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V2G Technology: Unlocking Flexibility Through Charging Patterns and Infrastructure Analysis

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Executive Summary

This paper evaluates the potential of Vehicle-to-Grid (V2G) technology across public, semi-public, and home charging applications, focusing on its technical feasibility, while discussing economic benefits and its impact on grid stability. By analyzing usage patterns from real world charging data, energy demands, and stakeholder benefits, this work highlights the varying role of each application type in enabling V2G adoption. The findings suggest that public charging could be ideal for grid support during peak hours, semi-public charging offers flexibility for institutional use, and home charging could provide a decentralized approach to energy storage. Recommendations will include tailored policy frameworks, financial incentives, and technical advancements to maximize V2G participation across these domains. This research aims to provide actionable insights for utilities, policymakers, and EV owners, driving sustainable energy integration and broader V2G adoption.

Keywords: V2H & V2G, Smart charging, Optimal charging locations, Consumer Behaviour, Electric Vehicles

1 Introduction

In 2023, nearly 14 million new electric vehicles (EVs) were registered worldwide, increasing the total number on the roads to 40 million [1]. This figure is projected to rise significantly, reaching between 500 and 800 million by 2035, depending on various forecasting scenarios [2]. Building on the rapid growth of the EV market, V2G technology emerges as a transformative solution, leveraging the bidirectional charging capabilities of EVs to enhance grid stability [3], boost the integration of renewable energy sources [4], and provide economic benefits for consumers and utilities alike [5].

EV charging can take place in various locations and at different power levels. These locations can by classified to home, semi-public and public. While the definition of home and public charging is quite straight forward, semi-public is covering the middle space between these two categories (e.g. workplace, hotels, shopping malls and supermarkets, etc). In addition, several actors, such as EV driver, Charging Management System, Utilities, DSOs, etc., need to be synced on information layer to achieve V2G sessions, with the physical connection been enabled by the charger, the EV and the grid/load.

Even though chargers with V2G capabilities are already becoming a common market practice and EV OEMs following that trend, V2G is still very much in the pilot project or prototype stage and has large difficulties getting market traction. Main challenges can be divided into four groups: technical, financial, social-environmental, and behavioral [6].

This paper will focus on the behavioral analysis of EV drivers' charging patterns and dive into real case EV charging sessions data with the aim to show that there is flexibility for V2G applications. This means that there is enough time for the EV not only to be charged according to its mobility needs, but there is also idle time support to support V2G services.

2 Charging Infrastructure Characteristics

Home, semi-public, and public charging have unique characteristics and roles in supporting EV adoption. Home charging typically makes use of AC home network, offers EV owners the convenience of overnight charging and complete control over energy usage, making it ideal for decentralized V2G applications. Semi-public charging, located in private but publicly accessible spaces such as workplaces, shopping centers, or residential complexes, provides intermediate accessibility and supports institutional-level V2G participation, allowing organizations to optimize energy use and contribute to grid stability. Public charging, found in highways, urban areas, and public parking facilities, is the most accessible option, serving a wide range of EV users, particularly those without access to home charging. These key differences between them, are summarized in Table 1 below.

Table 1: Charging Location Characteristics

Feature	**Home**	**Semi-Public**	**Public**
Access	Private use	Restricted groups	Open
Location	Residential spaces	Workplaces, hotels, etc.	Public spaces
Cost Model	Home utility bill	Free or fee-based	Price per kWh
Charging Power	7.4/11kW AC	7.4/11kW AC or up to 50kW DC	11/22 kW AC or up to 400 kW DC

3 Methodology

During this study, publicly available charging session data have been gathered and analyzed. The data attributes are the session ID, the charging point/site ID, the user ID (EV driver) the plugin duration time, the energy consumed during that session, and the location category of the charger.

The following methodology was proposed.

Step 1. Data cleaning: All the charging sessions with plugin duration lower than 0.5 hours and greater than 48 hours have been filtered out. The same was done for charging sessions with energy consumed out of the range 1 - 100kWh.

