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Enhancing Shared Electric Vehicles Fleet Profitability with Vehicle to Grid Integration

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Abstract—Decarbonizing the transport sector is crucial for achieving sustainability goals, and two key strategies are the adoption of Electric Vehicles (EVs) and the expansion of Car Sharing Systems (CSS). EVs eliminate tailpipe emissions, while CSS reduces overall vehicle ownership and usage, leading to lower carbon emissions. Combining these two solutions into Electric Car Sharing Systems (ECSS) enhances their environmental and economic benefits. The integration of Vehicle-to-Grid (V2G) technology further strengthens this synergy by enabling EVs to support the energy grid, optimize charging costs, and improve system efficiency.

This study investigates the integration of Vehicle-to-Grid technology within an Electric Car Sharing System to enhance Car Sharing Operator (CSO) profitability. A mathematical model is developed to optimize the financial performance of a CSO managing a station-based ECSS with EVs across five stations. The model considers vehicle driving, relocation, charging, and discharging under time-varying electricity prices. Results show that V2G increases profitability by enabling energy sales during periods of low driving demand and high electricity prices. These findings provide insights for optimizing EV-sharing systems in dynamic electricity markets and highlight the need for advanced vehicle management strategies.

Index Terms—Relocation, Shared Electric Vehicles, Vehicle to Grid

I. INTRODUCTION

Decarbonizing the transport sector is crucial to mitigating climate change, as road transport accounts for nearly 75% of global CO_2 emissions from fuel combustion, with cars alone responsible for 45% [1]. While shifting towards cycling and public transport can reduce emissions [2], these alternatives are not always feasible, particularly in urban environments where car transport remains a necessity. Therefore, electrification and shared mobility services offer promising pathways to reduce transport-related emissions while maintaining accessibility.

The adoption of Electric Vehicles (EVs) is widely regarded as a key strategy for reducing transport emissions [1], [3]. EVs, powered by electricity instead of fossil fuels, have the potential to significantly cut greenhouse gas (GHG) emissions, particularly when charged with renewable energy sources [4].

However, large-scale EV deployment presents challenges, including high upfront costs, battery material extraction impacts, and increased demand on the electricity grid [5]. To accommodate widespread EV adoption, power grids must

be expanded and increasingly powered by renewable energy sources [6].

The intermittent nature of renewables and the additional electricity demand from EVs necessitate flexible energy management solutions [7], [8]. Smart Charging Algorithms (SCAs) help optimize charging schedules by adjusting charging times based on electricity prices and grid conditions [9]. SCAs can also participate in demand response programs, delaying or modulating charging power to alleviate grid congestion [10], [11].

Beyond SCAs, Vehicle-to-Grid (V2G) technology provides additional flexibility by enabling bidirectional energy flow between EVs and the grid [1]. V2G allows EVs to act as distributed energy storage, charging during periods of excess renewable generation and discharging when demand peaks, thereby supporting grid stability and renewable energy integration [6].

Car Sharing Systems (CSS) have emerged as another key strategy for reducing transport emissions [1], [3]. By increasing vehicle utilization rates and reducing private car ownership, CSS can lower emissions associated with car manufacturing and usage. One shared car can replace between four and eight private vehicles, significantly reducing urban congestion and parking space requirements [12]. Additionally, studies in the Netherlands have shown that car-sharing users drive 1,600 km less per year and reduce their car travel distances by approximately 20%, as they become more aware of alternative mobility options [12], [13].

Different CSS models offer varying degrees of flexibility, including two-way station-based, one-way station-based, and free-floating systems [4], [14], [15]. In two-way station-based CSS, users return vehicles to their original departure station, whereas one-way station-based CSS allows returns at different stations. Free-floating CSS provides the highest flexibility, enabling users to pick up and park vehicles within designated service zones. Dutch companies such as Greenwheels (two-way station-based) [16], Felyx, and Check (free-floating) [17], [18] exemplify the success of car-sharing services in urban environments.

