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Recharging scenarios for differently electrified road vehicles: A methodology and its application to the Italian grid

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ABSTRACT

Promoting the adoption of plug-in hybrid electric (PHEVs) and battery electric vehicles (BEVs) is essential to meet local environmental requirements. A way to favour the use of these vehicles is to improve the ability to recharge vehicles at home or at the workplace, and to predict their residual energy state of charge throughout the day. This paper presents a novel user-friendly methodology to assess different recharging scenarios. The methodology was applied to a real case study on an international car manufacturer based in Italy. Several scenarios were addressed regarding the recharge at home of electrified vehicles, considering meter upgrades and different recharging speeds. The Vehicle-to-Grid (V2G) case was also investigated. The results show that PHEVs are the most flexible solution where domestic slow recharging is the only or preferred choice. BEVs become viable when at least a 4.5 kW supply contract is available together with a fast-recharging infrastructure with a suitable home grid, or where daytime parking lots with recharging facilities are available. The application of the proposed methodology to a real case study suggests that this approach can usefully help decision makers to identify the type of investments to be made and where they should be carried out.

Introduction

In the current energy transition context, an important issue concerns the mobility of people and, to a lesser extent, the transport of goods through the electrification of road transport systems. The negative impact on public health derived from the use of conventional internal combustion engines in cities and metropolitan areas has been widely demonstrated (Anenberg et al., 2019; Gaidar et al., 2020; Krupnova et al, 2020), although transport systems are neither the only nor the prevailing cause. Chronic Obstructive Pulmonary disorder is due, among other causes, to pollution from fine dust (PM 2.5), representing an increasingly frequent cause of death, together with other illnesses of the cardio-respiratory system (Zhu et al., 2020).

Because of their ability to reduce the TTW (Tank-To-Wheel) and local emissions, electrified vehicles – including the use of the electric traction of PHEV in addition to BEV – may improve the air quality in urban centres, where the majority of daily mobility at global level is concentrated. Therefore, their use should be encouraged, trying to meet at best user preferences (Hoeft, 2021; Krishna, 2021; Lavee and Parsha, 2021; Logan et al., 2020). Moreover electrified vehicles can represent an effective tool to fight against global warming only as far as also their Well-To-Wheel (WTW) impact is lower, along their lifecycle.

Investments to increase the battery driving range and the number of charging spots are planned in many areas of the world. Car manufacturers include new electrified powertrains in their catalogue, whereas public administrations promote policies to push users to become an integral part of this migration and support the setting up of installations to favour innovative powertrains (Dale and Lutsey, 2017).

However, a number of challenges still need to be addressed in order to adopt electrified vehicles on a large-scale. Some currently open issues, such as high costs and limited battery driving ranges, may prevent the adoption and utilisation of electric vehicles by the great majority of the population.

Battery Electric Vehicles (BEVs) have so far not been a viable alternative for everyday flexible use, due to their shorter range than traditional automobiles, recharge duration, recharging behaviours

