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How Convenient Is Vehicle-to-Grid? An Economic and Environmental Perspective

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Executive Summary

Vehicle-to-Grid technology has emerged as a promising solution for grid stabilization and renewable energy integration, yet its practical viability remains debated. This article, result of the ERDF 1040 V2G-BOOST project, presents a comprehensive analysis of the costs and benefits of V2G, focusing on two key aspects: the economic implications and the environmental footprint. From an economic perspective, we assess the potential benefits V2G can offer to the power grid, such as peak shaving, energy arbitrage, and grid balancing, alongside the costs related to battery degradation due to the additional charging and discharging cycles. In parallel, we conduct an environmental analysis using the Life Cycle Assessment method, evaluating V2G's environmental impact across multiple indicators. By comparing these two perspectives, this study provides a holistic view of the convenience of V2G, helping to guide policy decisions and adoption strategies.

Keywords: Vehicle-to-Grid (V2G), Battery Degradation, Economic Assessment, Life Cycle Assessment (LCA), Energy Grid Integration

1 Introduction

The transition towards sustainable energy systems has sparked increasing interest in Vehicle-to-Grid (V2G) technology as a potential solution for grid stability and renewable energy integration. V2G enables bidirectional power flow between electric vehicles (EVs) and the power grid, transforming EVs from mere consumption units into active participants in grid operations. This dual role presents both opportunities and challenges that require careful evaluation from economic and environmental perspectives. V2G technology offers several substantial benefits to grid operations. These include active power regulation, load balancing, peak shaving, frequency regulation, and crucial support for renewable energy integration. By leveraging the stored energy in EV batteries during peak demand periods or grid instabilities, V2G can potentially reduce the need for additional conventional power plants while facilitating the integration of intermittent renewable energy sources [1].

However, the implementation of V2G technology also presents significant challenges. These include necessary modifications to distribution network infrastructure, the complexity of establishing reliable communication protocols between EVs and the grid, and perhaps most critically, the impact on battery degradation. The latter represents a particular concern as it directly affects both the economic viability of V2G participation and its environmental footprint [1].

Battery degradation, a key factor in V2G feasibility assessment, occurs through two primary mechanisms: calendar aging and cycle aging. Calendar aging represents the irreversible capacity loss during storage periods, while cycle aging occurs during the charging and discharging processes. At the microscopic level, several phenomena contribute to this degradation, including Solid Electrolyte Interphase (SEI) growth, chemical decomposition, and lithium plating. Among these, SEI formation is widely recognized as the predominant mechanism responsible for battery degradation. These electrochemical reactions manifest macroscopically as capacity fade and power fade, directly impacting the battery's utility and lifespan [1].

The complexity of battery degradation is further compounded by various stress factors that influence both calendar and cycle aging. Calendar aging is primarily affected by battery temperature and State of Charge (SOC), while cycle aging is influenced by Depth of Discharge (DOD), cycle numbers, energy throughput, and C-rate. Understanding these factors is crucial for accurately assessing the true costs and benefits of V2G implementation [1].

Geng et al. [2] (2024) developed a detailed techno-economic model to evaluate vehicle-side costs and profits of V2G services. Their analysis revealed that V2G's levelized cost of storage ranges from $0.085/kWh to $0.243/kWh, with net present values varying from $-1,317 to $3,013, depending on operational strategies. The study highlighted that with advancements in battery technologies, V2G's net present value could reach approximately $7,000, demonstrating potential cost competitiveness against mainstream stationary energy storage technologies.

Similarly, Gomes and Costa Neto [3] (2024) conducted an economic analysis specific to the Portuguese context, creating a numerical model to compute potential earnings for users providing V2G services. Their findings indicated that V2G services could be highly beneficial when electricity sale prices are high (0.50 €/kWh) for users with very low car usage, generating profits of 624 € per month and 1,547 € in total after accounting for new battery costs. However, the profitability diminished significantly at lower electricity selling prices.

