend (20 days per month)
AvN_{Kmday}	100 km's a day during the five days of the week (average of 65,75 km's per day of the month)
$N_{Km/month}$	2000 km's
FR_{Road}	8,76 (needs to recharge the EV only due to road environment use from 8,76 to 8,76 days)
NC_{Road}	3,47 cycles
PS_{ele}	0,50 €/kWh
PP_{ele}	0,11 €/kWh

Table 5
- "Uber" user characteristics.

Uber	
Characteristics	Values
Car	Tesla Model X
B_c	100 kWh (of which only 80 kWh are sold)
C_{bat}	1500 cycles
EV_R	576 km's
NC_{V2G}	2 cycles - Every two Sundays
Vehicle use	Sixteen hours a day every day of the week; except on Sundays every two weeks (29 days a month)
AvN_{Kmday}	300 km a day except on Sundays every two weeks (average of 286,02 km's per day of the month)
$N_{Km/month}$	8700 km
FR_{Road}	2,01 (needs to recharge the EV only due to road environment use from 2,01 to 2,01 days)
NC_{Road}	15,10 cycles
PS_{ele}	0,50 €/kWh
PP_{ele}	0,11 €/kWh

Finally, it is important to calculate the number of charging cycles in a road environment per month:

$$\mathrm{NC_{Road}} = \frac{\mathrm{A_{NDays/month}}}{\mathrm{FR_{Road}}} \quad (4)$$

where NC_{Road} is the number of charging cycles in a road environment per month.

2.4. Revenue model calculations

We then move on to perform the calculations that enable us to determine the revenue each user will receive from the grid operator, which is based on the number of V2G cycles they complete.

2.4.1. Calculation of monthly and annual battery degradation by V2G cycles and road environment cycles

First, we need to calculate the monthly degradation of the battery caused by V2G cycles, based on Eq. 5:

$$\mathrm{Bmd}_{\mathrm{V2G}} = \frac{\left(\frac{\mathrm{NC}_{\mathrm{V2G}}}{\mathrm{C}_{\mathrm{bat}}}\right) \times 80}{100} \tag{5}$$

where Bmd_{V2G} corresponds to the monthly degradation of the battery by V2G cycles (in percentage – monthly degradation rate). NC_{V2G} corresponds to the number of V2G cycles to be carried out with the grid per month and C_{bat} are the battery cycles until it drops to 80 % of its capacity (1500 cycles), the usual value considered when the battery is at the end of its useful life [52]. 80 (kWh) is the battery capacity made available to be consumed by the grid.

To calculate the monthly battery degradation from road use, we use Eq. 6:

$$\mathrm{Bmd}_{\mathrm{Road}} = \frac{\left(\frac{\mathrm{NC}_{\mathrm{V2G}}}{\mathrm{C}_{\mathrm{bat}}}\right) \times 100}{100} \tag{6}$$

where Bmd_{Road} corresponds to the monthly degradation of the battery by road environment cycles (in percentage – monthly degradation rate). 100 (kWh) is the battery capacity for road use, remembering that each user uses the entire range of their EV's battery in a road environment and only then charges again.

The total monthly degradation of the battery is achieved using Eq. 7:

$$\mathrm{Total}_{\mathrm{Bmd}} = \mathrm{Bmd}_{\mathrm{V2G}} + \mathrm{Bmd}_{\mathrm{Road}} \tag{7}$$

where $Total_{Bmd}$ is the total monthly degradation of the battery.

The annual degradation of the battery (in percentage – annual degradation rate) by V2G cycles can then be calculated from Eq. 8:

$$\mathrm{Bad}_{\mathrm{V2G}} = \mathrm{Bmd}_{\mathrm{V2G}} \times \mathrm{N}_{\mathrm{months/year}} \tag{8}$$

where Bad_{V2G} corresponds to the annual degradation of the battery by V2G cycles.

The annual degradation of the battery (in percentage – annual degradation rate) by road environment cycles can then be calculated from Eq. 9:

$$\mathrm{Bad}_{\mathrm{Road}} = \mathrm{Bmd}_{\mathrm{Road}} \times \mathrm{N}_{\mathrm{months/year}} \tag{9}$$

where Bad_{Road} corresponds to the annual degradation of the battery by road environment cycles.The total annual degradation (in percentage) of the battery is achieved using Eq. 10:

$$\mathrm{Total}_{\mathrm{Bad}} = \mathrm{Bad}_{\mathrm{V2G}} + \mathrm{Bad}_{\mathrm{Road}} \tag{10}$$

where $Total_{Bad}$ is the total annual degradation of the battery.

2.4.2. Calculation of monthly and annual revenue generated by the V2G service

The gross monthly profit obtained from providing the V2G service is calculated based on Eq. 11:

$$\mathrm{M}_{\mathrm{rV2G}} = \mathrm{NC}_{\mathrm{V2G}} \times \mathrm{B}_{\mathrm{c}} \times \mathrm{PS}_{\mathrm{ele}} \tag{11}$$

where M_{rV2G} corresponds to the gross monthly revenue by V2G service, B_c to the battery capacity used for the service (80 kWh) and PS_{ele} to the selling price of electricity to the grid.

The user's monthly expenses for charging their EV due to V2G cycles can be calculated in Eq. 12:

$$\mathrm{C}_{\mathrm{CostsV2G}} = \mathrm{NC}_{\mathrm{V2G}} \times \mathrm{B}_{\mathrm{c}} \times \mathrm{PP}_{\mathrm{ele}} \tag{12}$$

where $C_{costsV2G}$ are the monthly charging costs for charging the EV by the user/owner due to V2G cycles and PP_{ele} corresponds to the purchase price of electricity by the user/owner to charge the EV at night, when it is cheaper.