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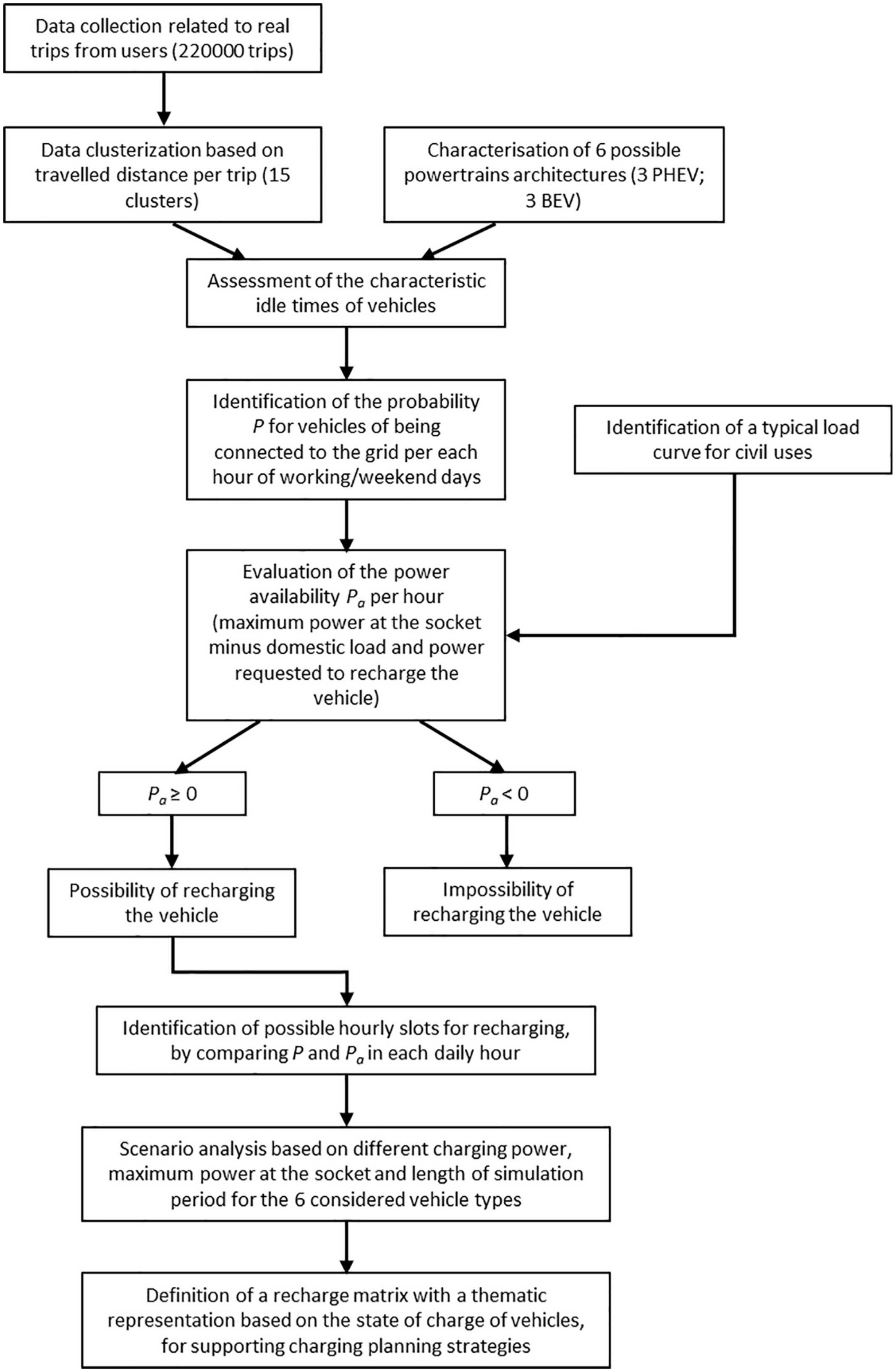

Fig. 1. Logical flow of the proposed methodology.

(Chakraborty et al., 2020; Ge et al., 2020; Ge et al., 2018; Hardman et al., 2018; Li et al., 2016), ageing of batteries and inadequate power grids (Matulka, 2014). Some of these issues are relevant also for other pioneering technologies in transportation such as hydrogen fuelled vehicles (Inci et al., 2021), in which drivers may experience similar anxiety due to unavailability or complexity of refuelling points (Ghahari et al., 2019). However, the same issues have been addressed and solved in other battery-relying applications, although battery sizes and charging infrastructure are not comparable. The fear of users of not having sufficient driving range for their vehicle and of not finding an available recharging point within an acceptable time are concerns already successfully addressed in the case of smartphones. Thanks to the technological improvement of batteries, increasingly long lasting, and to the widespread diffusion of recharging points (e.g. seat-mounted charging sockets in high-speed trains), the use of smartphones is no longer experienced as a source of anxiety. Unmistakably, for motor vehicles the power and energy scale is different. The electric grid present inside buildings is not usually accessible for such vehicles. Moreover, the national electricity grids may be unable to contemporarily support the recharging of both domestic appliances and plug-in vehicles, especially if EV market share becomes substantial.