Step 2. Charging behavior analysis: Various data and their corresponding statistical values are presented to understand the behavior of the users. Since, all the datasets are missing the values of charging power for each session, a new term was introduced as

$$P^i_{average} = \frac{E^i}{t^i_{plugin}} \quad (1)$$

where $P^i_{average}$ is the calculated average power in kW, E_i the consumed energy in kWh over the plugin duration time t^i_{plugin} of the i-th charging session.

Step 3. V2G Energy potential: To demonstrate that there are charging sessions that could support V2G schemes/services, the following expression is proposed to calculate the V2G energy

$$E^i_{v2g} = \max\left(\frac{CP_{cap} * t^i_{plugin} - E_i}{2}, 0\right) \quad (2)$$

where E^i_{v2g} is the potential energy in kWh that could be extracted from the EV for V2G services, and CP_{cap} is the theoretical installed bidirectional capacity of the charger.

Different energy values schemas/tariffs could be applied on that energy, as summarized in [7], to indicate the potential revenue for each charging session. However, a 0.15€ flat rate was selected, to keep simplicity.

Step 4. Grouping: Group and sum up the result per charging point or charging site and

Step 5. Comparison: Result analysis and insights inferences drawn between the different locations

4 Results

In the following subsections each charging location is analyzed.

4.1 Residential Charging

The methodology was initially applied to a dataset of residential charging sessions reported in [8], yielding the results summarized below.

The original dataset contained 6,878 charging sessions recorded between December 2018 and January 2020. After applying the data cleaning steps outlined in Section 3, the final dataset consisted of 5,074 sessions involving 56 unique EV drivers and 23 charging points.

Figure 1 presents the distribution of plugin durations across the dataset. A multi-modal distribution is observed, with notable peaks in the 0–5-hour range (short-term charging), the 8–10-hour range (consistent with overnight residential charging patterns), and beyond 15 hours (potentially representing vehicles parked for extended periods without active charging). These prolonged connection times are particularly relevant for V2G applications, providing windows for grid services without impacting user mobility.

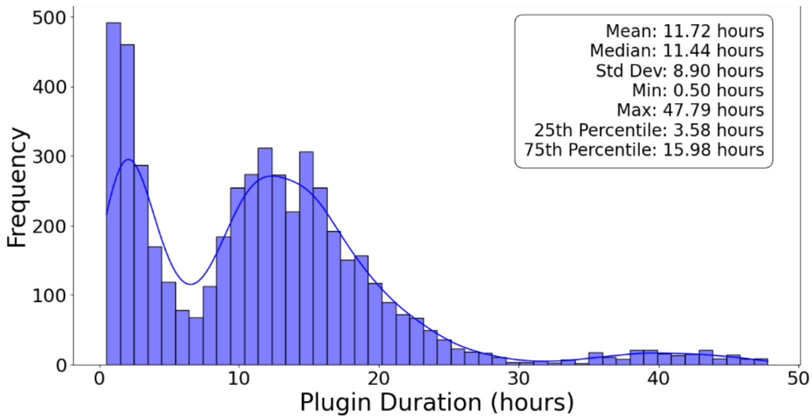

Figure 1: Distribution of Charging plugin duration

The distribution of calculated average charging power, according to (1), is shown in Figure 2. The mean average power is 1.72 kW, while the median is 1.12 kW, indicating that most sessions occur at significantly lower power levels than the typical 7.4 kW AC home charging rate. The observed max at 7.4 kW corresponds to full utilization of single-phase 32A residential chargers, confirming that a subset of users consistently charges at maximum available capacity.