The user's monthly expenses for charging their EV due to road environment cycles can be calculated in Eq. 13:

$$\mathrm{C}_{\mathrm{CostsRoad}} = \mathrm{NC}_{\mathrm{Road}} \times \mathrm{B}_{\mathrm{c}} \times \mathrm{PP}_{\mathrm{ele}} \tag{13}$$

where $C_{costsRoad}$ are the monthly charging costs for charging the EV by the user/owner due to road environment cycles. Remember that, in the case of road use, the battery capacity “available” (B_c) is 100 kWh.

The total monthly charging costs for charging the EV by the user/owner are calculated by Eq. 14:

$$\mathrm{TM}_{\mathrm{Ccosts}} = \mathrm{C}_{\mathrm{CostsV2G}} + \mathrm{C}_{\mathrm{CostsRoad}} \tag{14}$$

where TM_{Ccosts} is the total monthly charging costs for charging the EV by the user/owner.

The total annual costs for charging the EV can then be calculated in Eq. 15:

$$\mathrm{TA}_{\mathrm{Ccosts}} = \mathrm{TM}_{\mathrm{Ccosts}} \times \mathrm{N}_{\mathrm{months/year}} \tag{15}$$

where TA_{Ccosts} is the total annual costs for charging the EV.

The user's net monthly profit only from V2G service can then be obtained in Eq. 16:

$$\mathrm{NM}_{\mathrm{profitV2G}} = \mathrm{M}_{\mathrm{rV2G}} - \mathrm{C}_{\mathrm{CostsV2G}} \tag{16}$$

where $NM_{profitV2G}$ corresponds to the net monthly profit of each user only from providing the V2G service to the grid.

However, it is essential to calculate the net monthly profit of each user, deducting from the net monthly profit received by the V2G service the monthly charges for charging the EV due to the use in a road environment, and this can be calculated by Eq. 17:

$$\mathrm{Total}_{\mathrm{NMprofitV2G}} = \mathrm{NM}_{\mathrm{profitV2G}} - \mathrm{C}_{\mathrm{CostsRoad}} \tag{17}$$

where $Total_{NMprofitV2G}$ is the net monthly profit received by the V2G service deducting the expenses in road environment.

The user's net annual profit only from the V2G service can be calculated from Eq. 18:

$$\mathrm{NA}_{\mathrm{profitV2G}} = \mathrm{NM}_{\mathrm{profitV2G}} \times \mathrm{N}_{\mathrm{months/year}} \tag{18}$$

where $NA_{profitV2G}$ corresponds to the user's net annual profit only from the V2G service.

The total net annual profit needs to be calculated deducting the annual recharging costs in a road environment from the net annual profit from providing the V2G service, like in Eq. 19:

$$\mathrm{Total}_{\mathrm{NAprofitV2G}} = \mathrm{NA}_{\mathrm{profitV2G}} - \mathrm{A}_{\mathrm{CcostsRoad}} \tag{19}$$

where $Total_{NAprofitV2G}$ is the total net annual profit from providing the V2G service and $A_{CcostsRoad}$ is the annual costs for charging the EV due to the road environment use.

2.4.3. Calculation of the time needed to profit from the V2G service to cover the cost of purchasing a new battery due to the wear and tear caused

First, we need to know the number of months of V2G service it would take for the user to obtain the necessary income to buy a new battery for their EV. This can be calculated in Eq. 20:

$$\mathrm{T}_{\mathrm{months}} = \frac{\mathrm{C}_{\mathrm{nb}}}{\mathrm{NM}_{\mathrm{profitV2G}}} \tag{20}$$

where T_{months} corresponds to the number of months of V2G service it would take for the user to obtain the necessary income (10,000 €) to buy a new battery for their EV and C_{nb} corresponds to the cost of a new battery.

To convert months into years, we can use Eq. 21:

$$T_{years} = \frac{T_{months}}{N_{months/year}} \tag{21}$$

where T_{years} corresponds to the number of years of V2G service it would take for the user to obtain the necessary income to buy a new battery for their EV.

To subsequently calculate the total revenue generated by the V2G service after T_{years} corresponding to the number of years it would take for the user to obtain the necessary revenue to buy a new battery, Eq. 22 is obtained:

$$P_{Tyears} = NA_{profitV2G} \times T_{years} \tag{22}$$

where P_{Tyears} corresponds to the user's profit after T_{years} corresponding to the number of years it would take for the user to obtain the income necessary to buy a new battery.

It is also necessary to calculate how many years it would take, in each specific case, for the battery to need to be changed due to degradation caused by the V2G service and by road environment use. We can calculate this value from the Eq. 23:

$$T_{bat} = \frac{U_{Bcap}}{Total_{Bad}} \tag{23}$$

where T_{bat} is the number of years that, according to each specific case (annual battery degradation rate for each user), it would take for the EV battery to be changed. U_{Bcap} corresponds to the useful capacity of the battery (20 % or 1500 cycles) until it enters a "deactivation" state, remembering that when reaching 80 % capacity it is considered that the battery no longer serves the vehicle's purposes in the best way.

Finally, it is also important to know the net profit generated by each user's V2G service after the cost of changing the battery. First, we need to know the revenue generated by providing the V2G service at the time of battery replacement (before changing the battery), like in Eq. 24:

$$P_{Tbat} = T_{bat} \times NA_{profitV2G} \tag{24}$$

where P_{Tbat} is the total gross profit generated by providing the V2G service at the time of battery replacement. To know the net profit achieved by the V2G service after changing the battery, we must subtract the cost of a new battery (for this calculation we assume that the cost of a new battery is always 10.000 Euros) from the gross value generated, according to Eq. 25:

$$NP_{V2G} = P_{Tbat} - C_{nb} \tag{25}$$

where NP_{V2G} is the total net value of profit that each user obtains for the V2G service after the costs for changing the battery in their EV.

