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Flexible Charging to Energy Saving—Strategies Assessment with Big Data Analysis for PHEVs Private Cars

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Abstract: In road transport, most vehicles today still rely on internal combustion engines. However, these engines have lower efficiency and generate higher pollution levels compared to electric motors. Consequently, there is a growing interest in the transition from conventional vehicles to electric ones. However, the transition to an electrified road transport system is not without challenges. Among these, the impact that electric vehicle charging will have on the electricity grid is of particular concern. This paper analyzes different charging scenarios for plug-in hybrid electric vehicles (PHEVs) and proposes charging strategies to minimize their impact on the electricity grid. The analysis is based on a large dataset of trips in urban areas in Italy. The study shows that smart charging of PHEVs can be implemented to minimize the impact on the electricity grid. The implementation of optimized charging strategies can contribute to making PHEVs a valid, eco-sustainable alternative to conventional vehicles while also promoting the stability and efficiency of the electricity grid. The study aims to verify the effectiveness and efficiency of the flexible charging strategy by comparing the common charging operation (first in–first out) with other, less impactful charging schemes.

Keywords: charging strategy; plug-in hybrid vehicle; electric mobility

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1. Introduction

In Europe, most vehicles on the road run on internal combustion engines, even though the number of electric ones has increased in recent years. According to the European Environment Agency (EEA), [1] transportation is responsible for approximately one-quarter of the European Union's greenhouse gas emissions, of which three-quarters come from road transportation. Transport is the only significant economic sector in Europe where greenhouse gas emissions have grown since 1990, and it is the leading contributor to nitrogen oxide emissions. Italy's transport sector consumes a substantial 28.98 million tons of oil equivalent (Mtoe) annually [2], with fossil fuels accounting for approximately 94% of its final energy demand. This reliance presents a significant challenge in terms of achieving sustainability goals. Fortunately, technological advancements offer promising solutions. Electric motors represent a true paradigm shift, boasting an impressive 81% tank-to-wheel efficiency compared to the 30–36% range of internal combustion engines (ICEs) [3]. This translates to substantial potential for reduced emissions, lower fossil fuel dependence, and ultimately, a more sustainable transportation system for Italy. These inherent advantages contribute to the increased appeal of electric vehicles (EVs) over conventional vehicles [4,5]. The Italian car market experienced a downturn in recent years, largely attributed to the pandemic's impact. In 2022, passenger car sales reached 1.317 million units, with ICE vehicles comprising the dominant segment at 57.1%. Hybrid electric vehicles (HEVs) held a significant share at 34%, while plug-in hybrids (PHEVs) and battery electric vehicles (BEVs) accounted for 5.1% and 3.7%, respectively [6]. Increasing users' awareness of a more efficient way of charging is an objective of this work, as well as the enhancement of knowledge of professionals, as defined within the Sustainable Development Goals (SDGs) of the UN Agenda 2030 [7].

Despite comparable environmental benefits, distinct approaches are crucial for the widespread adoption of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). BEVs excel in zero tailpipe emissions and energy independence from fossil fuels, but necessitate major investments in charging infrastructure and might face range-related adoption barriers. Conversely, PHEVs offer superior flexibility through dual powertrains, mitigating range anxiety with gasoline backup and integrating seamlessly with existing platforms. However, their dependence on fossil fuels could hinder long-term emission reduction aspirations [8,9]. Despite this concern, PHEVs represent a large share of the electric fleet in Europe [10]. This is partly due to their lower purchase price thanks to incentives made available by some nations [11], the sense of familiarity with gasoline-powered cars [12], and more flexibility in satisfying all travel needs [13]. Moreover, their smaller battery capacities minimize strain on the electricity grid. Furthermore, PHEVs' ability to charge strategically during off-peak hours and complete charging within typical parking durations allows for grid-friendly smart charging strategies. This is enhanced by Vehicle-to-Grid (V2G) technology, where PHEVs act as temporary storage, discharging energy during peak demand to both alleviate network stress and generate income for owners [14–17].

This study explores an optimized approach to smart charging for PHEVs in the Rome metropolitan area. Leveraging real-world travel data, it aims to:

- Minimize grid stress by strategically coordinating the charging and discharging of PHEVs;
- Quantify the potential benefits of V2G adoption for both the grid and vehicle owners;
- By optimizing how PHEVs interact with the power grid, this study seeks to unlock their full potential for a more sustainable and efficient transportation future.

In the next session, we illustrate the dataset, the selection of PHEVs, and the approaches proposed for different scenarios. In the Section 5, we will summarize the main results of the research and outline possible future scenarios.

2. Materials and Methods

This study presents a methodology for managing PHEV charging requests in urban environments, considering various PHEV penetration scenarios and their impact on the electricity grid. The proposed method analyzes three distinct PHEV battery sizes and compares the effects of uncontrolled charging against controlled charging with and without vehicle-to-grid (V2G) technology integration. By developing a computationally efficient algorithm to regulate PHEV battery charging, the research aims to evaluate its potential benefits for grid operators, paving the way for informed optimization strategies. The vast amount of information provided by big data allows for making predictions and estimates that can benefit the management of the energy system, meeting the demand and enhancing social well-being. However, to fully exploit the big data potential, it is crucial to overcome various technological problems associated with processing large amounts of data, as well as ensuring cybersecurity and privacy protection [18]. Using big data in EV mobility enables us to identify recurring patterns (travel habits) and quantify the variability concerning a given behavior. This information can be utilized to enhance the management and forecasting of demand and optimize the design and size of charging services offered.

2.1. Data

In support of the study presented in this document, ENEA obtained raw monitoring data from OctoTelematics for vehicles circulating within the Rome metropolitan area during May 2013. The data encompass 157,514,383 records for 150,633 monitored vehicles. Each vehicle carried a GPS receiver, accelerometer, and GSM/GPRS transceiver for exchanging information with the Multiservice Centre. The system captured trip start/end times and vehicle positioning data with varying sampling frequencies: typically, every two kilometers on regular roads and every 30 s on motorways. The record layout was as follows:

- ID_term: Unique identifier of the device;

- Date Time: UTC timestamp of the recording (dd-mm-yyyy hh:mm:ss);
- Latitude: Geographic coordinate in the WGS84 system in millionths of a degree;
- Longitude: Geographic coordinate in the WGS84 system in millionths of a degree;
- Speed: Instantaneous speed in km/h;
- Direction: Direction of travel (in degrees 0 = North, 90 = East, 180 = South, 270 = West);
- Quality: GPS signal quality (1 = does not navigate, 2 = 2d, 3 = 3d);
- Status: Status (0 = departure, 1 = motion, 2 = arrival);
- DeltaPos: Distance in meters from the position of the previous point;
- Road: Road type attributed by OctoTelematics (U = urban, E = extra-urban, A = highway).

The monitored area, shown in Figure 1 with a blue rectangle, corresponds roughly to the metropolitan area of Rome, delimited by the following coordinates expressed in sexadecimal degrees in the WGS84 reference system:

- Latitude North 42.297;
- South latitude 41.408;
- Longitude West 11.733;
- Longitude East 13.297.