Despite its advantages, one of the primary challenges in CSS—particularly in one-way and free-floating systems—is

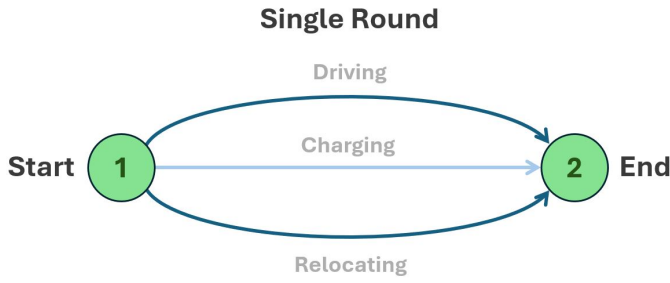


Fig. 1: Proposed System

vehicle imbalance. High-demand areas experience shortages, while low-demand zones accumulate underutilized vehicles, leading to suboptimal fleet distribution and financial inefficiencies [14], [15]. Additionally, EVs in CSS often return with low battery levels, requiring operators to deploy staff for both relocation and charging [14], [15].

This issue, referred to in the literature as the Electric Vehicle Relocation Problem (EVReP) [15], [19], [20] or Dynamic Electric Car Relocation Problem (DECRP) [14], revolves around optimizing vehicle relocation strategies to maximize financial returns while ensuring efficient charging operations. Addressing this challenge requires advanced modeling techniques that balance vehicle distribution, charging needs, and operational costs.

Integrating V2G technology into Electric Car Sharing Systems (ECSS) presents a promising solution to improve financial performance while supporting grid stability. By enabling shared EVs to discharge energy when parked, operators can capitalize on price fluctuations, enhance load balancing, and reduce peak demand. However, incorporating V2G adds complexity to fleet management, as relocation and charging strategies must also consider energy market dynamics.

This study develops a mathematical model to assess the impact of V2G integration in a station-based ECSS. The model optimizes financial profitability by considering vehicle relocation, charging, and discharging under different electricity pricing structures. The findings provide insights into how V2G can enhance the sustainability and economic viability of shared mobility services, contributing to decarbonization efforts in both the transport and energy sectors.

II. FORMULATION

To assess whether integrating V2G into relocation strategies for an EVSS can enhance overall profitability, a mathematical Mix Integer Linear Programming (MILP) model is developed. The model describes a one-way, station-based EVSS over a single day. During each time step, SEVs can either be driven by consumers, relocated by staff or (dis)charged. The model inputs are the stations' load, PV and price data, as well as driving demand.

A. Objective functions

The objective function aims to maximize the difference between the revenue generated by consumers driving the

SEVs, D_r , and energy trading, E_r , and the cost of relocation, R_c , as shown in Equation (1).

$$\max D_r - R_c + E_r \quad (1)$$

For all fulfilled driving demand, D_{tijk} , the total driving revenue is shown by Equation (2) and consists of a fixed initial fee, F^i and a per-distance fee, F^d , that is proportional to the distance between the departure and arrival station, SD_{ij} .

$$D_r = \sum_{t \in T} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} D_{tijk} * (F^i + SD_{ij} * F^d) \quad (2)$$

The relocation costs are calculated by multiplying the total number of relocation trips, R_{rijk} , by a fixed per-relocation worker fee, F^w , Equation (3).

$$R_c = \sum_{t \in T} \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} R_{rijk} * F^w \quad (3)$$

The energy revenue is calculated as the sold energy, E^{sold} , multiplied by the energy price, C^E , the timestep duration Δt , and the selling factor, SF , minus the bought energy, E^{bought} , multiplied by the energy price, C^E , Equation (4).

$$E_r = \sum_{t \in T} \sum_{i \in I} P_{ti}^{sell} * \Delta t * C_{ti}^E * SF - P_{ti}^{buy} * \Delta t * C_{ti}^E \quad (4)$$

B. Movement Constraints

The movement constraints model each trip made by each car, either by fulfilling the demand or by being relocated. Equation (5) and Equation (6) ensure that the cars' distribution at the first timestep, $t = 1$, is equal to the initial distribution and that the cars' initial distribution before sequential timesteps is equal to the cars' end distribution of the previous timestep respectively.

$$PreMD_{[1]ik} = IPreMD_{ik} \quad \forall i, \forall k \quad (5)$$

$$PreMD_{tik} = PMD_{(t-1)ik} \quad \forall t \in 2..T, \forall i, \forall k \quad (6)$$

Equation (7) ensures that no more cars are driven than are demanded.