3. Results and discussion

Table 6 presents the results obtained from calculations based on an electricity selling price of 0,50 €/kWh to the grid for each of the four users, as per the previously discussed numerical model. All the equations presented before were used to compute these results. These results will be discussed in more detail in the next section of the paper. Subsequently, calculations for the prices of 0,30 €/kWh and 0,20 €/kWh will also be analyzed and compared.

In this scenario, the 'Retired' (1547 €) and 'Worker' (1260 €) users are able to turn a profit by providing the V2G service, even after accounting for the costs of battery replacement. Interestingly, the profits of these two users are not significantly different, despite the 'Worker' user's battery life being twice as long as that of the 'Retired' user. This could potentially make the 'Worker' user's case more favorable. Although these users need to replace their batteries every 1,5 years ('Retired') and every 3 years ('Worker'), they consistently see a substantial profit after covering the costs of battery replacement. For the 'Commercial Technician' user, a battery change would be necessary every 3,4 years due to wear and tear. Every 3,4 years, this user would need to purchase a new battery. Based on our results, a new battery for this user would cost 3737 € (the profit from the V2G service minus the cost of a new battery). It may not be economically sensible for this user to accelerate battery degradation with that amount of V2G service provided and spend 3737 € every 3,4 years on battery replacements. In the case of the 'Uber' user, this service could be a promising solution. In this instance, battery degradation would occur rapidly even without the V2G service. However, the revenue that this type of user earns from the minimal V2G service provided to the grid allows to offset the cost of a new battery by more than 1000 €.

Table 6
- Results of the model for the electricity selling price of 0,50 €/kWh.

	Values (***PS****ele*=0,50 €/kWh)			
	Retired	Worker	Commercial technician	Uber
Bmd_{V2G}	1,07 %	0,53 %	0,27 %	0,11 %
Bmd_{Road}	0,01 %	0,02 %	0,23 %	1,00 %
$Total_{Bmd}$	1,1 %	0,6 %	0,5 %	1,1 %
Bad_{V2G}	12,8 %	6,4 %	3,2 %	1,3 %
Bad_{Road}	0,2 %	0,2 %	2,8 %	12,1 %
$Total_{Bad}$	13,0 %	6,6 %	6,0 %	13,4 %
$C_{CostsV2G}$	176 €	88 €	44 €	18 €
$C_{CostsRoad}$	2,3 €	3,4 €	38,2 €	166,2 €
TM_{Ccosts}	178 €	91 €	82 €	184 €
TA_{Ccosts}	2140 €	1097 €	986 €	2205 €
M_{rV2G}	800 €	400 €	200 €	80 €
$NM_{profitV2G}$	624 €	312 €	156 €	62 €
$Total_{NMprofitV2G}$	622 €	309 €	118 €	−104 €
$NA_{profitV2G}$	7488 €	3744 €	1872 €	749 €
$Total_{NAprofitV2G}$	7460 €	3702 €	1414 €	−1245 €
T_{months}	16	32	64	160
T_{years}	1,3	2,7	5,3	13,4
P_{Tyears}	10,000 €	10,000 €	10,000 €	10,000 €
T_{bat}	1,5	3,0	3,4	1,5
P_{Tbat}	11,549 €	11,260 €	6263 €	1120 €
NP_{V2G}	1547 €	1260 €	−3737 €	−8879 €

3.1. Number of charge-discharge cycles per month

Fig. 3 illustrates the number of V2G and on-road charge-discharge cycles each user performs monthly. In this model, it's assumed that users fully recharge their EVs whenever they need to, due to either on-road or V2G usage. This means they always recharge up to 100 %. However, for V2G usage, only 80 % (80 kWh) of the battery charge is utilized, and the grid consumes the entire 80 kWh each time. Following each V2G cycle, all users recharge their EVs to full capacity overnight, with an electricity price of 0,11 €/kWh. For on-road usage, recharging is only done when the EV's range is depleted. Again, these recharges are performed up to the maximum battery capacity. From the four scenarios created, it's evident that the "Commercial Technician" user maintains a better balance between the number of charges due to on-road usage and V2G usage (and achieving the best balance in this respect does not guarantee this user a good balance of income received from the V2G service, as we already saw above). We can also observe extremes in the cases of the "Retired" and "Uber" users. For the former, most monthly charge-discharge cycles are allocated for the V2G service. For the latter, most cycles are intended for intensive on-road usage, due to the numerous transport services this user performs daily.

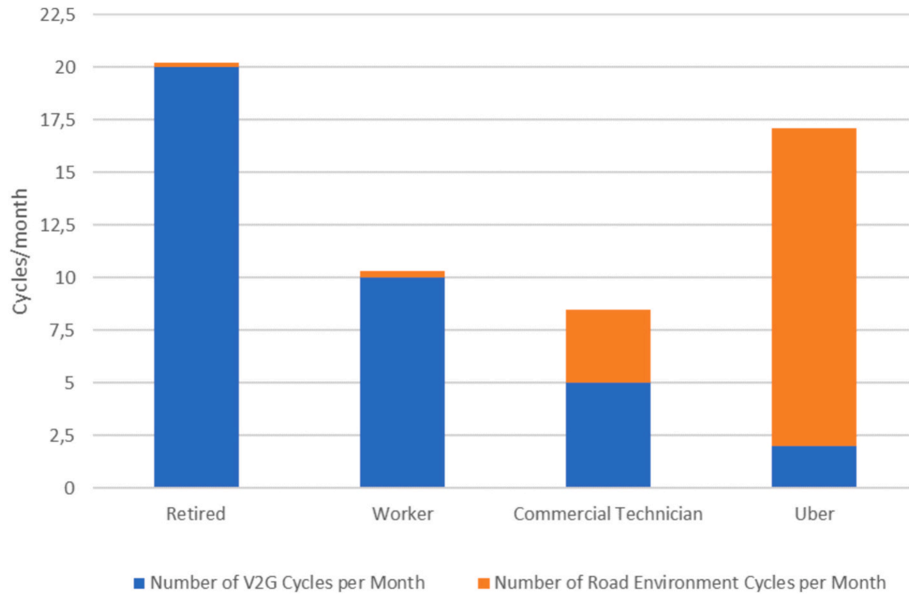

Fig. 3. - Number of charge-discharge cycles each user performs per month: number of times each user performs a V2G charge/discharge cycle and a road environment charge/discharge cycle.