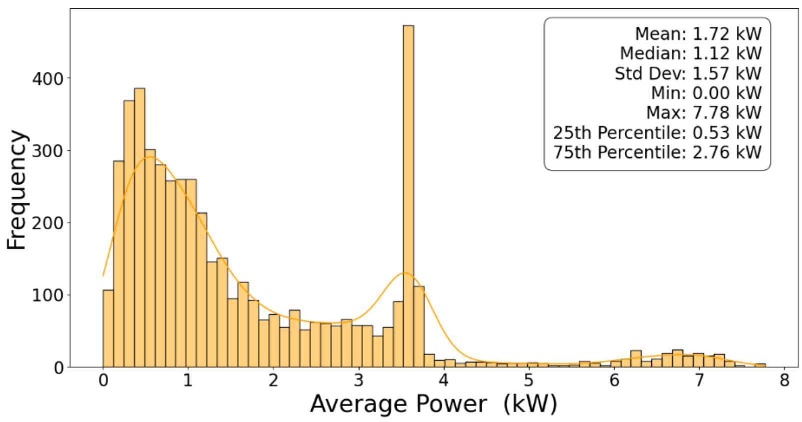

Figure 2: Distribution of average charging power

Figure 3 plots the energy consumption against plug-in duration for each session. The scatter plot illustrates two key observations: (a) a high density of sessions within the 0–10-hour range with moderate energy consumption, and (b) that longer plug-in durations do not necessarily correlate with proportionally higher energy transfer, emphasizing the presence of idle times suitable for V2G exploitation.

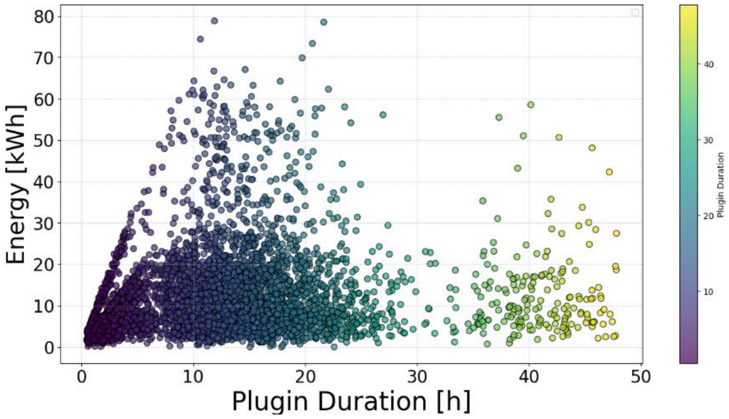

Figure 3: Energy consumption with plugin duration

Figure 4 aggregates the V2G flexibility potential and the associated revenue per charging site. The analysis reveals that a small number of sites (e.g., site B12) contribute disproportionately to the total flexibility potential, likely driven by either higher user density or longer connection durations. Several other sites, such as AdO3, AdO5, and AdO7, also exhibit substantial flexibility opportunities.

Similarly, Figure 5 presents the V2G flexibility and estimated revenue on a per-user basis. A considerable number of EV drivers could realize annual revenues exceeding €250 through participation in V2G programs, highlighting a meaningful incentive for residential users to engage in energy flexibility schemes.