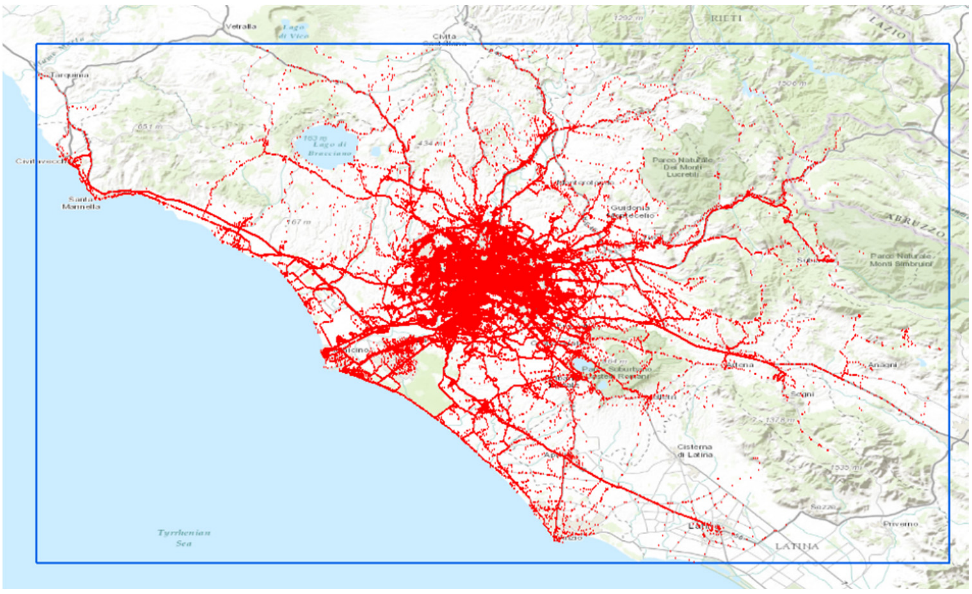

Figure 1. Area of study (blue rectangle) and GPS positions recorded for Wednesday 15 May 2013 for the selected sample (red dot).

The data were processed to eliminate anomalies due to faulty terminals or communication errors between terminals and the control panel. After cleaning the raw data, 148,287 vehicles devices remained, corresponding to 146,870,292 GPS records. From these data, we obtained information on individual journeys and on the stops between one journey and the next. For each trip identified, the following information was stored:

- Trip ID;
- Terminal ID;
- Departure date and time;
- Starting position;
- Date and time of arrival;
- Arrival position;
- Distance traveled;
- Trip duration;
- Stop duration upon arrival.

By applying clustering techniques to recurrent nighttime parking locations, we identified residences as the predominant destinations based on both the frequency and duration of vehicle parking events. From the complete vehicle database, we extracted a representative sample encompassing vehicles registered within the Rome urban area and operating within the Rome metropolitan area. This resulted in a sample size of 16,615 vehicles. As an illustrative example, Figure 1 displays the GPS positions recorded for these vehicles on Wednesday, 15 May 2013. Additionally, Figure 2 depicts the distribution of vehicles in the sample during the specified day, where each data point represents the number of vehicles moving at a given time. This distribution can be interpreted as the probability of a randomly chosen vehicle from the sample being in motion at that time.

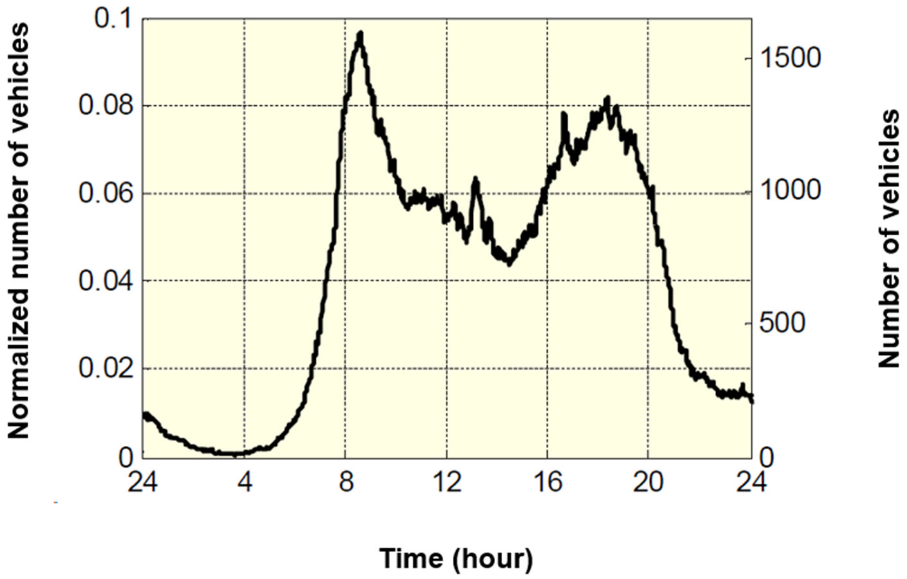

Figure 2. Vehicles from the reference sample circulating on Wednesday 15 May. The scale on the left represents the probability that a generic vehicle is in circulation at a given time.

2.2. PHEV Model Selection

PHEVs are experiencing some success in Italy, with a share of 5.1% of the market in Italy in 2022. Table 1 reports the three top sold models worldwide, along with their respective all-electric ranges (AERs), which correspond to the distance the PHEV can travel without using the ICE.

Table 1. Top sold PHEV models worldwide.

Model	All-Electric Range	Market Launch	Global Sales	Cumulative Sales Through
Mitsubishi Outlander P-HEV	37 mi (60 km)	January 2013	290,000	September 2021
Chevrolet Volt(1)	35 mi (56 km)	December 2010	~186,000	December 2018
Toyota Prius PHV	11 mi (18 km)	January 2012	174,586	December 2018

Over the past years, PHEVs have seen a notable shift towards longer, electric-only ranges, reflected in the increasing prevalence of larger batteries. While models with less than 9 kWh are less common today, it is still valuable to consider the classic PHEV 10, 20, and 40 categories (corresponding to approximately 16, 32, and 64 km of electric range) for their broad applicability. The electric autonomy ranges for the study were chosen deliberately to emphasize the differences among the three cases being studied. Additionally, the selected autonomy levels were within the range of the most used PHEVs currently available. The PHEV mock-up models details are reported in Table 2.

Table 2. PHEV mock-model characteristics.

PHEV Mock-Up Model	PHEV of Reference	All-Electric Range	Battery Size
PHEV 10	Toyota Prius PHV Model Year 2012	11 mi	4.5 kWh
PHEV 20	Ford Fusion Model Year 2017	21 mi	7.6 kWh
PHEV 40	Opel Astra 1.6 PHEV	40 mi	12.4 kWh

To develop efficient charging strategies, it is essential to have access to some vital information. This information includes the arrival and departure time of each vehicle, the amount of energy required for charging, and the charging power needed. All charges are supposed to use up to 3 kW of power absorbed from the grid. While this simplification may not be entirely accurate, it still provides useful information since PHEVs generally charge using up to 11 kW of power at most, although the usual charge power for PHEVs does vary depending on the specific model and its capabilities [19]; see Table 3.