3.2. Monthly degradation of the battery

The battery's lifespan may be shortened depending on the number of V2G and road use cycles each user undergoes. As depicted in Fig. 4, the battery of the 'Commercial Technician' user takes the longest to reach 80 % of its capacity, a threshold considered critical for optimal battery performance. The 'Retired' and 'Uber' users, who use V2G more frequently and drive more respectively, experience faster battery degradation, with their batteries lasting between one and a half to two years. An interesting comparison can be made between the 'Worker' and 'Retired' users: both make a substantial profit after replacing the battery, but the 'Worker' user's battery lasts longer despite more intensive car use. Even though the 'Retired' user may earn a few hundred more in profits, the 'Worker' user's situation could be more beneficial. This battery degradation simulation begins on January 1, 2023, and concludes on May 1, 2026, when the 'Commercial Technician' user's battery reaches its end of life after 3,4 years. Each user's timeline ends when their respective battery reaches its end of life: 'Retired' at 1,5 years, 'Worker' at 3 years, and 'Uber' at 1,5 years.

3.3. Annual spendings on total EV recharges

Fig. 5 illustrates the annual total cost incurred by each user for recharging their electric vehicles (EVs). This total cost encompasses both the costs of recharging due to Vehicle-to-Grid (V2G) cycles and the costs associated with road usage. In this scenario, the 'Retired' and 'Uber' users are once again at the forefront, incurring significantly higher expenses than the other two users. This is primarily attributed to the larger number of recharges these two users need to perform, whether for V2G (in the case of 'Retired') or for road usage (in the case of 'Uber'). Interestingly, we can observe that the 'Worker' user spends only half as much on recharging their EV compared to the 'Retired' user. This is a

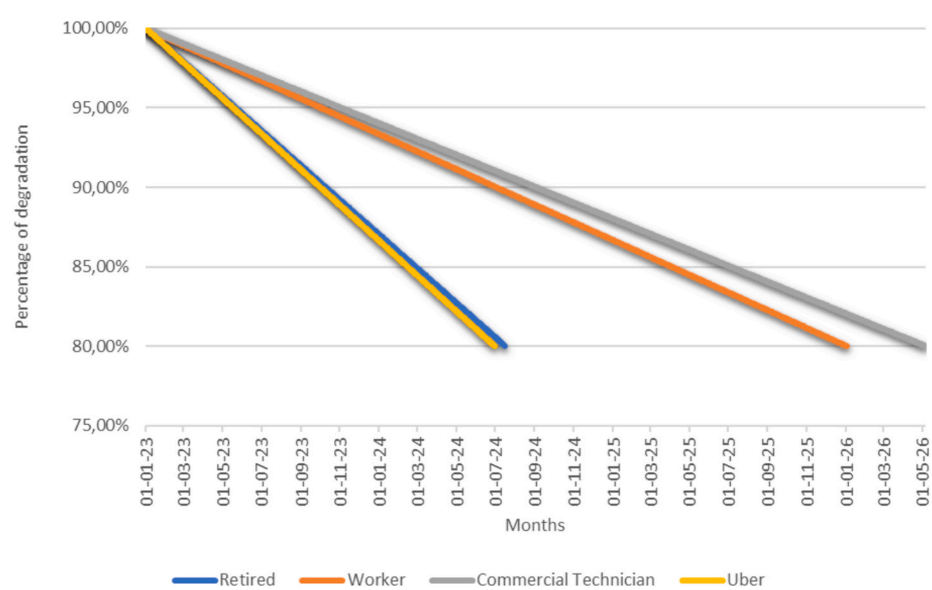

Fig. 4. - Represents the monthly degradation of each user's EV battery. The lines depict the decline in battery capacity over several months, from 100 % down to 80 %, indicating the battery's end of life.

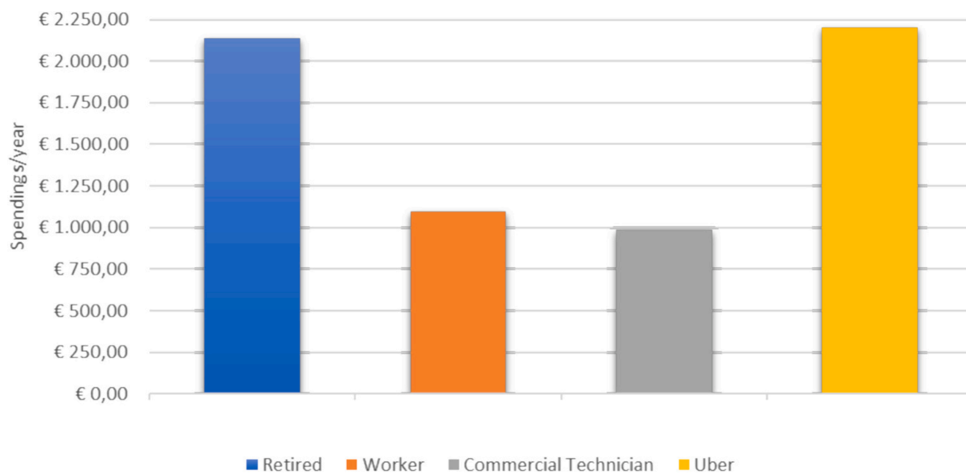

Fig. 5. - Annual spendings on total EV recharges by each user: the total amount of money that each of them spends in recharging their EV for V2G cycles and road environment cycles.

noteworthy observation, given that the 'Worker' user tends to use their car more frequently for road usage compared to the 'Retired' user. Yet, the net profits of these two users from providing the V2G service, even after accounting for the cost of a new battery, are not significantly different.