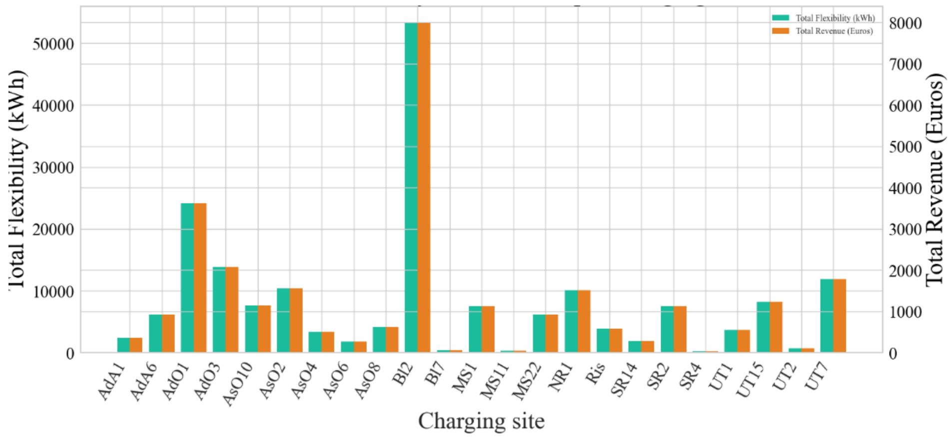

Figure 4: Total V2G flexibility and potential revenue per charging site

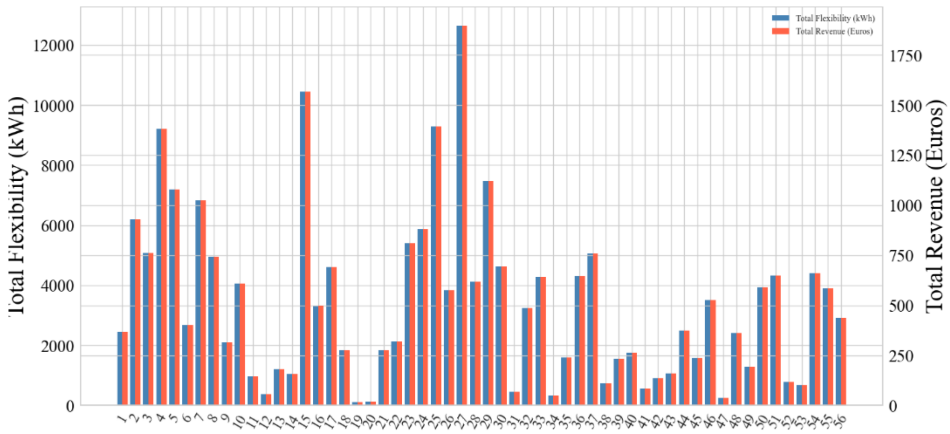

Figure 5: Total V2G flexibility and potential revenue per EV driver (user)

These findings affirm that residential charging environments, characterized by long dwell times and relatively low power transfers, are highly conducive to the effective deployment of V2G services.

4.2 Semi-public Charging

The methodology was subsequently applied to a dataset of semi-public charging sessions, specifically workplace charging behaviors documented in [9].

The original dataset contained information about 40,979 individual charging sessions from November 2016 to October 2021. Following the data filtering criteria of Step 1., the final dataset consisted of 29,784 sessions involving 376 EV drivers and 139 charging stations.

Figure 6 illustrates the distribution of plug-in durations. Most sessions fall within the 4 – 10-hour range, aligning well with typical office working hours. This pattern confirms a predictable and structured usage behavior, which is crucial for implementing automated or scheduled V2G operations during peak demand windows. The tail beyond 10 hours, though less dense, represents additional flexibility windows that could support extended V2G discharging or buffering services.

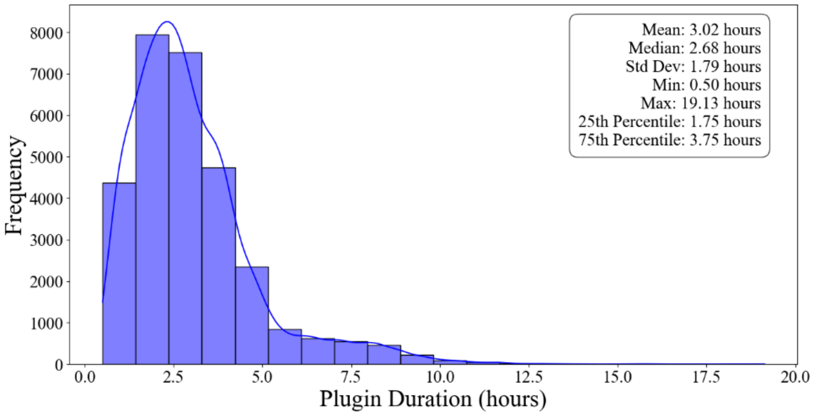

Figure 6: Distribution of Charging plugin duration

In Figure 7, the average charging power distribution indicates that most sessions occur below 4 kW, with a median value around 2.4 kW. While many chargers in semi-public environments support up to 7.4kW AC single phase or 11 kW AC, this underutilization implies that charging is occurring at slower rates—either due to vehicle limitations, load management strategies, or simply the long dwell times available. This is advantageous for V2G, as lower charging rates over longer durations increase the opportunity for controlled discharging without interfering with vehicle usability.