There is a notable gap in the literature regarding comprehensive assessments that simultaneously consider both economic and environmental dimensions of V2G technology. While existing studies have thoroughly examined financial viability, infrastructure requirements, and market dynamics, they have not adequately addressed the environmental implications alongside economic considerations. This integrated perspective is crucial for understanding the full impact of V2G technology, as environmental benefits or drawbacks could significantly influence its overall viability and societal value.

This study aims to provide a comprehensive analysis of V2G convenience by examining both economic and environmental implications. The economic analysis evaluates the financial trade-offs between grid service revenues and accelerated battery degradation costs, while the environmental assessment employs Life Cycle Assessment (LCA) methodology to quantify the environmental impact of increased battery wear and potential early replacement needs. By considering both the country of battery production and the location of vehicle use, including their respective electricity generation mixes, this research offers a nuanced understanding of V2G's overall viability and potential role in future energy systems.

2 Materials and methods

The economic assessment of V2G technology employs a cost-benefit analysis framework. We started from the analysis of the electricity prices in Italy for the years 2022, 2023, and 2024 (see Figure 1). Due to the variability of prices in 2022 and 2023, consequences of different geopolitical events, it has been decided to use electricity prices of the year 2024.

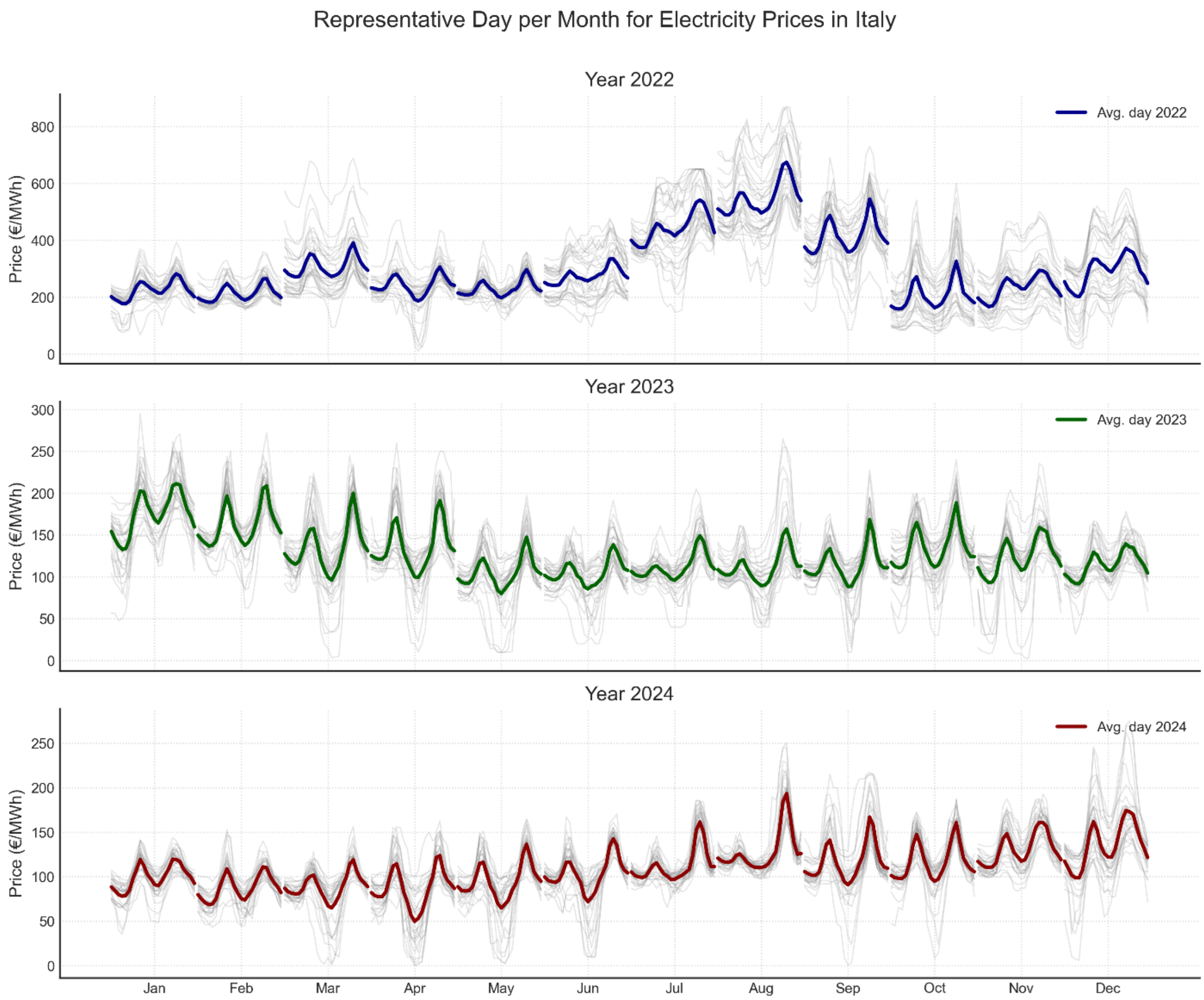

Figure 1 Representative day per month for electricity prices in Italy in 2022, 2023 and 2024.

Benefits are calculated from energy arbitrage revenue streams, based on the Italian electricity market prices of the year 2024. The environmental impact evaluation is based on a LCA methodology which follows ISO 14040 and 14044 standards, with system boundaries encompassing the additional burden from V2G-induced battery degradation. Using the EU Environmental Footprint impact assessment method, we analyze different impact categories. The geographical scope considers both battery production location (China) and vehicle operation location (for Italy), accounting for different electricity generation mixes. Primary data comes from the ecoinvent 3 database [4].

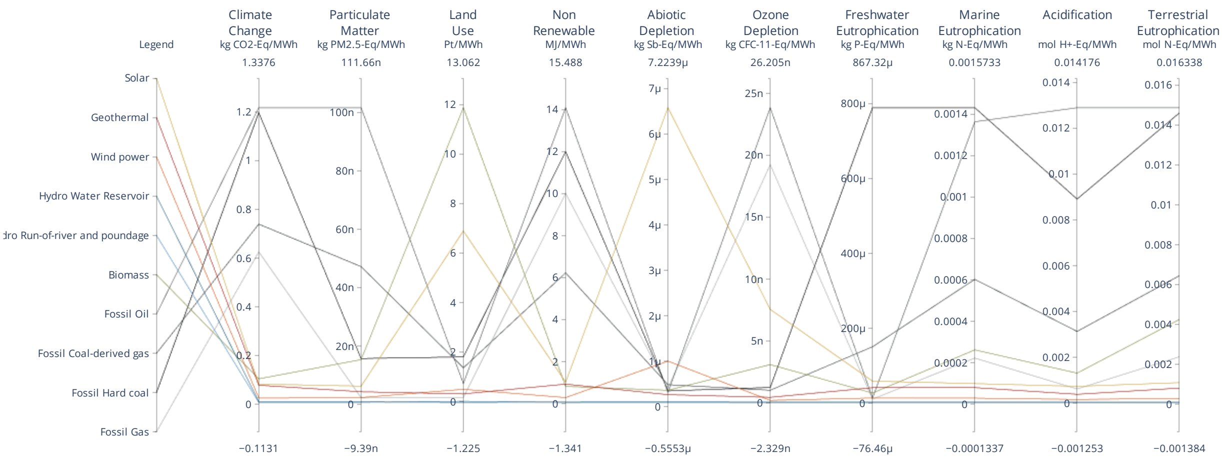

Figure 2 LCA environmental indicators (only 10 are displayed for readability reasons).

We develop an integrated framework comparing V2G scenarios against a baseline of conventional EV usage. Multiple V2G operation scenarios with varying service provision levels are analyzed to examine the relationship between economic returns and environmental impacts.