3.4. Annual profit from V2G service

Two distinct values are represented in Fig. 6 below: the darker green bars denote the annual profit each user makes solely from their V2G service. This profit only includes the earnings from the V2G service, and the expenses incurred from recharges related to the V2G service. The lighter green bars, on the other hand, represent each user's annual net profit. However, this value subtracts the annual amount spent on recharges for road use from the profit made through the V2G service. It's noticeable that for the 'Retired' and 'Worker' users, the two bars are quite similar. This similarity is due to the minimal annual recharge expenses these two users incur from using their EV on the road. In contrast, for the 'Uber' user, the value generated by the V2G service minus the costs of annual recharges due to intensive road use results in a negative value.

3.5. V2G service time to pay for a new battery

Fig. 7 illustrates the number of years each user would need to participate in V2G service to generate enough revenue to purchase a new battery (€10,000). For instance, the 'Retired' user could accumulate sufficient funds to buy a new battery after just 1.3 years of V2G service.

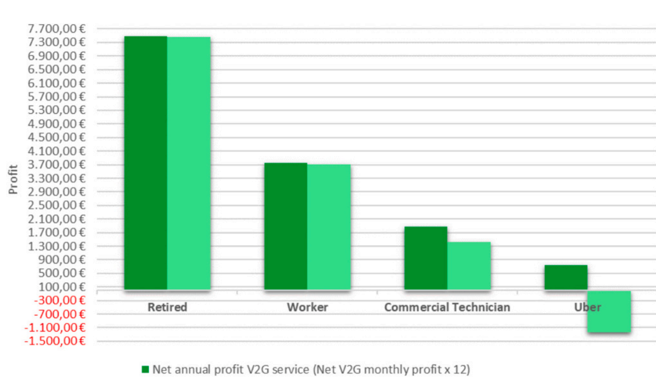

Fig. 6. - Annual profit of each user from providing the V2G service.

Conversely, the 'Uber' user would need to complete 13.4 years of V2G service to reach the same financial goal. The time required for each user to earn the necessary amount for a new battery is directly related to the number of V2G cycles they perform with the grid each month.

3.6. Number of years it would take before the battery needs to be replaced

Fig. 8 illustrates the lifespan of the vehicle battery in each specific scenario, indicating when it would need to be replaced due to reaching the end of its useful life cycle. It's clear that the more frequently the battery is used, whether for Vehicle-to-Grid (V2G) or on-road usage, the quicker it will degrade and the shorter its lifespan will be. In some instances, where electricity selling prices are particularly high (0,50 €/kWh), it may be advantageous to replace the battery every 1,6 years. However, as we will discuss later (in the analysis of the 0,20 and 0,30 €/kWh prices), this is not always the case.

3.7. Revenue generated at the time of battery replacement

Fig. 9 illustrates the revenue each user was able to generate through the V2G service at the point when they needed to replace their battery due to degradation. One of the primary goals of this work is to determine the conditions under which a user can still turn a profit from providing the V2G service, even after factoring in the cost of a new battery. For an electricity sales price of 0,50 €/kWh, it is evident that only the 'Retired' and 'Worker' users can make a profit after accounting for the expenses of replacing the battery. While the other two users also earn a significant income, it may not be economically viable for them to provide this service to the grid and further degrade their battery. However, for the 'Uber' user, this could present an intriguing scenario. This user would need to replace the battery just as quickly even if he did not offer the V2G service (which does twice a month). Given that the 'Uber' user uses their vehicle extensively on the road, the car's battery would degrade rapidly anyway. Therefore, the modest contribution of the V2G service that this user provides to the grid enables him to earn money to offset the cost of the new battery, which is priced at 10,000 €.

However, the trend is that battery prices will continue to fall in the coming years and therefore the profit for some users and the discount that others may have when changing the battery will be even greater, as we can see from the price of batteries predicted for 2030. The forecasted price of a new EV battery for 2030 is proposed by Wei-Hsuan Chen and I-Yun Lisa Hsieh [53], assuming the price of 75,1 $/kWh for battery packs in EVs. Converting Dollars into Euros (February 2024), an estimated price of 69,31 €/kWh was achieved. Since the Tesla Model X battery has a capacity of 100 kWh, the final estimated price for a new battery in

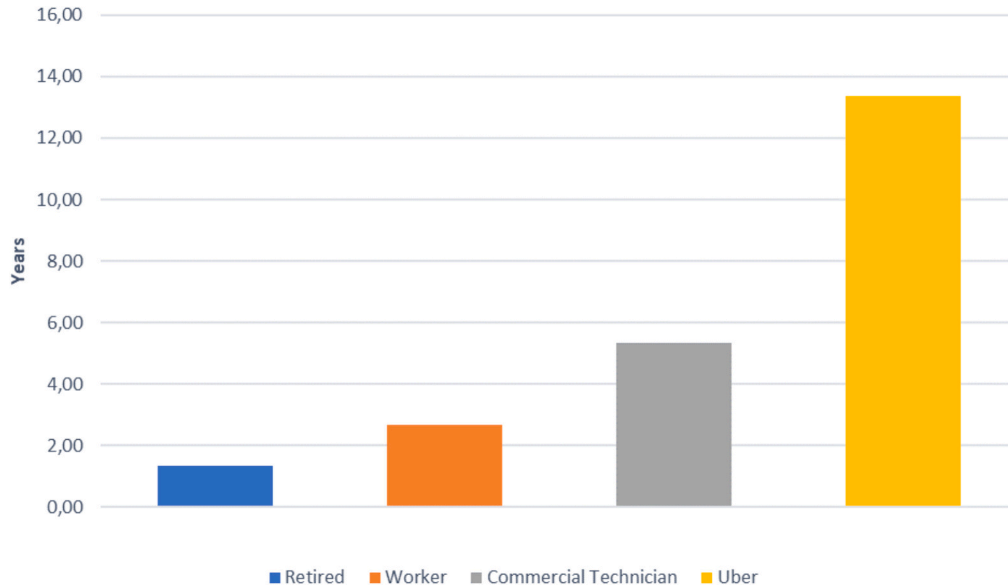

Fig. 7. - Each user's V2G service time to have the income to pay for a new battery (10,000 €).