Table 3. Charge levels for PHEV, with some examples from PHEV technical specifications.

Charging Level	Power Output	Supported PHEVs
Level 1	1.4 kW	All PHEVs
Level 2	3.3 kW–7.2 kW	Most PHEVs (e.g., Toyota Prius Prime, Chrysler Pacifica Hybrid)
Level 2	11 kW–19.2 kW	Newer PHEVs with compatible charging capabilities (e.g., Hyundai Ioniq PHEV, Kia Niro PHEV)

2.3. Analysis of All Electric Mileage

This study investigated the potential for increased electric vehicle (EV) usage by simulating the replacement of a fleet of 16,615 vehicles with plug-in hybrid electric vehicles (PHEVs) offering three electric range options (10, 20, and 40 miles).

Consumption data from the PHEV of reference reported in Table 2 was used to calculate the monthly "electric running" distance for each vehicle under two charging scenarios:

- Night charging only: Vehicles are charged overnight when electricity demand is typically lower;
- Night charging supplemented by low-power intermediate charging during extended stops (>1 h): Vehicles are charged at low power levels during extended stops to further increase electric driving.

The results are presented in Figure 3, with the first column showing the percentage of electric driving achieved with intermediate charging and the second column representing it without. As expected, the percentage of electric driving increases proportionally to the PHEV's electric range due to a larger battery size.

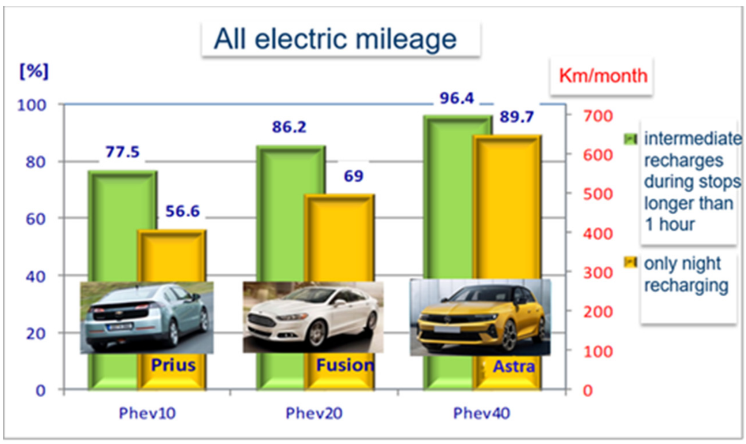

Figure 3. Monthly mileage in electric mode for three PHEV AERs, using night charging only or night charging with intermediate recharges during stops.

Notably, a PHEV40 like the Astra would demonstrably improve the results due to its significantly extended electric range. In fact, simulations indicate that it could operate in purely electric mode for 96.4% of the total distance. Even under restricted nighttime charging, this percentage remains remarkably high, at 89.7%.

2.4. Analysis of Loads for Charging Strategies

In the following, the charge demand is evaluated for three different charging strategies:

- Uncontrolled charging: the PHEVs start charging as soon as they arrive at the station, for parking durations above 1 h;
- Delayed charging: charges are scheduled to begin when the electricity rate is the cheapest;
- Charging with V2G.

For analytical simplicity, we adopt a model with two time-of-use (TOU) electricity price periods: a low-rate period (LRP) encompassing overnight hours (8:00 p.m.–07:40 a.m.) and a high-rate period (HRP) applicable during the remaining hours of the day.

2.4.1. Uncontrolled Charging

In uncontrolled charging, indicated in the following as Mode 1, PHEV starts charging immediately upon vehicle stop, provided the duration exceeds a pre-defined threshold (e.g., one hour). This often occurs during daytime due to prevalent parking patterns. Mode 1 charging provides an energy quantity linked to parking duration, capped at the battery capacity. Prior knowledge of parking duration is irrelevant for mode 1.

2.4.2. Delayed Charging

Managing delayed charging sessions critically hinges on accurate stop duration information, as maximizing grid energy utilization during LRP minimizes overall electricity costs. We present two distinct approaches:

- Full Energy Replenishment (Mode 2): Aims to completely fulfill the energy demands of all arriving vehicles;
- Partial Energy Replenishment (Mode 3): Focuses on replenishing 75% of vehicle energy needs during HRP.

In mode 2, the knowledge of the parking duration allows a portion of the charging to be transferred from HRP to LRP without reducing the amount of energy recharged. Therefore, compared to uncontrolled charging, the temporal profile of power requests is modified, but the energy withdrawn from the grid remains unchanged.

In mode 3, it is guaranteed that at least 75% of the energy demand is satisfied for every charge request. This mode applies only if the stop falls within HRP.

Concentrating most of the charging demand within LRP can induce a significant surge in demand at the beginning of this period. To mitigate this issue, we propose a two-pronged approach: (1) an initial phase shift to distribute charging requests across the LRP and (2) dynamic power modulation to further smooth the demand curve. The specific algorithm implementing this strategy is presented below.

For each charging request, the following quantities are calculated: the time needed to satisfy the charge request at the maximum power (T_0), and the time available (T_a), which coincides with the stop duration.

If: $T_a > T_0$, the extra time available is defined as:

$$T_e = T_a - T_0. \tag{1}$$

Four equal time intervals are obtained from the extra time:

$$\Delta T = T_e/4 \tag{2}$$

We define the time horizon available for charging as:

$$T_h = T_0 + 3\Delta T. \tag{3}$$

Consequently, the charging power is reduced from P_{max} to

$$P_{max} * T_0/(T_0 + 3\Delta T). \tag{4}$$

Charge starts after a randomly chosen delay time in the range $[0, \Delta T]$.

2.4.3. V2G

When operating in this mode, the knowledge of the parking duration allows the possibility for the vehicle to charge during off-peak periods when electricity prices are lower, and contributes to grid stability by reducing demand during periods of high market prices and peak grid demand. The operational constraint is to fully satisfy the vehicle's energy demand before the next trip. The energy evaluation accounts for the losses from charging and discharging the battery to and from the grid. The availability of power for V2G operations directly depends on the temporal distribution and duration of vehicle stops.

3. Results

To evaluate the impact of the four modes of charging, it is assumed that the entire car fleet in the analyzed database is made up of PHEVs. In other words, based on the recorded trips, the impact of the charging on the network is evaluated on the assumption that all the vehicles considered are PHEV. To emphasize the effect of the battery size, we consider three cases for the fleet composition: only PHEV with 10 miles of AER (PHEV10); PHEV with 20 miles AER (PHEV20); and PHEV with 40 miles AER (PHEV40). The main characteristics for the three PHEV paradigms are reported in Table 4 and correspond to the typical values for Toyota Prius, Ford Fusion Energy, and Ford Kuga, respectively.

Table 4. Main characteristics for the three PHEV paradigms.