2.1 Dumb charging profiles

The first tool used in this study is emobpy, an open-source, Python-based tool developed in 2020 by the German Institute for Economic Research [5]. This tool allows for modeling the consumption of electric vehicles and their resulting electrical energy demand for recharging. Emobpy generates EV charging profiles using a sampling approach based on customizable assumptions, physical properties of vehicles, and empirical mobility statistics.

To obtain the grid electricity demand profile for each vehicle, emobpy creates four key time-series: vehicle mobility patterns, driving electricity consumption, grid availability, and grid electricity demand. For our study, we adapted emobpy to the Italian context by modifying input data on weather conditions, population distribution between employment categories (unemployed, part-time, and full-time), and electric vehicle market share to reflect Italian values rather than the German default values in the tool.

The mobility patterns were generated based on probability distributions for different population categories (full-time commuters, part-time commuters, and non-commuters), with location types including home, workplace, shopping, and leisure activities. The driving electricity consumption was calculated based on power balance across the battery, considering auxiliary power, heating/cooling requirements, power to the motor, and regenerative braking.

For each timestep, emobpy determines whether a BEV (Battery Electric Vehicle) is connected to the electricity grid, and if so, with what charging power, based on the probability distributions of finding available charging stations with specific power ratings at different locations. In our study, we implemented the "Immediate - full capacity" charging strategy, where vehicles charge at maximum power as soon as a charging station becomes available, reflecting a situation without incentives for more distributed charging behavior. This "dumb charging" approach provides our baseline scenario for comparison with more intelligent charging strategies.

Due to computational constraints, one week per season was simulated to capture seasonal variations, with resulting profiles repeated for the remaining weeks of each season [6].

2.2 Smart charging and Vehicle to grid profiles

The second tool used in this study is the Oemof [7,8] (Open Energy Modelling Framework) framework, which we employed to evaluate different charging strategies and their integration with the electricity grid. In this paper we focus specifically on the charging profiles of individual vehicles under different strategies. For modeling smart charging and vehicle-to-grid (V2G) profiles, we created a simplified system where an electric vehicle is connected to a charging station, which in turn is connected to the grid with no additional generation sources. We used Italian electricity market prices from 2024 as input data, enabling the model to determine optimal charging and discharging patterns that maximize economic returns for the vehicle owner.

3 Results

This section presents the hourly charging profiles obtained for different charging strategies and their relationship with electricity market prices. Figure 3 illustrates the relationship between hourly electricity prices and the charging behavior of an electric vehicle under the smart charging strategy. The figure consists of two subplots that provide complementary information. The top subplot displays hourly electricity prices in Italy during a week in January 2024. The price pattern shows significant daily variations, with pronounced peaks typically occurring during morning and evening hours when electricity demand is highest across the network. These price variations create economic opportunities for optimizing charging schedules. The bottom subplot presents the charging profile of a single electric vehicle, displaying three key elements: (1) the electricity consumption during driving (shown in blue, “Consumption”), which depends on the vehicle's mobility pattern; (2) the battery charging profile (shown in orange, “Battery Charging”), which represents the electricity that flows into the vehicle's battery under the smart charging strategy; and (3) the periods when the vehicle is connected to the grid (shown in grey). The smart charging profile clearly demonstrates how the charging schedule shifts to minimize costs. Most charging occurs during nighttime hours when electricity prices are lowest, with minimal charging during high-price periods. This behavior contrasts sharply with the "dumb charging" approach, where vehicles would charge immediately upon connection regardless of electricity prices.