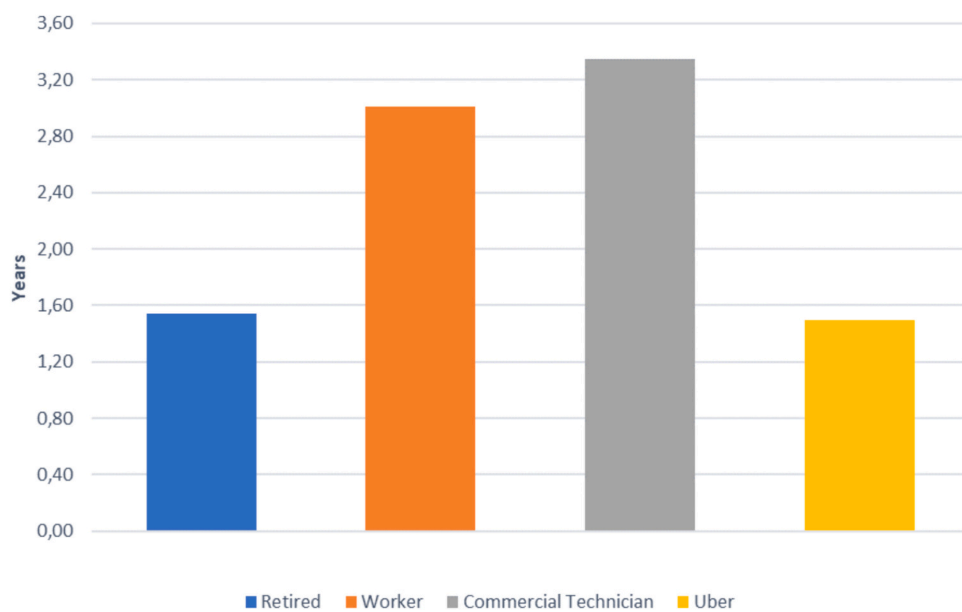

Fig. 8. - Number of years it would take before each user's EV battery needs to be replaced.

2030 was 6931 €.

3.8. Total net profit after battery replacement

Fig. 10 shows the total net profit each user gains from the Vehicle-to-Grid (V2G) service, taking into account the costs of purchasing a new battery. It's evident that, at a selling price of 0.50 €/kWh, only the 'Retired' and 'Worker' users can turn a profit even after accounting for the cost of a new battery. This suggests that the service, at this electricity selling price, could be profitable for both. Despite the necessity to replace the battery every two or three years, these two users are consistently assured of a satisfactory net income. Conversely, for the 'Commercial Technician' user, the service might not be as beneficial. Without the monthly V2G cycles, their Electric Vehicle (EV) battery would have a longer lifespan. While the V2G service they provide does reduce the cost of a new battery, it may not be worthwhile to accelerate battery degradation while storage prices remain high. However, once these prices decrease by half, the service could also become viable for the 'Commercial Technician' user. In the case of the 'Uber' user, this service might be advantageous. Given their intensive road use, they would need to replace the battery frequently regardless. By adding the modest V2G service they provide each month, they can generate some income and offset the costs of a new battery. As storage prices drop significantly, this type of service will become increasingly sensible for this user to undertake periodically.

4. Sensitivity analysis

The data obtained from the calculations (for electricity selling prices to the grid of 0,20 and 0.30 €/kWh) are presented in Tables 7 and 8. These calculations were carried out again for each of the four users presented previously, according to the numerical model presented earlier. Information regarding battery degradation is not shown in these tables, as it remains the same across all calculations for different

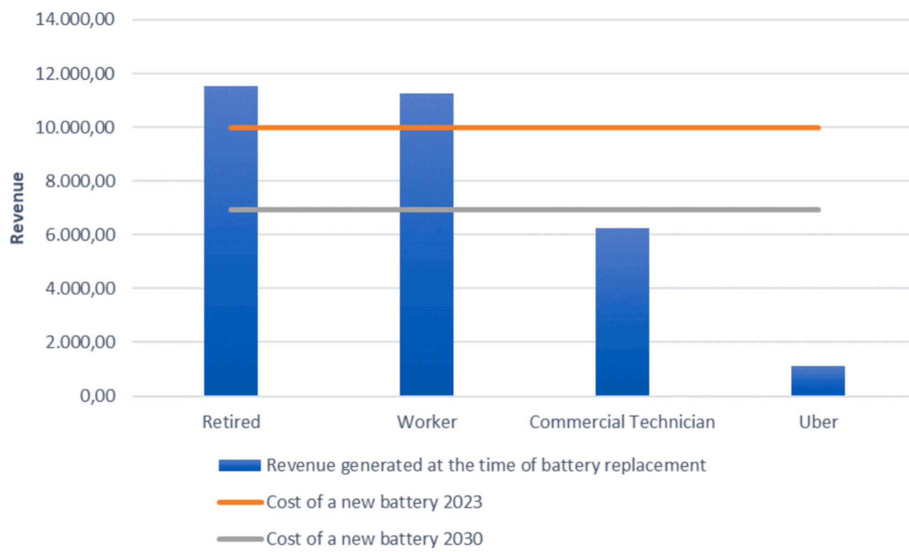

Fig. 9. - Each user's revenue at the time of battery replacement.