	PHEV10	**PHEV20**	**PHEV40**
Battery capacity (kWh)	4.4	7.6	14.4
AER (km)	17.7	33.8	61.2
Electricity efficiency (Wh/km)	179	210	212
Fuel efficiency (L/km)	0.0464	0.0541	0.0678

In the following, we illustrate the results for a particular day (15 May) of the dataset, which is representative of a typical working day.

3.1. PEHV 10

The analysis presented in this paragraph assumes that the entire fleet of vehicles is replaced with PHEV10s. We apply the different charging strategies to compare the outcomes.

Figure 4 shows the trend of the power requested to the network for uncontrolled charges. The ordinate on the right shows the total power required by the vehicles in the sample, while on the left, it reports the average power per vehicle. The area under the curve represents the average daily consumption per vehicle, and is 3.8 kWh. On average, a third of the vehicles in the sample do not circulate during the day. Therefore, the remaining 70% of vehicles are charged on average with 5.4 kWh per day, which is more than the capacity of the PHEV10 battery. This result can be justified by assuming that some vehicles need to charge more than once a day.

Although uncontrolled charging allows full energy demand satisfaction, achieving only 77.5% electric mileage (Table 5) highlights underutilization of the electric range. This low mileage stems from journeys exceeding electric autonomy and limited pauses exceeding 1 h for charging. Importantly, Figure 4 shows that uncontrolled charging concentrates 84.4% of recharged energy within high-electricity-cost periods (early morning to late afternoon). This behavior, where vehicles recharge immediately after use, presents an opportunity for optimization. Figure 5 compares the distribution of the power requests for the three different charging strategies. Delayed charging can significantly reduce the share of energy absorbed in HRP. Figure 5 shows that mode 2 (magenta curve), with 100% guaranteed charging, offers the same electric range as uncontrolled charging, with the added advantage of better charging distribution. Only 51% of charging occurs in HRP, as opposed to 84% in uncontrolled charging. In the case of mode 3, high-end charging drops to around 35%, with a modest reduction in electric mileage of less than 4%.

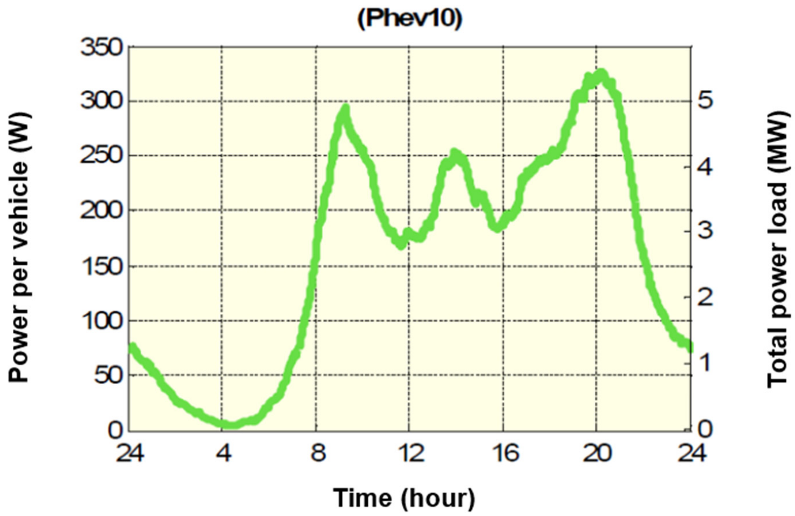

Figure 4. Power load (green line) in a typical working day for a fleet of PHEV10.

Table 5. Comparison between uncontrolled and delayed charge strategies for PHEV10.

Charge Mode	Electric Mileage/Total Distance (%)	Energy Charged in HRP (%)	Average Electric Mileage (km/Vehicle/Month)	Average Energy Absorbed from the Network (kWh/Vehicle/Month)	Energy Absorbed from the Network (MWh/Month)
Uncontrolled	77.5	84.4	564	119	1.980
Delayed, 100%	77.5	51.1	564	119	1.980
Delayed, 75%	73.8	35.6	537	113	1.886

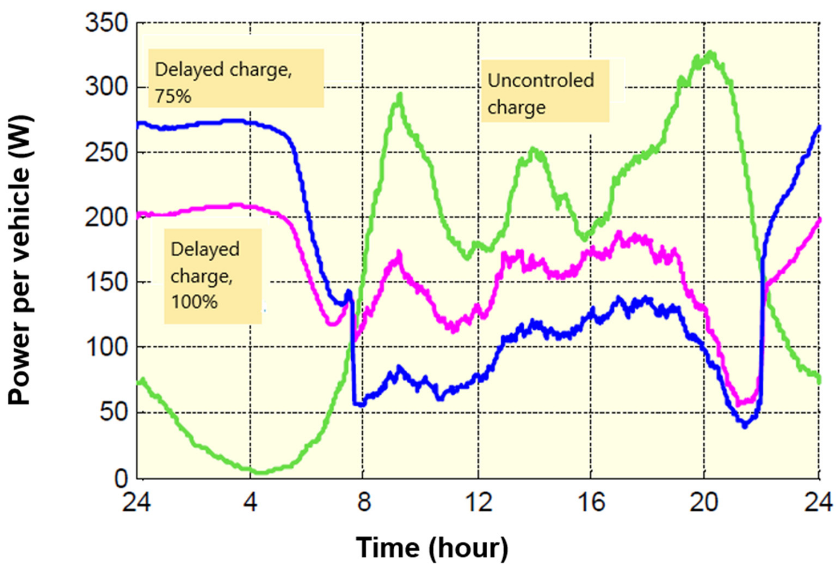

Figure 5. Temporal distribution of power for uncontrolled and delayed charge strategies for a PHEV10 fleet. Green line: uncontrolled charge; blue line: 75% of delayed charge; magenta line: 100% of delayed charge.

3.2. PEHV 20

For the analysis of the PHEV20, it is assumed that all the sample vehicles considered are replaced with vehicles with the same characteristics as those reported in Table 4.

In this case, the electric range obtained with uncontrolled, or free, charging is higher than that obtained for PHEV10, and reaches 86.2% of the total, as shown in Table 6. This advantage stems from the significantly larger battery capacity of PHEV20 vehicles, translating to superior autonomy in electric mode. However, the percentage of charging during HRP is still high, equal to 82.4% of the total charge energy. Mode 2 has the same electric range as free charging, with the advantage of better charging distribution, as seen in Figure 6, showing that only 50% of the charging takes place during HRP. For mode 3, the charge in HRP falls to around 31% with a modest reduction in electric mileage, which drops by only 2.7%.

Table 6. Comparison between uncontrolled and delayed charge strategies for PHEV20.