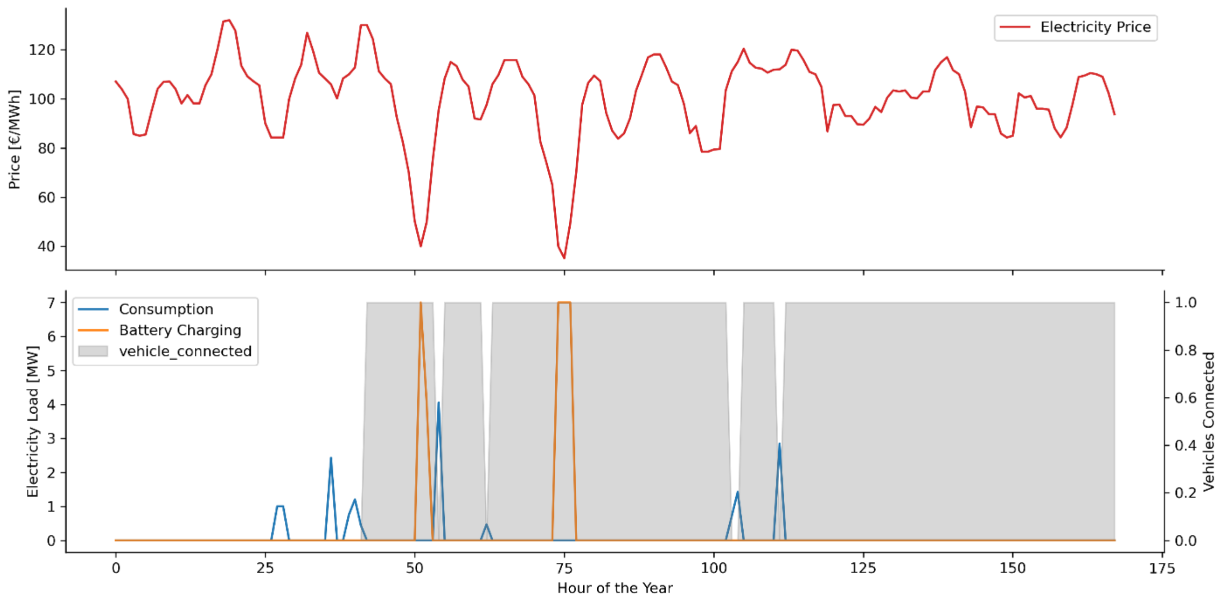

Figure 3 Smart charging profile.

Figure 4 extends the analysis to the V2G strategy, using the same format as Figure 3 but with an additional element. The top subplot again shows hourly electricity prices, while the bottom subplot displays the vehicle's electricity flows. In addition to the three elements shown in Figure 3, Figure 4 includes a fourth component: electricity injected back to the grid (shown in green, “Electricity to the grid”). This bidirectional flow is the defining feature of V2G technology, allowing the vehicle to function as a distributed energy resource. The V2G profile reveals a more complex charging and discharging pattern optimized to maximize economic benefits. The vehicle not only shifts charging to low-price periods but also strategically discharges back to the grid during high-price intervals. This bidirectional functionality creates additional value for the vehicle owner while potentially providing valuable grid services. The charging pattern in the V2G scenario tends to be more aggressive during low-price periods, building up a higher state of charge that enables the vehicle to discharge during high-price periods while still maintaining sufficient energy for driving needs.