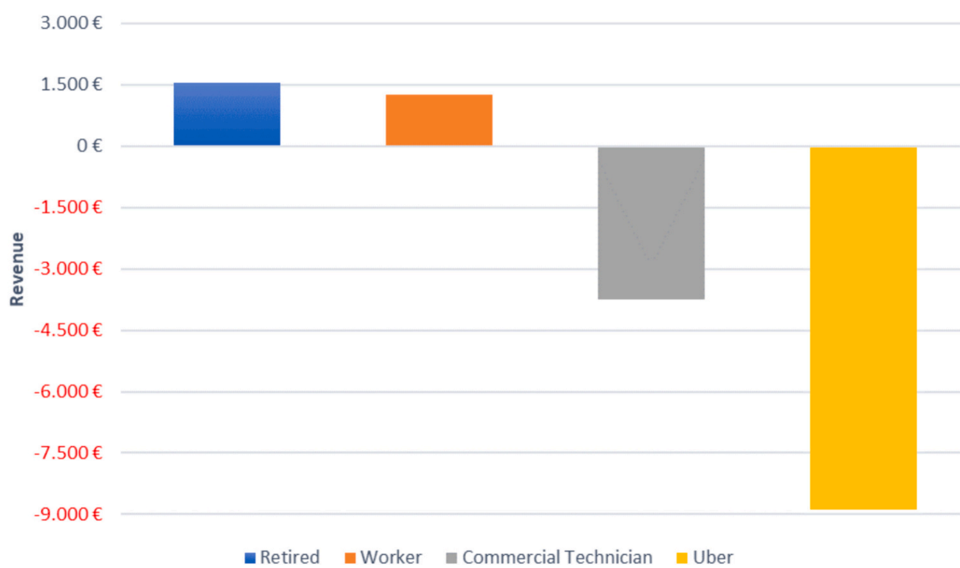

Fig. 10. - Each user's total net profit from providing the V2G service after the costs of purchasing a new battery.

Table 7
- Results of the model for the electricity selling price of 0,30 €/kWh.

	Values (PS_{ele} = 0,30 €/kWh)			
	Retired	Worker	Commercial technician	Uber
M_{rV2G}	480 €	240 €	120 €	48 €
$NM_{profitV2G}$	304€	152€	76€	30€
$Total_{NMprofitV2G}$	301,71 €	148,56 €	37,81 €	−135,75 €
$NA_{profitV2G}$	3648 €	1824€	912€	364€
$Total_{NAprofitV2G}$	3620€	1782€	453€	−1628€
T_{months}	32,89	65,79	131,58	328,95
T_{years}	2,74	5,48	10,96	27,41
P_{Tyears}	10,000 €	10,000 €	10,000 €	10,000 €
P_{Tbat}	5626 €	5485 €	3051 €	545 €
NP_{V2G}	−4373 €	−4514 €	−6948 €	−9454 €

Table 8
- Results of the model for the electricity selling price of 0,20 €/kWh.

	Values (PS_{ele} = 0,20 €/kWh)			
	Retired	Worker	Commercial technician	Uber
M_{rV2G}	320 €	160 €	80 €	32 €
$NM_{profitV2G}$	144 €	72 €	36 €	14 €
$Total_{NMprofitV2G}$	142 €	68 €	−2 €	−151 €
$NA_{profitV2G}$	1728 €	864 €	432 €	173 €
$Total_{NAprofitV2G}$	1700 €	823 €	−26 €	−1821 €
T_{months}	69,44	138,89	277,78	694,44
T_{years}	5,79	11,57	23,15	57,87
P_{Tyears}	10,000 €	10,000 €	10,000 €	10,000 €
P_{Tbat}	2665 €	2598 €	1445 €	259 €
NP_{V2G}	−7335 €	−7401 €	−8555 €	−9741 €

electricity selling prices.

Table 9 displays the net profits of each user from providing the V2G service, considering the costs of purchasing a new battery and the various electricity selling prices considered in this study. Fig. 11 presents a sensitivity analysis graph, illustrating the variability in each user's net profit after accounting for battery replacement costs, based on different electricity selling prices.

We can deduce that the optimal scenarios for offering the V2G

Table 9
- Total net profit of each user after the purchase of a new battery depending on different selling prices of electricity.

	NP_{V2G}			
PS_{ele}	Retired	Worker	Commercial Technician	Uber
0,50 €/kWh	1,549,61 €	1,260,15 €	-3,736,80 €	-8,879,32 €
0,30 €/kWh	-4,373,26 €	-4,514,29 €	-6,948,70 €	-9,454,03 €
0,20 €/kWh	-7,334,70 €	-7,401,50 €	-8,554,65 €	-9,741,38 €