$$\sum_{k \in K} D_{tijk} \leq DD_{tij} \quad \forall t, \forall i, \forall j \quad (7)$$

Equation (8) introduces the decision variable Movements, containing the demand, D_{tijk} , and relocation, R_{tijk} , moves

$$M_{tijk} = D_{tijk} + R_{tijk} \quad \forall t, \forall i, \forall j, \forall k \quad (8)$$

Equation (9), (10) and (11) ensure that cars can only be moved to and from one station and cannot be moved to a station equal to the departure station.

$$\sum_{i \in I} M_{tijk} \leq 1 \quad \forall t, \forall j, \forall k \quad (9)$$

$$\sum_{j \in J} M_{tijk} \leq 1 \quad \forall t, \forall i, \forall k \quad (10)$$

$$\sum_{i \in I} M_{tjik} = 0 \quad \forall t, \forall j, \forall k \quad (11)$$

Equation (12) ensures that there cannot be more cars leaving a station than there are located at that station at the start of each timestep.

$$\sum_{i \in I} M_{tijk} \leq PreMD_{tjk} \quad \forall t, \forall i, \forall k \quad (12)$$

Equation (13) ensures that the distribution after the cars' movements is equal to the distribution before the cars' movements plus cars arriving from any other station i to station j minus cars departing from stations j to any other station i .

$$PMD_{tjk} = PreMD_{tjk} + \sum_{i \in I} (M_{tijk} - M_{tjik}) \quad (13)$$

Equations (14) and (15) ensure that all cars that do not move are considered connected to a charger C_{tijk} .

$$C_{tijk} = PreMD_{tik} - \sum_{j \in J} M_{tijk} \quad \forall t, \forall i, \forall k \quad (14)$$

$$C_{tijk} = 0 \quad \forall t, \forall i, \forall j : i \neq j, \forall k \quad (15)$$

Equation (16) ensures that the vehicle distribution at the final time step aligns with the optimal end distribution. This optimal end distribution is an input provided by the CSO and represents the most favourable start-of-day vehicle distribution for the following day.

$$\sum_{k \in K} PMD_{Tik} = OED_i \quad \forall i \quad (16)$$

Equation 17 ensures that there are no more cars parked at a station than there are parking spots, p_i^{max} .

$$\sum_{k \in K} PMD_{tik} \leq p_i^{max} \quad \forall t, \forall i \quad (17)$$

C. Electric Vehicle Constraints

Equation (18) and (19) ensure that a car can only (dis)charge when it is connected and that the (dis)charging power must be equal to or lower than the maximum (dis)charging power.

$$P_{tik}^{ch} \leq P_i^{ch,max} * C_{tijk} \quad \forall t, \forall i, \forall k \quad (18)$$

$$P_{tik}^{dch} \leq P_i^{dch,max} * C_{tijk} \quad \forall t, \forall i, \forall k \quad (19)$$

Equations (20) and (21) ensure that the battery charge at the initial and final timesteps is equal to the initial battery charge levels.

$$BC_{(1)k} = BC_k^i \quad \forall k \in K \quad (20)$$

$$BC_{(T+1)k} = BC_k^i \quad \forall k \in K \quad (21)$$

Equations (22) and (23) ensure that battery charge levels always remain within their minimum and maximum values respectively.

$$BC_{tk} \geq BC_k^{min} \quad \forall t \in T, \forall k \in K \quad (22)$$

$$BC_{tk} \leq BC_k^{max} \quad \forall t \in T, \forall k \in K \quad (23)$$

Equation (24) ensures that the battery state of charge at the start of the timestep is equal to the battery state of charge of the previous timestep, minus the energy used for movements, plus the energy charged minus the energy discharged at the previous timestep.

$$BC_{tk} = BC_{(t-1)k} - \sum_{i \in I} \sum_{j \in J} M_{(t-1)ijk} * \frac{SD_{ij}}{\eta_k} + \sum_{i \in I} (\eta_k^{ch} * E_{(t-1)ik}^{ch} - \frac{1}{\eta_k^{dch}} * E_{(t-1)ik}^{dch}) \quad (24)$$

$$\forall t \in 2..T + 1, \forall k$$

D. Grid Constraints

Equation (25) sets the power flow for all stations considering the load P_{ti}^{LD} and PV generation of each station P_{ti}^{PV} and the power demanded by the EVs connected to that station $\sum_{k \in K} (P_{tik}^{ch} - P_{tik}^{dch})$

$$P_{ti}^{buy} - P_{ti}^{sell} = \sum_{k \in K} (P_{tik}^{ch} - P_{tik}^{dch}) + P_{ti}^{LD} - P_{ti}^{PV} \quad (25)$$