Charge Mode	Electric Mileage/Total Distance (%)	Energy Charged in HRP (%)	Average Electric Mileage (km/Vehicle)	Average Energy Absorbed from the Network (kWh/Vehicle/Month)	Energy Absorbed from the Network (MWh/Month)
Uncontrolled	86.2	82.4	627	156	2.587
Delayed, 100%	86.3	50.1	627	156	2.587
Delayed, 75%	83.5	31.4	607	151	2.504

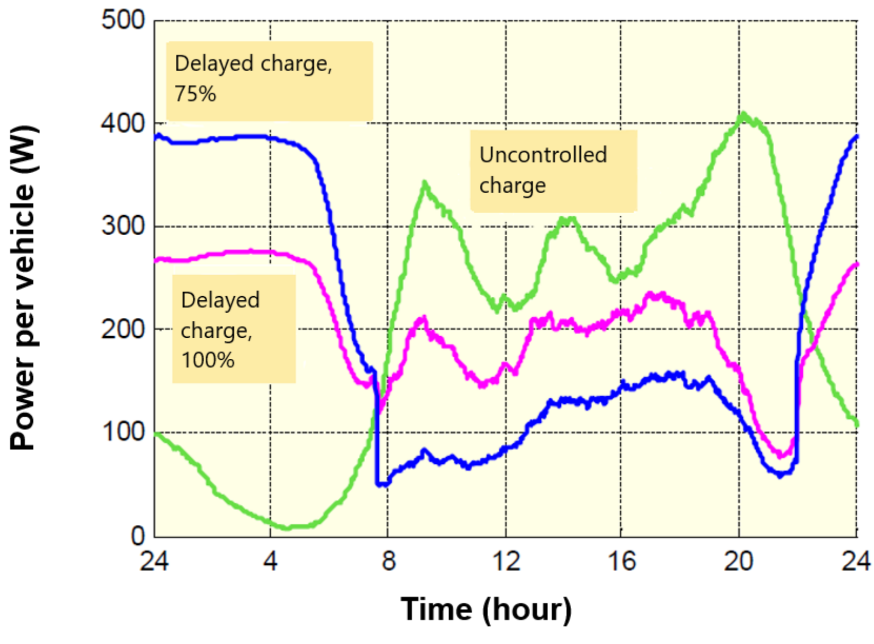

Figure 6. Temporal distribution of power of uncontrolled and delayed charge strategies for a PHEV20 fleet. Green line: uncontrolled charge; blue line: 75% of delayed charge; magenta line: 100% of delayed charge.

3.3. PHEV 40

For the analysis of the PHEV40, it was assumed that the entire sample was composed of vehicles with characteristics referring to Opel Astra, as reported in Table 1.

In this case, the electric mileage obtained with free charging reaches 96.4% of the total mileage, as shown in Table 7. However, the charging share in HRP is as high as 79.1%.

Table 7. Comparison between uncontrolled and delayed charge strategies for PHEV40.

Charge Mode	Electric Mileage/Total Distance (%)	Energy Charged in HRP (%)	Average Electric Mileage (km/Vehicle)	Average Energy Absorbed from the Network (kWh/Vehicle/Month)	Energy Absorbed from the Network (MWh/Month)
Uncontrolled	96.4	79.1	701	176	2.933
Delayed, 100%	96.4	47.8	701	176	2.933
Delayed, 75%	95.7	20.0	696	175	2.907

Mode 2 has the same electric mileage as uncontrolled charging, but with a better distribution of demand with respect to the TOU electric price. Indeed, the energy absorbed in the HRP is only 47.8% of the total, compared to 79.1% for free charging. For mode 3, HRP charging drops to around 20%, along with a very modest reduction in electric mileage of 0.7%. Figure 7 shows the trends of power required for controlled recharges and free recharges.

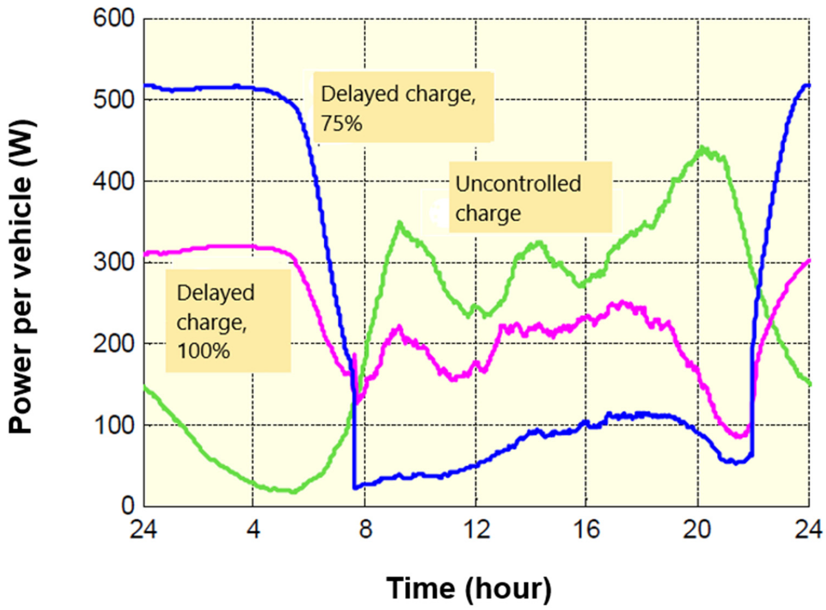

Figure 7. Temporal distribution of power for uncontrolled and delayed charge strategies for a PHEV40 fleet. Green line: uncontrolled charge; blue line: 75% of delayed charge; magenta line: 100% of delayed charge.

3.4. V2G

In V2G mode, PHEV batteries can inject energy back into the grid, potentially supporting grid stability and demand response. This study analyzed the behavior of three PHEV fleets with varying AERs under V2G operation and compared the results to an uncontrolled charging scenario. Notably, to maintain the same electric range as in uncontrolled charging, most charges in V2G mode were conducted within the LRP strategy. This study leverages the V2G service as a continuous contributor to network storage solutions, encompassing Vehicle-to-Home (V2H), energy communities, and Vehicle-to-Everything (V2X). This integrated approach enables us to accurately estimate the potential for PHEVs to supply energy to the grid under the investigated scenarios.

As mentioned before, the V2G availability depends on the distribution of arrivals and on stop durations. Notably, longer stops concentrated in the late afternoon and morning hours in HRP presented a challenge for consistent grid support. To address this, we implemented a dual charging strategy, tailoring approaches for both morning and late afternoon stops.

For each stop during HRP, the following quantities are calculated: the time needed to discharge the battery at the maximum power allowed (T_d) and the time available (T_a), which coincides with the dwell time minus the charging time at the maximum acceptable power.

If: $T_a > T_d$, the extra time available is defined as:

$$T_e = T_a - T_d. \tag{5}$$

We define six intervals:

$$\Delta T = T_e/6. \tag{6}$$

$$T_{V2G} = T_d + T_e - T_s * 6/2, \tag{7}$$

with discharging power:

$$P_d = P_{max,d} * T_d/(T_d + T_e - T_s * 6/2), \tag{8}$$

For the LRP, the approach is similar, but the extra time is divided into eight intervals:

$$\Delta T = T_e/8. \tag{9}$$

$$T_{V2G} = T_d + 3\Delta T, \tag{10}$$

$$P_d = P_{max,d} * T_d/(T_d + 3\Delta T) \tag{11}$$

Table 8 reports the extent of energy flows exchanged between PHEVs and the grid for different AERs. The corresponding values in the case of uncontrolled unidirectional charging are shown in brackets. As expected, the average energy delivered to the network per vehicle increases with increasing PHEV battery size.