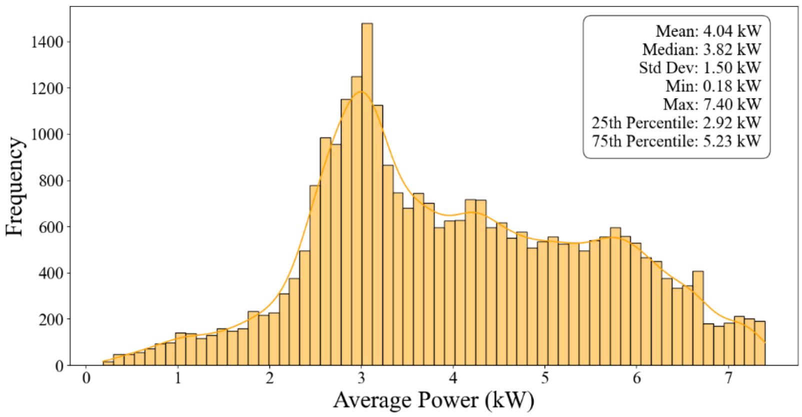

Figure 7: Distribution of average charging power

Figure 8 presents energy consumption as a function of plug-in duration. The trend again illustrates that longer plug-in durations are not always linked with higher energy demands. A considerable cluster of sessions with moderate energy consumption and long duration suggests substantial idle times, where the vehicle is connected but not actively charging. These idle periods are critical opportunities for enabling V2G, as they allow for grid interaction without disrupting the primary purpose of recharging the battery.

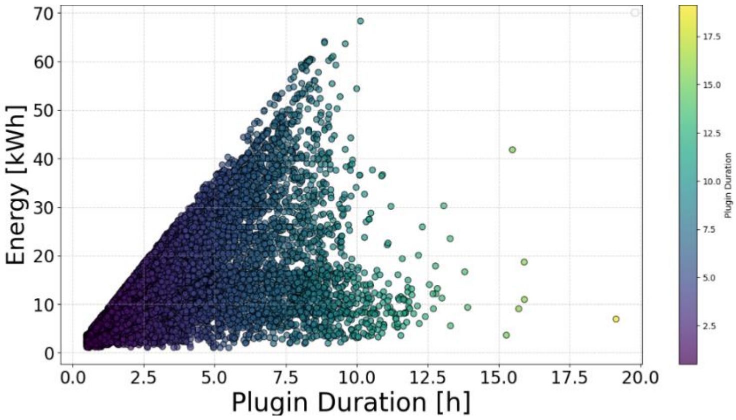

Figure 8: Energy consumption with plugin duration

Unlike residential environments, where the EV owner directly benefits from V2G participation, semi-public charging infrastructure (e.g., workplace chargers) is typically owned by corporations or institutions. Therefore, V2G flexibility was aggregated and analyzed at the organizational level. Table 2 summarizes the total V2G flexibility and associated potential revenue across all sites.

Table 2: V2G flexibility and potential revenue aggregated

Feature	Total	Average	Min.	Max.
V2G flexibility [kWh]	163407	1175	1.5	4301
Potential Revenue [€]	24511	176	0.22	645

The results demonstrate that semi-public environments, particularly workplace settings, offer a structured and predictable context for V2G deployment. The combination of fixed schedules, moderate average power use, and significant idle times represents an optimal foundation for institutional energy management strategies that integrate V2G services.

4.3 Public Charging

Following the application of the previously described methodology to charging session data obtained from Joltie, a public Charge Point Operator (CPO) network, the following results were derived and are presented below.

The dataset comprised 1,800 randomly selected individual charging sessions recorded between May 2023 and April 2024 on AC 22 kW public chargers. After applying the data cleaning criteria outlined in Step 1, the final dataset consisted of 1,712 sessions involving 640 EV drivers across 139 charging stations.