Equations (26) and (27) limit the power that is being sold/bought to/from the grid by the grid capacity.

$$P_{ti}^{sell} \leq P^{GC} \quad \forall t \in T, \forall i \in I \quad (26)$$

$$P_{ti}^{buy} \leq P^{GC} \quad \forall t \in T, \forall i \in I \quad (27)$$

III. CASE STUDIES

Simulations were carried out for a full day with a set of 24 EVs and 5 locations, as shown in Figure 2. Each station has a different number of parking spaces and different (dis)charging power. The driving demand is modelled to resemble a working day, with peaks in the morning, after working hours, and late in the evening for people doing leisure activities after work.

Load demand, PV generation have been obtained from an average residential house in the Netherlands on a summer day. All stations use the same power and PV profile, but are scaled differently between locations to see the impact of PV generation across locations. The price profile is based on the real Dutch day-ahead summer electricity price data from the ENTSO-E Transparency Platform [21].

The primary objective of this research is to assess the potential benefits of integrating V2G technology into ECSS.

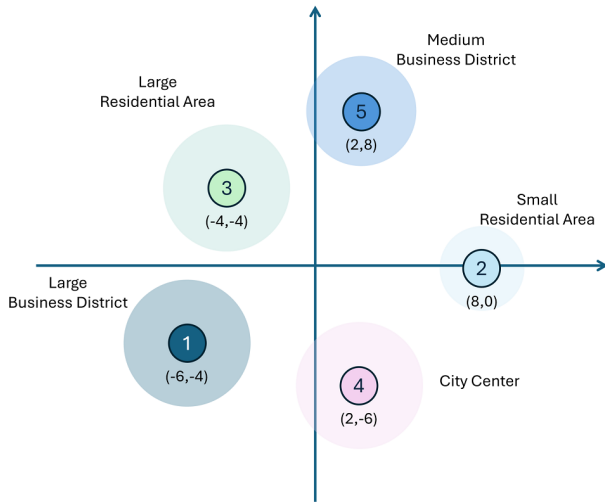


Fig. 2: Stations Coordinates (km)

Simulations were evaluated using IBM ILOG CPLEX, using a mixed-integer programming (MIP) gap of 0.1 to achieve a balance between computational efficiency and solution accuracy.

- Smart charging: This simulation provides a baseline scenario where V2G is disabled, and all charging stations offer electricity at the same time-varying price. This test case simulates typical shared EV operations without any grid interaction.
- Vehicle to Grid: This simulation builds on this by enabling V2G while maintaining equal time-varying electricity prices across stations. This will highlight the revenue potential of V2G services in a uniform price environment.

IV. RESULTS

This section presents the results of the scenarios, comparing their performance under uniform time-varying electricity prices. The analysis highlights the impact of V2G on energy cost reduction and load balancing within the system.

A. Smart charging

As illustrated in Table I, Driving Revenue constitutes the largest share of total revenue, with 97.2% of driving demand being fulfilled. In contrast, Energy Sold Revenue contributes only a small portion (1.14%) of total revenue because V2G is disabled. Energy is sold infrequently, occurring only when P^{PV} exceeds P^{LD} .

Driving Revenue	€ 2,859.30
Relocation Costs	€ 360.00
Energy Sold Revenue	€ 33.08
Energy Bought Costs	€ 616.68
Profit	€ 1,915.70