Table 8. Comparison between energy flows of V2G for different PHEV AER. Corresponding values for uncontrolled charging mode are reported in brackets.

PHEV AER	Electric Mileage/Total Distance (%)	Average Energy Absorbed from the Network (kWh/Vehicle/Month)	Energy Absorbed from the Network (MWh/Month)	Average Energy Delivered to the Network (kWh/Vehicle/Month)	Energy Delivered to the Network (MWh/Month)
10	77.5 (77.5)	228 (119)	3.791 (1.980)	79 (0)	1.311 (0)
20	86.2 (86.2)	343 (156)	5.704 (2.587)	138 (0)	2.291 (0)
40	96.4 (96.4)	542 (176)	9.005 (2.933)	274 (0)	4.553 (0)

To investigate daily power exchanges between the grid and PHEV fleets, we selected May 15th as a representative work day. Figure 8 depicts the normalized power profiles, both requested from (left) and supplied to (right) the grid for these fleets. Additionally, the required power for free charging is overlaid for comparison.

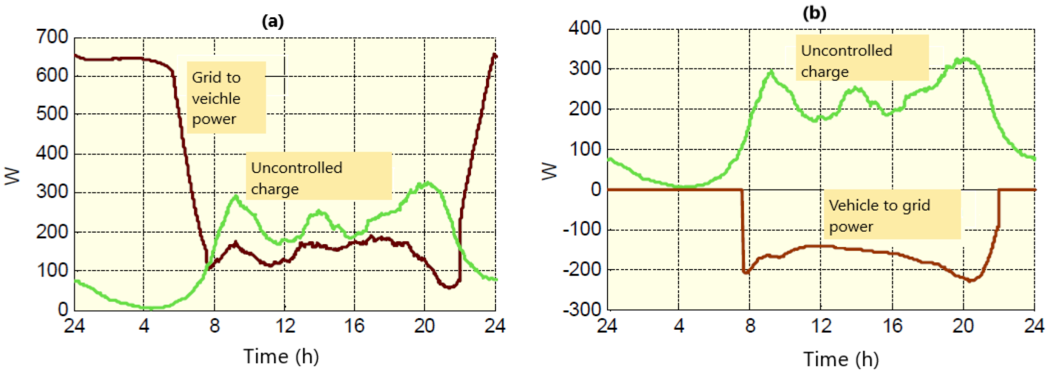

Figure 8. *Cont.*

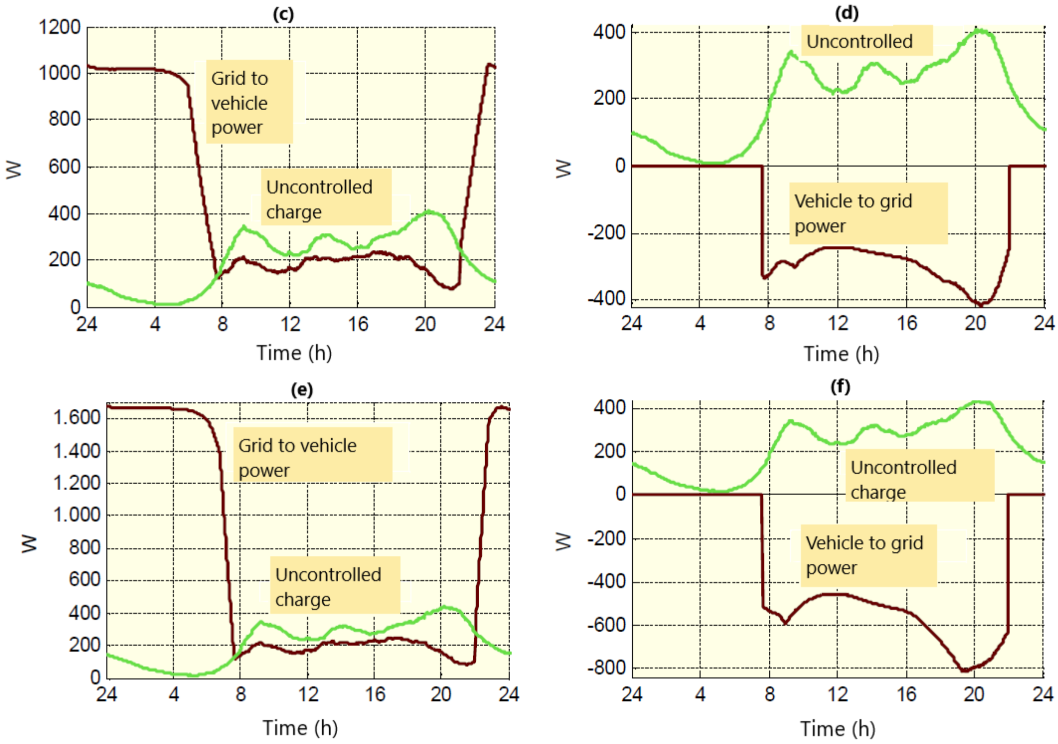

Figure 8. Power flow for V2G mode compared to uncontrolled charge in a typical working day: green line: uncontrolled charge; red line: V2G power flow. (**a**) power absorbed from the grid for a PHEV10 fleet; (**b**) power transferred to the grid for a PHEV10 fleet; (**c**) power absorbed from the grid for a PHEV20 fleet; (**d**) power transferred to the grid for a PHEV20 fleet; (**e**) power absorbed from the grid for a PHEV40 fleet; (**f**) power transferred to the grid for a PHEV40 fleet.

For PHEV10s (Figure 8a), the power required at night is approximately four times higher than that required during the day. Furthermore, it is observed that the power required during daytime hours is slightly lower than that of free charging. During daylight hours, the power requested and that supplied are equivalent, except for brief moments around 8am and 9pm, where there is a modest prevalence of the energy supplied by the battery to the grid (Figure 8b).

From Figure 8c, we can observe that the power required by PHEV20s during the night hours is five times higher than that required during the day. This allows higher power to be delivered during daytime compared to PHEVS10s, as can be seen from the graph in Figure 8d.

For PHEV40s, the power required at night is now eight times higher than that required during the daytime (Figure 8e). This allows for the delivery of an average power per vehicle which is always above 400 W during daytime hours (Figure 8f).

4. Discussion

Three distinct charging modes are evaluated in this study: uncontrolled charging, mode 2 (delayed 100%), and mode 3 (delayed 75%).

- Uncontrolled charging: Vehicles initiate charging based on need during planned stops exceeding one hour, regardless of electricity price;
- Mode 2 (delayed 100%): Charging commences predominantly during low-cost electricity periods while ensuring sufficient energy for planned electric mileage;
- Mode 3 (delayed 75%): The energy constraint of mode 2 is relaxed to 75%, allowing for greater flexibility in charging timing.

Our analysis revealed that mode 3 significantly reduces peak energy demand, lowering it to 20–35% of overall demand. This benefit comes at the cost of a slight decrease in electric mileage.