The histogram in Figure 9 illustrates the distribution of plug-in durations. Most charging events are concentrated within the 1–4-hour range, indicative of short-term parking behavior typical of urban commercial environments. Nevertheless, a non-negligible tail extending beyond 8 hours is observed, corresponding to cases of extended parking at locations such as transport hubs, shopping centers, or residential spillover facilities. These extended sessions represent valuable opportunities for V2G service integration without adversely impacting user convenience.

Figure 10 presents the distribution of calculated average charging power, as defined in Equation (1). Most sessions exhibit average powers below 11 kW despite charger capabilities of up to 22 kW AC. The median value is 6.32 kW, reflecting either limitations in the vehicle onboard chargers, user-driven cost optimization strategies, or charging behaviors favoring lower power transfer rates over longer connection periods.

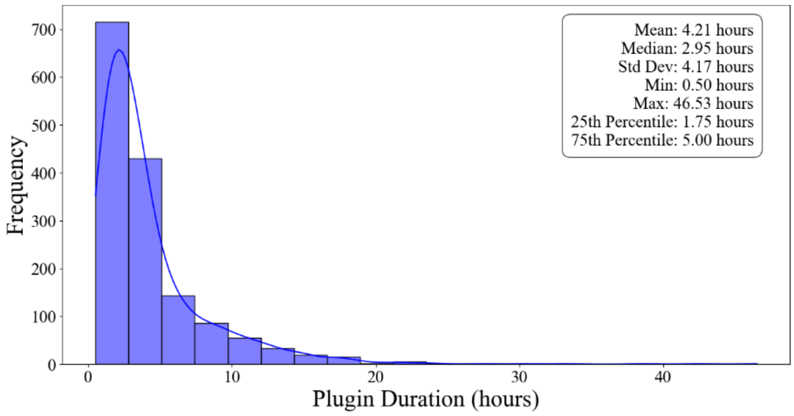

Figure 9: Distribution of Charging plugin duration

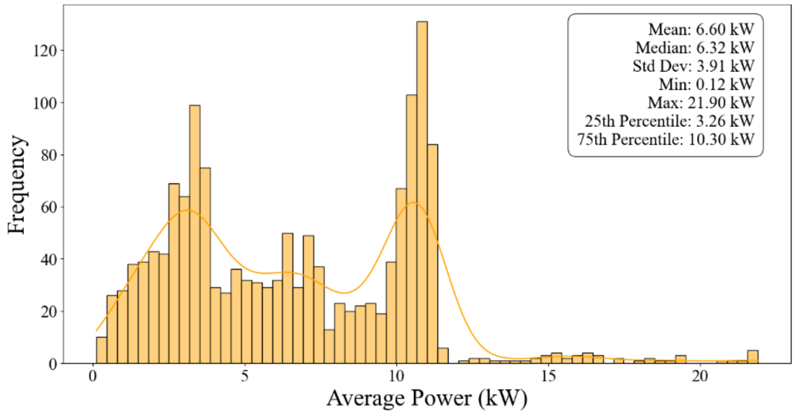

Figure 10: Distribution of average charging power

The relationship between energy consumption and plug-in duration is shown in Figure 11. While a general positive trend is observed—energy consumption increasing with connection time—a high degree of variability persists. Many sessions of short-to-moderate duration result in limited energy transfer, indicative of vehicles remaining connected beyond the required charging time. These idle periods are critical in the context of V2G deployment, offering windows where grid services can be delivered without compromising the user's mobility needs.