TABLE I: Revenue and Cost Breakdown

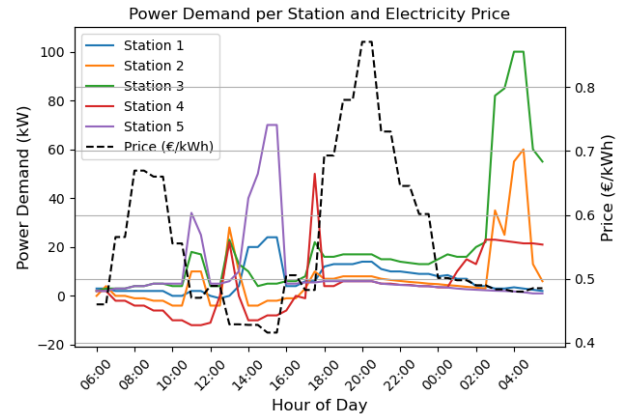


Fig. 3: Power Demand of Stations with Smart Charging

Results show stations 2 and 3 have the highest energy demand of all stations. This is due to a significant peak in charging power occurring between 3 and 5 AM, as shown in Figure 3. The peak is driven by the station's role as a residential area with a high driving demand in the morning. Since electricity prices are low during these hours, vehicles are charged there, resulting in the station's peak power. Stations 1 and 5 show pronounced peaks between 14:00 and 16:00. These peaks occur because most vehicles are located at these stations in the afternoon, as they correspond to business districts that are active during working hours. During this period, driving and relocation demand is low, and electricity prices remain relatively low, making it an optimal window for charging.

B. Vehicle to Grid

Since driving generates more revenue than selling energy, the number of fulfilled drives has remained consistent with the smart charging scenario. Consequently, both Driving Revenue and Relocation Costs remain largely unchanged. However, overall profit has increased by 2.25%, as shown in Table II. While the increase is modest, it is not unexpected. This growth is primarily driven by a significant rise in Energy Sold Revenue, which has increased by 371.5% following the introduction of V2G. However, Energy Bought Costs have also risen, as vehicles are charged more frequently to maintain higher energy levels in anticipation of discharging back to the grid during periods of elevated electricity prices.

Driving Revenue	€ 2,886.30
Relocation Costs	€ 363.00
Energy Sold Revenue	€ 155.96
Energy Bought Costs	€ 720.60
Profit	€ 1,958.66

TABLE II: Revenue and Cost Breakdown

In the V2G scenario, vehicles not only charge during periods of low electricity prices but also discharge when prices are relatively high. This behavior is particularly evident in the power profiles of Stations 3 and 5 and even more so for Station

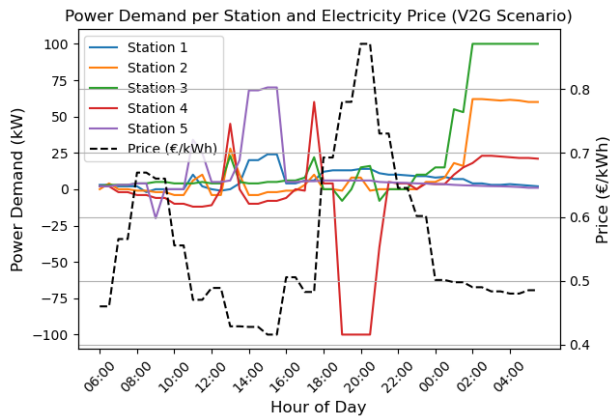


Fig. 4: Power Demand of Stations with Vehicle to Grid

4. While Stations 3 and 5 sold little to no energy under smart charging, they actively sell energy during peak price periods with V2G. Station 4 remains the largest contributor to energy sales, benefiting from peak electricity prices, low vehicle demand, and a relatively high share of vehicles available for discharging, as shown in Figure 4.

V. CONCLUSIONS

This study presents a novel approach to integrating V2G technology with ECSS to enhance the profitability of transportation services. The results show that V2G can improve financial outcomes by enabling EVs to participate in energy markets.

The integration of V2G not only provides economic benefits but also supports the broader goal of decarbonizing the transport sector by optimizing the use of renewable energy. The findings align with existing literature on the potential of V2G technology.

Nevertheless, this study has limitations, including simplified assumptions regarding vehicle operation, user behavior, and grid conditions. Future research should address these limitations by incorporating real-world data and developing more advanced and realistic models that account for dynamic pricing, as well as variations in user demand, vehicle availability, and other relevant factors. Additionally, further exploration of policy incentives for V2G participation and the development of more efficient vehicle relocation algorithms could enhance the practical application of these systems.

By combining car-sharing with V2G, this research contributes to the growing body of knowledge on sustainable urban mobility and renewable energy integration, providing a promising direction for future innovation in transportation and energy systems.

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