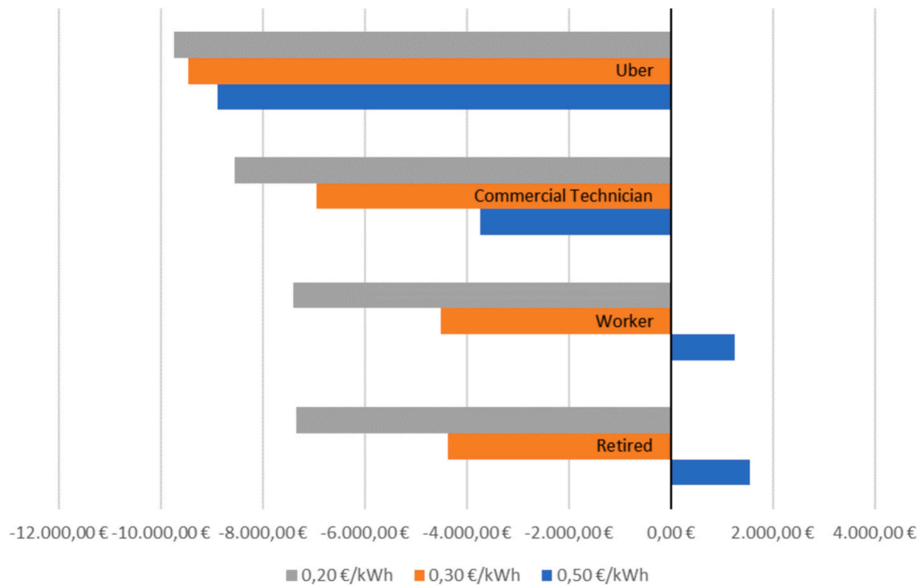

Fig. 11. - Differences on the total net profit after purchasing a new battery (10,000 €) based on electricity selling prices variation.

service occur in the cases of the 'Retired' or 'Worker' user, when the electricity sell-back price to the grid is 0,50 €/kWh. Even though these two types of users need to replace their batteries every two to three years, it would be advantageous if they could still net 1549 € and 1260 € respectively after these expenses, by providing the V2G service. However, as the sell-back price of electricity decreases (0,30 and 0,20 €/kWh), it becomes impractical for these users to continue degrading their batteries as they did when the sell-back price was 0,50 €/kWh. Why would these users allow their batteries to degrade to the point of needing replacement every one to two years if they can't profit from it after purchase? Essentially, under these conditions, these users would be spending thousands of euros every two to three years unnecessarily. Perhaps when the prices of energy storage significantly decrease, it might become feasible again to provide V2G service even with sell-back prices of 0,30 €/kWh and 0,20 €/kWh.

Currently, the 'Commercial Technician' user finds the least value in utilizing the V2G service. This user never achieves a profit after accounting for the cost of a new battery and doesn't use their vehicle as intensively as the 'Uber' user. Therefore, it's clear that it's not beneficial for this type of user to provide this service to the grid frequently and accelerate battery degradation. On the other hand, the case of the 'Uber' user can be deceptive. Despite consistently showing negative profit values after the battery purchase, considering the three electricity selling prices, this user primarily degrades the battery through road use. The few V2G cycles per month contribute minimally to the total degradation of this user's battery. Consequently, they would need to replace the battery within a short period regardless. However, the provision of the V2G service allows this user to offset the cost of a new battery. For instance, with an electricity selling price of 0,50 €/kWh, instead of paying 10,000 € upfront, this user would only pay 8879 €.

5. Conclusion

5.1. Final considerations

V2G technology is a groundbreaking innovation with the potential to fundamentally alter our interaction with electrical energy. This technology serves not only as a feasible solution for managing energy demand and integrating renewable energy into the grid, but also empowers EV owners by enabling them to actively participate in the electricity market. By considering operational and investment costs, along with associated benefits, we illustrate that V2G can present a financially appealing opportunity for certain EV owners under various circumstances. The outcomes of this model suggest that V2G can significantly enhance the personal profitability of numerous participants while simultaneously improving several grid parameters such as renewable energy penetration and storage, frequency, and voltage. However, it's crucial to acknowledge that the successful deployment of V2G comes with its own set of challenges. Regulatory issues, vehicle and system interoperability, and the necessity for infrastructure investment must be thoroughly addressed and studied. It's imperative that all stakeholders, including governments, vehicle manufacturers, energy traders, and consumers, collaborate to surmount these challenges.

This work concludes that the viability of the V2G service as a profitable opportunity hinges on the fluctuating prices of selling electricity back to the grid. For users with minimal vehicle usage, a high and optimistic selling price (0,50 €/kWh) presents an extremely attractive scenario. However, the profitability diminishes for these users when the selling price drops to 0,20 or 0,30 €/kWh. For heavy users, such as Uber drivers, any selling price ranging from 0,20 to 0,50 €/kWh can be beneficial as it significantly offsets operational and maintenance costs. As the cost of energy storage is projected to decrease sharply in the coming decades, the V2G service could become increasingly profitable and appealing to other user types. For instance, under current storage prices, our analysis shows that the "Commercial Technician" type of user would not generate sufficient profit to justify regular use of the V2G service. However, this could change with the anticipated drop in energy storage costs like we demonstrated with the expected prices for batteries in 2030.

In this scenario, V2G presents itself as a promising solution for optimizing energy consumption and aiding the shift towards a more sustainable energy framework. The integration of EVs with V2G technology not only diminishes carbon emissions but also enhances the resilience of the electrical grid, paving the way for a more resource-efficient utilization.

5.2. *Future perspectives*

As we move forward, the following steps could be crucial in our journey: 1) Developing clear standards and regulations - It's vital for regulatory authorities to establish clear guidelines for the implementation of V2G technology. This will ensure security, reliability, and a fair distribution of benefits; 2) Investing in infrastructure - Expanding the V2G charging and discharging infrastructure is essential for broader and more efficient adoption; 3) Education and awareness - It's important to educate EV owners about the benefits of V2G and encourage their active participation in contributing to a more resilient electrical grid; 4) Continuous research and development - Ongoing research and innovation are necessary to improve the efficiency and scalability of this technology. With the right measures in place, we can ensure that V2G becomes not just a reality, but also a valuable contribution to a more sustainable future. This study serves as a starting point for a broader discussion and a call to action, particularly in the case of Portugal. We hope that the results presented here can inspire future research and practical initiatives that allow the full realization of the potential of V2G technology in transforming the energy sector.

CRediT authorship contribution statement

Diogo Melo Gomes: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rui Costa Neto:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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