Daytime charging opportunities enable a high proportion of electric distances for PHEVs, ranging from 77.5% for PHEV10 to 96.4% for PHEV40. Overnight charging at home results in average electric mileage percentages of 56.6%, 69%, and 89.7% for PHEV 10, 20, and 40, respectively. The electric mileage increase with intermediate recharging is more significant for PHEV10 compared to PHEV40. Notably, PHEV10 achieves 77.5% electric mileage with a 4.4 kWh battery, while PHEV40 demands a 16 kWh battery for a 19% increase. These findings align with Wu et al.'s [20] assertion that PHEV10's lower battery cost contributes to its convenience. However, it is crucial to acknowledge that actual vehicle costs are subject to manufacturer strategies and incentive policies influencing consumer choices.

When mode 3 is applied, there is a reduction in the electric mileage (ElM) with respect to mode 2 or uncontrolled charging. The share of energy consumption in HRP with respect to the total electric mileage (HRP/ElM) is reported in Figure 9. The X-axis represents the PHEV AER, and each curve refers to a charging strategy.

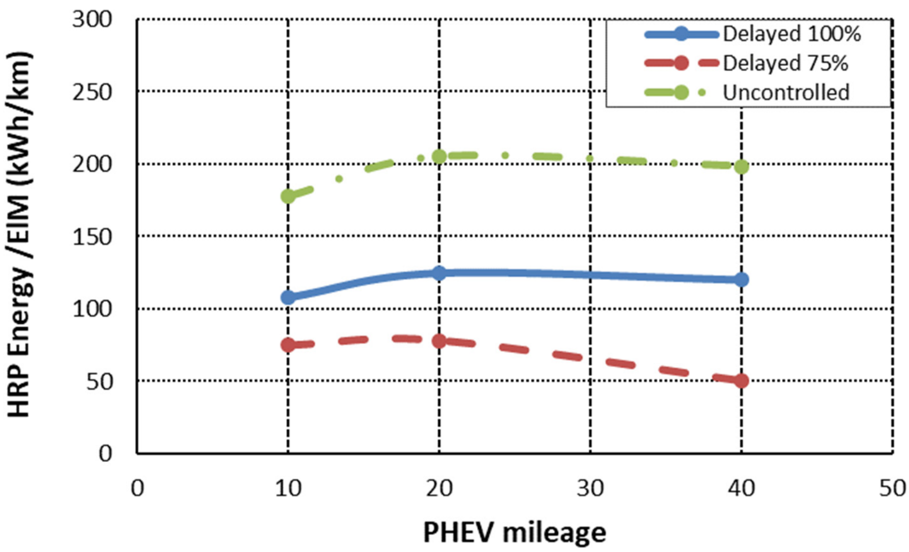

Figure 9. Energy consumption in HRP versus total electric mileage (ElM) for the three control modes, as a function of the PHEV AER. Green dotted-dashed line: uncontrolled mode; red dotted line: 75% delayed mode; blue solid line: 100% delayed mode.

The HRP/ElM is a metric that measures the share of energy consumption in kWh/km during periods of high-price energy. In general, the lower the HRP/ElM value, the more cost-effective the charging strategy. Moving from uncontrolled to delayed charging with a decreasing percentage of guaranteed charge, costs decrease for all PHEVs with a given AER. However, for each charging mode, the savings are not proportional to PHEVs' AER: for an uncontrolled and delayed one with fully guaranteed charging, the saving is the maximum for PHEV10, while it is the minimum for PHEV20. For delayed charging with a 75% guarantee, PHEV40 realizes the most convenient gain, while the most unfavorable result is still for PHEV20. Even if there is a general economic gain for the electricity costs in charging mode 3 compared to the others, the greatest advantage is obtained from PHEV40.

Vehicle-to-Grid (V2G) technology enables PHEV batteries to act as grid storage, supplying energy during peak periods while recharging during off-peak hours. Larger batteries facilitate enhanced V2G performance by storing more charge for peak-time supply.

Analysis indicates that even the 4.4 kWh battery of PHEV10 significantly reduces high-demand-period (HRP) energy requirements. It supplies enough energy to compensate for the charging needs of other EVs during HRP. PHEV20 and PHEV40 demonstrate even better performance, with PHEV40 offering a surplus of approximately 300 W to the grid during peak hours, the net of its own partial recharge needs.

To illustrate the grid impact of different charging modes, Figure 10 presents the hourly power demand from the Italian grid on 15 May 2013 (green line). Assuming a 20% PHEV penetration for Italy, as predicted in [21] for a scenario with policies to support sustainable mobility, and further assuming an equal distribution (1/3 each) of the three PHEV types considered, the uncontrolled charging mode load is depicted by the dotted black curve. The dotted red line represents the mode 2 charging load, while the dotted blue line shows the load under V2G adoption for all PHEVs.

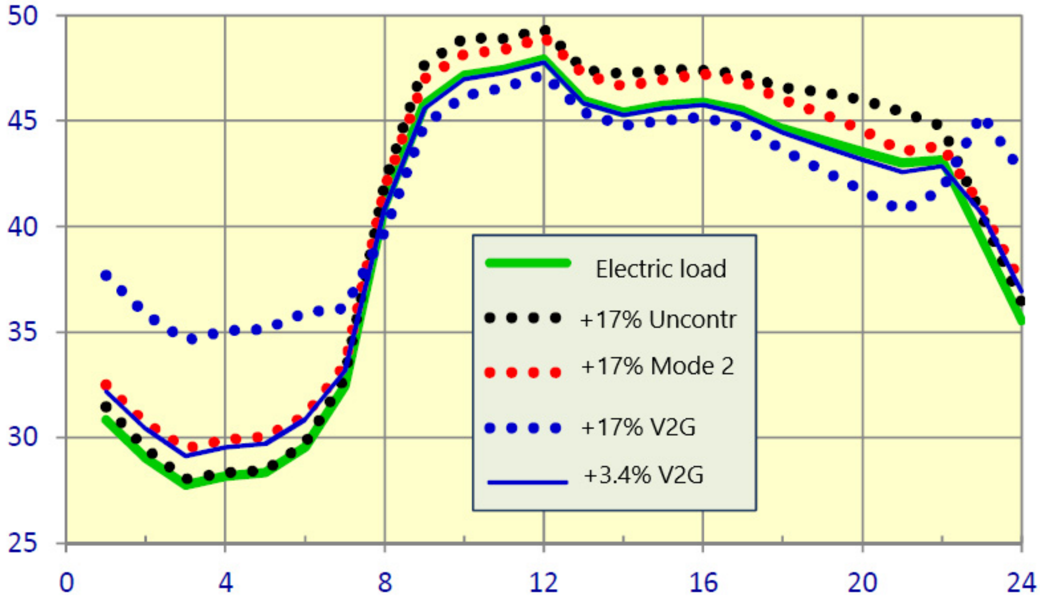

Figure 10. Italian power load, 15 May 2013 (red curve). Dotted curves: +17% PHEVs, uncontrolled (black), Mode 2 (red), V2G (blue). Continuous blue: V2G reduced to 3.4%.