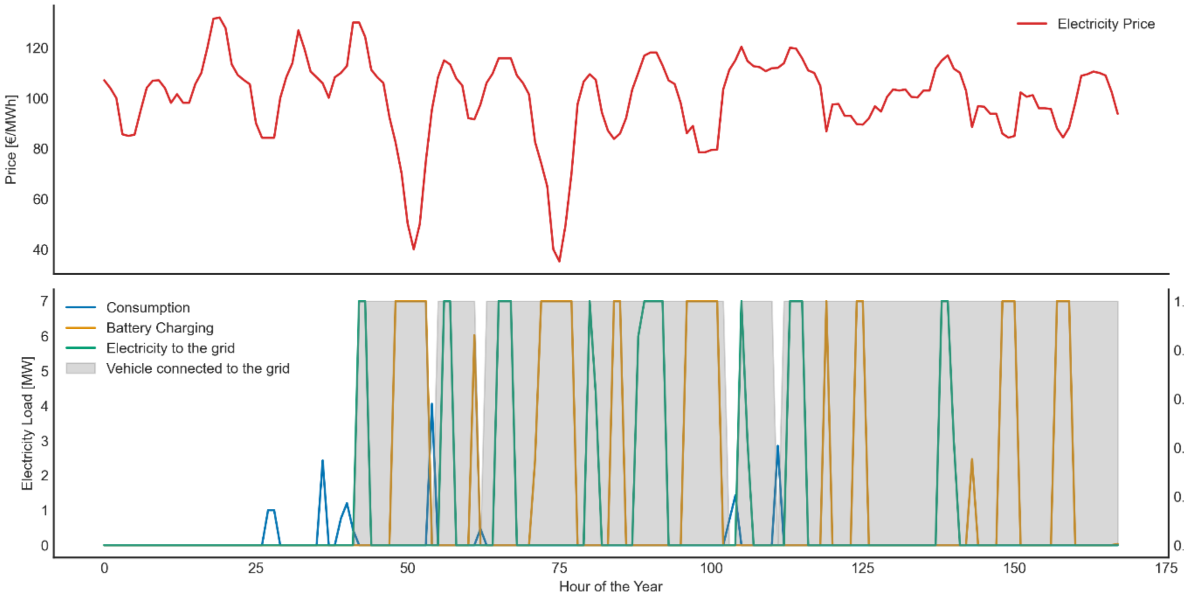

Figure 4 Vehicle to grid charging and discharging profiles.

Table 1 presents the economic performance and battery utilization metrics for the three charging strategies evaluated in this study. The results demonstrate clear financial differences between the approaches, highlighting the potential economic benefits of more sophisticated charging strategies.

Table 1 Comparison of resulting annual costs and charging cycles in the three considered charging strategies: dumb charging, smart charging and vehicle to grid.

	Annual costs [€]	*Annual costs [%]*	*Charging cycles*
Dumb charging	*140.4*	*-*	*260*
Smart Charging	*50.8*	*-63.8*	*71*
Vehicle to Grid	*-216.6*	*-254.2*	*513*

The dumb charging strategy, which represents the baseline case where vehicles charge immediately upon connection regardless of electricity prices, results in the highest annual costs at €140.4. This approach also leads to a moderate number of charging cycles (260) as the vehicle typically reaches full charge before disconnection. Smart charging demonstrates significant economic improvement, reducing annual costs by approximately 64% to just €50.8. This substantial saving is achieved by shifting charging to low-price periods, primarily overnight. Notably, smart charging also results in fewer charging cycles (71), which suggests less frequent but more complete charging events that efficiently utilize low-price periods.

The V2G strategy yields the most dramatic economic results, transforming the vehicle from a cost center to a revenue source with a negative annual cost (net profit) of €216.6. This represents a fundamental shift in the economic proposition of electric vehicle ownership. However, it's important to note that this economic benefit comes with significantly increased battery utilization, with 513 charging cycles per year—nearly twice the number under dumb charging and over seven times more than smart charging.

It is crucial to emphasize that these economic calculations do not account for the potential increased costs of battery replacement due to accelerated degradation from the higher cycling rates, particularly in the V2G scenario. Battery degradation is a complex phenomenon affected by numerous factors including depth of discharge, charging rates, and temperature conditions. The substantially higher number of cycles in the V2G scenario would likely lead to faster capacity fade and shorter battery lifespan, which could offset some of the economic benefits shown here. A comprehensive cost-benefit analysis would need to incorporate these long-term degradation effects and the associated replacement costs, which will be addressed in subsequent sections of this study.

While economic considerations are a primary driver for V2G adoption, environmental impacts represent an equally important dimension in evaluating the overall sustainability of these charging strategies. Table 2 presents the comparative environmental performance of the three charging approaches across selected key environmental indicators, with dumb charging serving as the baseline (indicated by "-") against which the other strategies are measured as percentage.