EV charging habits have been studied in the literature. Robinson et al. (Robinson et al., 2013) used a software to record data from 7704 recharging events of EVs circulating in the North-West of England. The impact on the Belgian national electric network of a considerable number of electrified vehicles was investigated by Rangaraju et al. (Rangaraju et al., 2015). Labeye et al. (Labeye et al., 2013) administered a satisfaction questionnaire to participants preselected to use the MINI E and reported their impressions and use habits.

However, the effect of the availability of home charging options for plug-in vehicles has not yet been sufficiently studied. Klein et al. (Klein et al. 2020) proposed an agent-based simulation to assess the behaviour of German consumers with reference to BEVs and PHEVs (Plug-in Hybrid Electric Vehicles), taking into account domestic charging, which seems to significantly affect the penetration of these kinds of vehicles. Moon et al. (Moon et al., 2018) analysed consumer charging patterns. They highlighted that consumers take into account the trade-offs between the full charge time and the charging price, and studied the related impacts on the electricity consumption. Huang and Kockelman (Huang and Kockelman, 2020) applied genetic algorithms to define the optimal location of charging stations in terms of maximisation of the profit, considering congestion, elastic demand and charging price elasticity. Dong and Lin (Dong and Lin, 2012) analysed the role of public charging infrastructure in increasing the share of driving on electricity over gasoline exhibited by PHEVs. The authors modelled the within-day recharging behaviour of drivers, considering travel patterns and availability of public chargers.

Kester et al. (Kester et al., 2019) provided an assessment of public perceptions of BEVs and Vehicle-to-Grid (V2G) systems across five Nordic countries using original data drawn from eight focus groups. An investigation was proposed by Zou et al. (Zou et al., 2020) concerning the impact of charging electric vehicles on low voltage networks structure and technology of electric vehicles, by using a distributed agent-based model. Meelen et al. (Meelen et al., 2020) presented an in-depth study of the fleet market in the United Kingdom and assessed synergies between V2G and vehicle fleets by analysing socio-technical trends. A comprehensive literature review can be found in (Bibak and Tekiner-Moğulkoç, 2021) regarding the implementation of EVs, especially considering their supporting roles for the grid in V2G.

This paper proposes a user-friendly methodology to evaluate different charging scenarios for electrified vehicles, including the V2G configuration. The methodology was applied to an Italian case study, using the real data provided by an important international car manufacturer. The constraints imposed by the national electric grid were taken into consideration. The compliance with the available domestic electricity capacity was analysed to highlight the best daytime hours for recharging, taking into account the curve of the electricity demand. The availability of a V2G infrastructure is assumed.

The contribution of the present work is to provide a decision support tool that may successfully provide advice for policy makers or end users. The tool is implemented in a widely used spreadsheet where a colour code is associated with the different levels of charge reached by the vehicle, on an hourly basis. The tool is easy to use and it is applicable in any national scenario and for any vehicle for which battery capacity and specific consumption are known. These features make the method advantageous for a wide range of stakeholders, not limited to experts and professionals.

Table 1
Characteristic values of the 15 clusters identified as a result of the analysis of the mean covered distance by the analysed vehicles.

Cluster ID	Length [km]	Duration [s]	Size of cluster [number of trips]	Cluster %
1	0.1	82	2772	1.3
2	0.2	127	11,797	5.3
3	1.2	348	21,348	9.6
4	2.2	532	23,476	10.6
5	3.2	456	27,134	12.2
6	7.3	637	20,420	9.2
7	8.3	791	288	0.1
8	6.8	764	18,000	8.1
9	8.6	736	21,937	9.9
10	10.6	772	25,771	11.6
11	10.8	915	24,157	10.9
12	32.3	2658	10,937	4.9
13	35.4	2409	9241	4.2
14	121.1	4864	3446	1.6
15	243.9	8982	1014	0.5

The results deriving from the simulations can support decisions regarding the type of public funding to plan for, or the investments needed for private contexts.

The methodology proposed in this research helps to foster the new electric paradigm, taking into account the present and future availability of recharging technologies, batteries and grid capacity.

The paper is structured as follows: Section 2 describes the methodology used and the scenarios considered, whereas in Section 3 the results obtained in the different scenarios are presented. Finally, conclusions are outlined in Section 4.

The methodological framework

The methodology and its implementation are synthesised in Fig. 1, which shows the logical flow of operations to model different recharge scenarios for differently electrified road vehicles, and assesses their effectiveness and the impacts on the electric grid.