Visual inspection of Figure 10 reveals that uncontrolled charging (dotted black curve) significantly elevates loads during HRP. Mode 2 charging (dotted red curve) exhibits a more balanced load distribution throughout the day, while V2G charging primarily draws energy at night, contributing to a slight reduction in peak hour demand.

It is important to acknowledge that these observations are indicative in nature. The actual load will likely reside between the depicted scenarios due to the inherent variability in charging behaviors. To reflect a more realistic scenario, we assume that only 20% of PHEV owners adopt the V2G mode, resulting in a combined PHEV penetration of 3.4%. The resulting continuous blue load curve illustrates this scenario. As observed, this strategy eliminates daytime load increases, concentrating demand solely during nighttime hours.

To make charging more flexible and contribute to energy savings, it is important to implement a comprehensive strategy. This strategy can include several demand control methods that vary in complexity and application areas. These methods include [22]:

1. Time-of-use (TOU) pricing: This approach involves providing different electricity costs during different times of the day, and it is particularly suitable for home or workplace charges.
2. Intelligent charging algorithms: These algorithms optimize the charging process by considering various factors, such as the cost of electricity, demand on the network, and user preferences. They are suitable for charging requests related to long stops, such as at residential off-street parking, workplaces, or park-and-ride.
3. Integration of charging infrastructure with network management systems: This enables monitoring and control of electric vehicle charging demand.

4. Predictive and adaptive charging methods: These methods use advanced algorithms and data analysis techniques to improve charging schedules and dynamically adapt to changing environmental conditions.

While V2G technology demonstrably enhances network performance, quantifying its precise benefits for grid operators remains a challenge. Conversely, cost assessments for vehicle owners are more readily attainable. Assuming that a battery contributes half its energy to the grid throughout its lifespan, owners need to recoup half the battery's cost through service remuneration. Based on current battery prices (150 €/kWh, https://www.energy.gov/eere/vehicles/articles/fotw-1272-january-9-2023-electric-vehicle-battery-pack-costs-2022-are-nearly, accessed on 28 March 2024) and average lifespans (1000 recharges), the cost per kWh supplied stands at EUR 0.15. Doubling the lifespan effectively halves this cost to 0.075 €/kWh, nearing the cost of conventional electricity production (https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, accessed on 28 March 2024). Further reductions in battery costs, efficiency improvements, and extended lifespans will make V2G services even more cost-competitive. As energy production costs continue to rise, V2G's economic attractiveness is poised to increase beyond its current perception [23,24].

The proposed method can be directly extended to any area for which sufficient mobility data are available. Since the study involves a control strategy, it is particularly suitable for electric vehicle fleets or charging facilities with centralized control, such as company car parks or shopping centers. Knowledge of the actual penetration of electric cars improves the performance of the estimates.

5. Conclusions

Studies demonstrate that electrifying road transport leads to significant energy savings across the entire life cycle, from fuel production to vehicle use. Considering the transportation sector's crucial role in achieving national energy consumption and emission reduction goals, the evident advantages of transitioning to hybrid and electric vehicles warrant implementing appropriate incentive measures.

The transformation of electricity networks from microgrids to transmission systems necessitates adequate storage capacity. In this context, intelligent vehicle charging management offers significant network benefits by providing both demand flexibility and distributed storage. However, while it is advantageous for the grid, V2G implementation requires not only a bidirectional converter (more complex than conventional chargers), but also optimal charge–discharge management adhering to constraints dictated by vehicle availability, usage needs, and maximum current/power limits to minimize battery aging. The National Integrated Plan for Energy and Climate (PNIEC) 2020, formulated by Italy, envisions the integration of 10 gigawatt-hours (GWh) of stationary storage by 2030 to facilitate the burgeoning utilization of renewable energy sources (RES). Notably, a mere 1 million plug-in hybrid electric vehicles (PHEVs) equipped with 10 kWh batteries could collectively represent a 10 GWh storage capacity.

Currently, V2G finds its primary application in grid regulation, providing essential flexibility and stability to the electrical grid by balancing real-time energy demand and supply. However, another potential use of V2G is a grid-scale energy reservoir. This scenario posits V2G batteries evolving beyond dynamic responders to serve as stationary storage, accumulating surplus energy for later release when needed. Such a paradigm shift holds significant promise, such as enhancing renewable integration by storing surplus production or reducing grid infrastructure costs by providing localized energy storage and release, effectively alleviating peak demand pressures in specific areas, thus optimizing existing infrastructure. V2G allows EV owners to earn revenue through price arbitrage, buying electricity when the price is low and selling when the price is high. On the other hand, the energy system benefits from voltage and frequency regulation and ancillary services. Bidirectional charging is a revenue opportunity for EV manufacturers, charging point operators, and software providers through product differentiation and energy management systems. However, there are still some challenges to address. Currently, only a few bidirectional chargers are available, mostly compatible with CHAdeMO chargers. Bidirectional AC and DC chargers are expected to be commercially available soon. From the regulatory point of view, the EU has provided general objectives for V2G through various legislative instruments, such as the Clean Energy for All Europeans and "Fit for 55" packages. However, several enabling legislations still need to be fully transposed and implemented by Member States, such as the 2019 EU electricity market design framework. Potential issues also include battery degradation and communication between system components [24].

The application of various charging strategies reveals that, while user-centric approaches based solely on time-of-use costs can incentivize off-peak charging, they may inadvertently generate a new peak at the beginning of lower-cost periods. This underscores the need for charging systems that strike a balance between user preferences and grid constraints, ensuring both stability and efficiency.

One of the biggest challenges of adopting plug-in hybrid electric vehicles (PHEVs) in the ecological transition is that their environmental benefits depend significantly on travel profiles [25]. However, control and management strategies can help to improve the energy efficiency of these vehicles [26]. The use of smart and connected technologies can also contribute to achieving efficiency goals [27]. For instance, intelligent transportation systems can help solve traffic congestion problems and reduce carbon emissions [28]. However, several challenges must be addressed to make the most of electric mobility [29], including:

1. Real-time load data forecasting poses a significant challenge;
2. The regulatory frameworks of most countries do not have mechanisms for contracting flexibility services between energy distributors, system operators, and consumers;
3. The lack of standardization of charging ports is also an obstacle;
4. Finally, there are potential security risks for communication networks in smart charging.

The proposed charging management algorithms, particularly those optimized for grid flexibility, offer promising solutions for immediate implementation. However, further research is imperative to enhance the economic viability of V2G services, their demonstrated performance advantages notwithstanding. This could involve exploring innovative pricing models, cost-sharing mechanisms, and regulatory frameworks that incentivize grid-supportive behavior from PHEV owners.

The main limitations of the study are that it considers a complete switch to one type of electric car, resulting in a uniform fleet, and it implies a system that ensures the implementation of flexible charging for all users. Future analysis could extend to an electric fleet with a composition that more realistically reflects that of the market, including PHEVs and BEVs, and which differentiates strategies according to parking times and the type of charging.

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