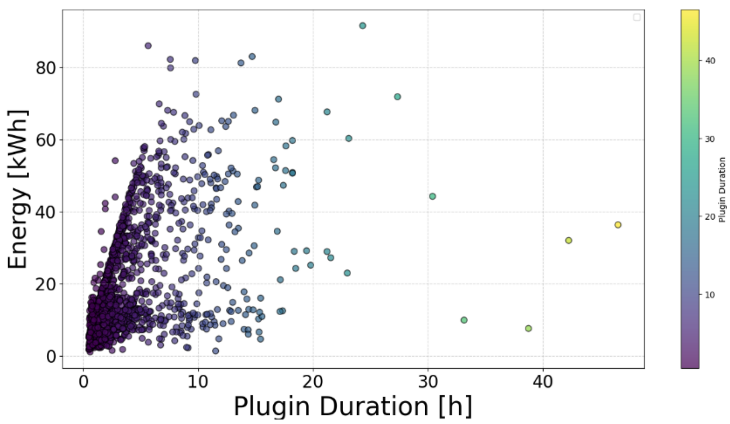

Figure 11: Energy consumption with plugin duration

The aggregate V2G potential and corresponding estimated revenue per charging site are depicted in Figure 12. A few high-utilization sites dominate the overall flexibility potential, suggesting strategic prioritization of these locations for initial V2G program rollouts. Conversely, sites with limited flexibility potential may require targeted interventions or incentive mechanisms to optimize their contribution.

Similarly, Figure 13 displays the V2G flexibility and revenue potential on a per-user basis. Compared to residential and semi-public datasets, the public charging user base exhibits greater dispersion, with a minority of users offering substantial flexibility potential. This variability underscores the opportunistic nature of V2G in public networks, necessitating the aggregation of multiple low-potential users to achieve meaningful grid service contributions.

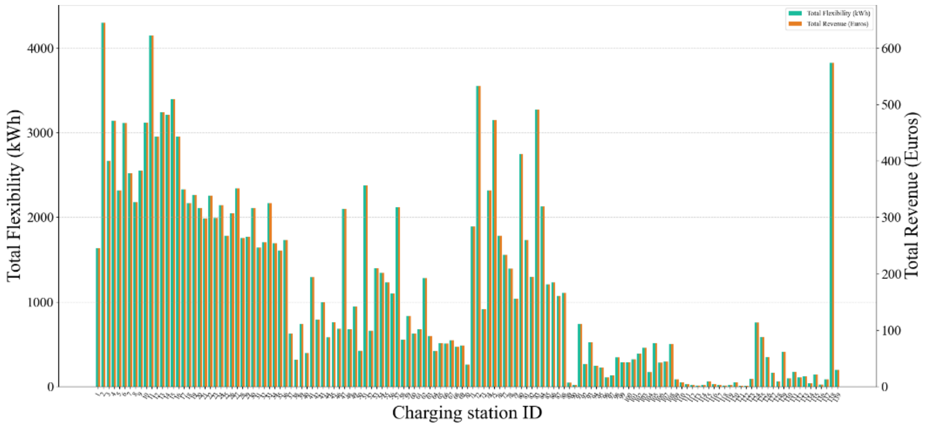

Figure 12: Total V2G flexibility and potential revenue per charging site

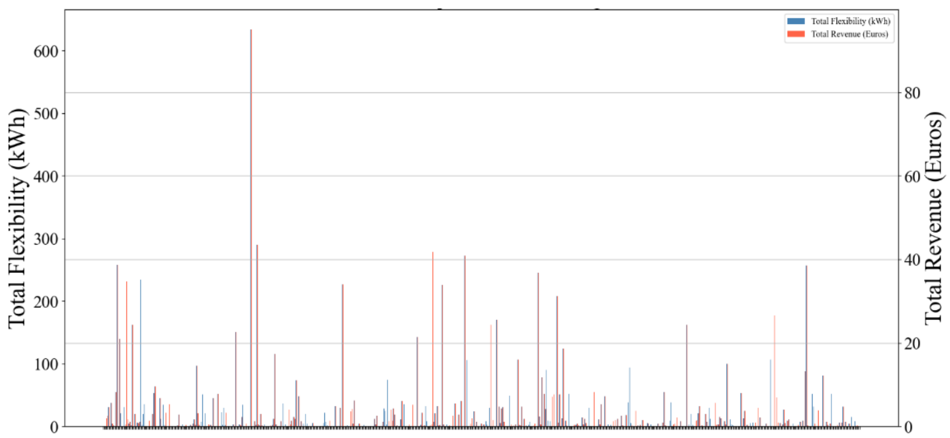

Figure 13: Total V2G flexibility and potential revenue per EV driver (user)

In summary, while public charging environments present more transient and less predictable usage patterns relative to residential or semi-public settings, they nevertheless offer significant V2G potential. By targeting high-traffic locations and leveraging dynamic incentive structures, public CPO networks can meaningfully participate in energy flexibility markets, contributing to grid stability and supporting broader V2G adoption.