Data used for this research were supplied by an important company in the automotive field and were obtained through a software program related to eco-driving installed in a range of C-SUV vehicles, which monitored their use. The software programme is able to record the time at which a vehicle is turned on, its movement in an urban, extra-urban and motorway context, as well as its mean and instantaneous consumption. The analysis of this data allowed insight into the typical use of the vehicles. More than 220,000 trips were analysed and grouped according to 15 routes called clusters, characterised by different travel distances. The shortest distance (0.1 km) refers to 1.3% of total trips, while the longest distance (243.9 km) represents 0.5% of total trips. In this way, it was possible to define an average daily distance per direction of 11.3 km. This value is reasonably compliant with results obtained in (Dalla Chiara et al., 2019a). Table 1 shows the data of the 15 clusters analysed.

The size of cluster column indicates how many of the 220,000 considered trips covered a distance within the range of the length reported in column 2. On the basis of these first results, six different powertrain architectures – including both BEV and PHEV – were hypothesised. These typologies are able to fulfil the majority of potential mobility needs. These architectures were defined in relation to the models currently on the market, from the PHEV 50 model (where 50 indicates the driving range in km in exclusively electric drive mode) and the BEV 150 model (Battery Electric Vehicles with 150 km of driving range), to the most recent, characterised by higher battery capacities, such as the PHEV 75 (indicatively 10–12 kWh of stored energy) of and

Table 2
Characteristic values of some PHEV and BEV models (all the data are declared by manufacturers; capacity refers to the installed capacity value).

Architecture	Model	Capacity [kWh]	Specific consumption [kWh/km]
PHEV 25	Mercedes Class C	6.2	0.16
PHEV 50	Audi A3 Sportback E-Tron	8.8	0.15
PHEV 75	Mitsubishi Outlander	13.8	0.12
BEV 150	Mitsubishi i-Miev	16.0	0.17
BEV 200	Citroën E-Mehari	30.0	0.15
BEV 300	E-Golf (2017)	35.8	0.13

the BEV 200 and 300 models.

This resulted in a total of three PHEV and three BEV, as summarized in Table 2, where capacity indicates the value of the on-board battery storage capacity, while specific consumption for PHEVs refers only to the electric drive mode.

Once the energy storable in the available alternative batteries is known, it is necessary to understand in which idle periods vehicles can be recharged. Idle periods are obtained from the analysis of data provided by the manufacturer. On the basis of the charging state, the charging time-energy (SOC or state of charge) relation can be obtained. SOC is necessary to trace the recharging scenarios for differently electrified road vehicles.

Study of idle times

Fig. 2 shows the features of vehicle idle times during the hours of a typical day. Two maximum points with different orders of magnitude can be identified on the density curve.

The first maximum is in the order of minutes and corresponds to stops at traffic lights or to short intermediate stops (brief shopping, waiting for a passenger, short errands, etc.). Such idle times are unsuitable for any type of recharge, with the exception of ultra-fast recharging, for which at least 10 min would be necessary. Alternatively, inductive charging while driving would be necessary. The second maximum is in an order of magnitude of 8 h, which is compliant with idle times at workplaces or during night hours at home or hotels. It would be possible to use home charging in these ranges, compatibly with the installed capacity in the house, as is discussed in section 2.5.