Table 2 Comparison of resulting main environmental indicators (complete results for all 17 environmental indicators) in the three considered charging strategies: dumb charging, smart charging and vehicle to grid.

	Climate change [%]	*Particular matter [%]*	*Ozone depletion [%]*	*Land use [%]*	*Resource Minerals [%]*
Dumb charging	-	-	-	-	-
Smart Charging	-58.3	-4.7	+50.9	-131.7	-144.8
Vehicle to Grid	-254.7	+133.4	+210.3	-1040.9	-1113.3

The environmental impact analysis reveals complex and sometimes counterintuitive relationships between charging strategies and their ecological footprints. Smart charging demonstrates significant environmental benefits across most categories compared to dumb charging, with particularly notable improvements in climate change impact, land use, and mineral resource depletion. These substantial reductions can be attributed to the optimization of charging times to coincide with periods of higher renewable energy penetration in the grid mix and lower overall system stress.

The V2G strategy presents a more complex environmental profile with dramatic improvements in some categories alongside significant increases in others. The climate change impact shows a remarkable reduction of 254.7% compared to dumb charging, suggesting that V2G not only reduces emissions but potentially delivers net positive climate benefits through its contribution to grid stability and renewable energy integration. Similarly, the substantial reductions in land use (-1040.9%) and mineral resource consumption (-1113.3%) highlight V2G's potential to optimize the utilization of existing infrastructure and resources across the energy system. V2G operation increases particulate matter emissions by 133.4% and ozone depletion potential by 210.3% compared to the baseline.

These findings highlight the importance of a holistic assessment approach that considers the full lifecycle implications of different charging strategies. While V2G offers promising economic and climate benefits, its implementation should be carefully managed to mitigate the potential negative impacts on other environmental indicators, particularly those related to air quality and resource depletion.

4 Conclusions

The presented economic and environmental assessment of smart charging and Vehicle-to-Grid technology reveals both significant opportunities and important trade-offs. Economically, V2G demonstrates the potential to transform EVs into revenue-generating assets, yielding a relevant annual profit. Environmentally, V2G shows a dual nature—offering substantial benefits for climate change mitigation, land use, and resource consumption, while simultaneously increasing particulate matter emissions and ozone depletion potential. Smart charging emerges as a balanced alternative, providing significant economic benefits with minimal environmental trade-offs.

This study has several limitations that should be addressed in future research. While we identified increased battery cycling in V2G scenarios, our economic analysis does not yet fully quantify the associated battery degradation costs and potential early replacement expenses. This represents a significant gap in the complete cost-benefit assessment. Additionally, our analysis is based on a limited set of consumption and mobility profiles. Real-world EV usage patterns vary considerably across different user segments, geographic regions, and socioeconomic factors, which could substantially impact the viability of different charging strategies. Expanding the study to include a more diverse range of usage patterns would provide greater insight into the uncertainty surrounding V2G benefits and help identify which user segments might benefit most from this technology.

These findings underscore the importance of context-specific implementation strategies for V2G technology, accounting for local electricity mix, grid infrastructure, battery technology, and user mobility patterns. Future advancements in battery management systems and chemistry could significantly improve V2G's overall sustainability proposition. Strategic deployment that carefully balances economic benefits against environmental and battery lifespan considerations will be crucial for realizing V2G's potential in supporting grid decarbonization while providing value to EV owners.

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Presenter Biography

Giuseppe Rotondo is a Junior Researcher at Eurac Research in Bozen/Bolzano, specializing in sustainable mobility and energy systems. His work focuses on energy demand modeling for electric vehicles, vehicle-to-grid technologies, and charging strategies. He has also contributed to the electrification of public transport fleets and light-duty vehicles for private companies, analyzing routes and defining the necessary charging infrastructure.
His research includes studies on mobility patterns, energy consumption, and the impact of charging strategies on grid stability. Committed to advancing electric mobility, he develops innovative solutions to support the transition to a more sustainable transport system.