4.4 Comparison

An additional analysis was conducted to quantify the distribution of V2G flexibility across the different charging environments. The results are summarized in the following figure.

These findings reinforce that residential and semi-public charging environment are particularly well-suited for V2G applications due to the consistently available flexibility. Public charging, while more variable, still presents valuable V2G opportunities, especially when targeted at high-dwell-time locations or aggregated across multiple users.

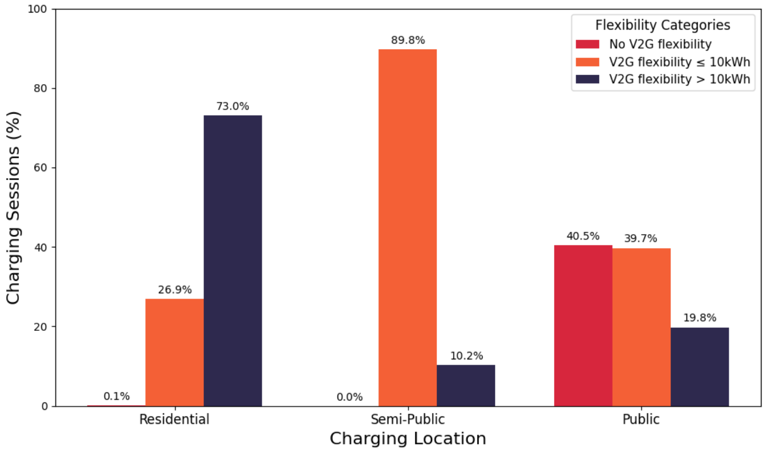

Figure 14: Normalized V2G Flexibility potential across charging locations

5 Summary

This study evaluated the potential for V2G service integration across residential, semi-public, and public charging environments by analyzing real-world charging behavior data.

The findings reveal that, although many charging sessions exhibit relatively short plug-in durations and modest energy transfers, a significant portion of sessions—particularly those characterized by extended plug-in periods and low active charging demand—demonstrate substantial untapped flexibility. Such flexibility windows are critical for enabling V2G operations without compromising user mobility or primary charging needs.

In residential settings, the prolonged and often overnight nature of charging behavior offers highly predictable opportunities for decentralized V2G deployment. Semi-public environments, notably workplaces, present structured schedules and moderate average charging rates, supporting the integration of V2G through coordinated site-level energy management strategies. Public charging, while more heterogeneous and transient in nature, still exhibits meaningful V2G potential, particularly at high-traffic and long-dwell sites, provided appropriate aggregation and dynamic management mechanisms are applied.

Overall, the analysis underscores that V2G capabilities can already be leveraged with existing charging patterns and infrastructure. However, maximizing this potential will require targeted interventions, including dynamic pricing incentives, bidirectional-capable hardware deployment, and integrated energy management systems. By aligning technical, behavioral, and economic dimensions, the large-scale adoption of V2G services can significantly enhance grid flexibility, facilitate renewable energy integration, and deliver financial benefits to both EV users and infrastructure operators.

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Presenter Biography

Andreas Zafeiropoulos holds a Master's degree in Electric Power Engineering from KTH and an Engineering Diploma in Electrical & Computer Engineering from University of Patras (UoP). He is currently pursuing his PhD in UoP on the topic of V2G technologies while working as an e-mobility R&D Engineer at Eunice Energy Group, leading product development in EV charging systems. Andreas has expertise in developing charging system solutions, participating in international e-mobility committees, and strategic partnerships.