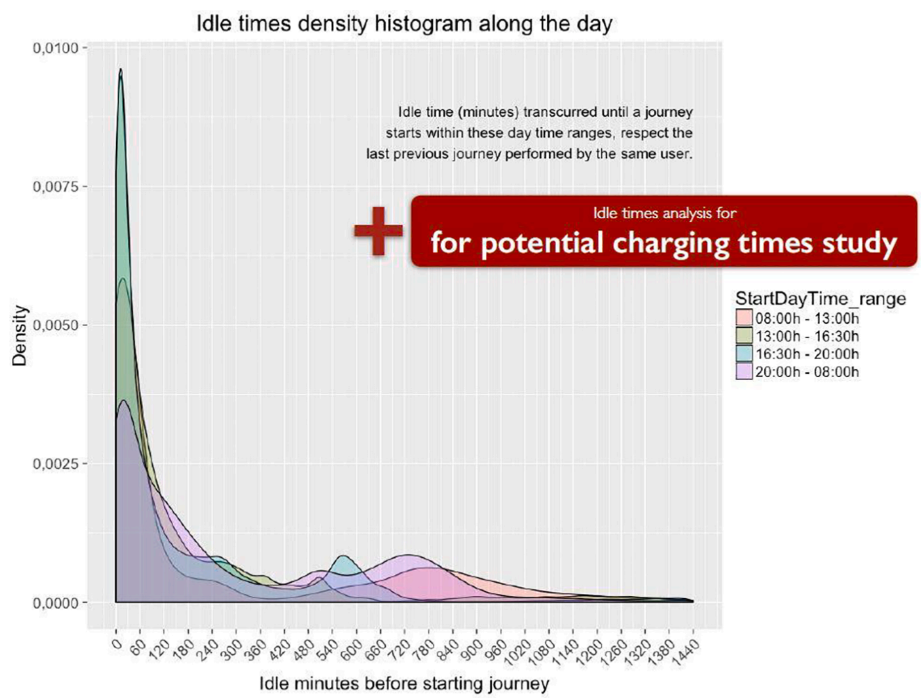

Fig. 2. Density curve of idle times during a typical day (Meler, 2016; Dalla Chiara et al., 2019b).

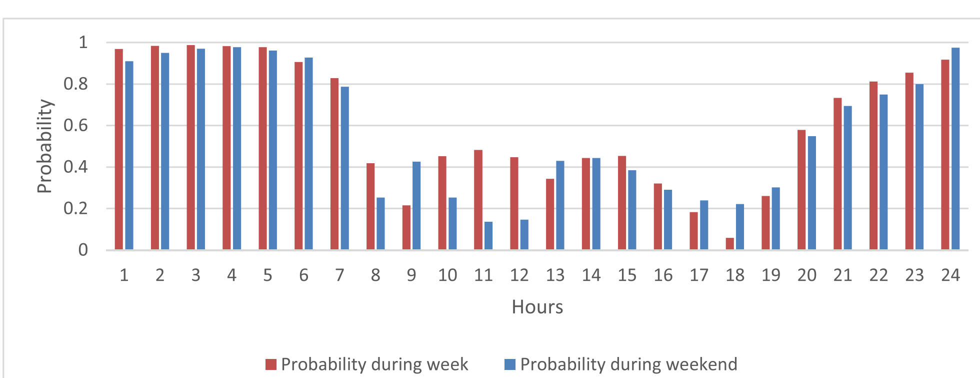

Fig. 3. Probability of BEV/PHEV vehicle of being idle at each hour of the day and of being available to connect to the grid.

Probability of connection to the grid

The data reveal the most frequent hours in which the vehicles are started. A distribution was created of the probability of the starting hours throughout the day as the complement of the probability of being idle, therefore available for recharging. In (1), p is the probability - expressed as fraction of unity - that a vehicle will be recharged because it is idle, and s is the probability value of the vehicle starting.

$$p = 1 - s \tag{1}$$

The distribution represented in Fig. 3 is obtained calculating p for each hour. It shows that vehicles have a greater chance of being parked during night hours, with numbers exceeding 80% from 23:00 to 7:00. Moreover, it can be observed that there are no major differences between the days of the week and the weekend.

Analytical definition of vehicle charging state

In the following, an analytical formulation of the charging state of an electrified vehicle is provided.

The power available at the socket in a certain time step can be expressed as in (2):

$$P_a(t) = P_m - L(t) - P_c \tag{2}$$

where

- P_m, is the maximum power meter (expressed in kW);
- $L(t)$, is the user load at time t (expressed in kW), i.e., how much energy the user absorbs to power its electrical appliances (user energy demand);
- P_c, is the recharge power (expressed in kW), i.e., the power required to recharge the vehicle. For the sake of this analysis, this term is assumed to be constant throughout the whole recharging process, since a conservative framework is considered.

Given a discretised time horizon, in a generic time step *t*, a vehicle may be in one of the following mutually exclusive states: (i) under recharge, (ii) in use, or (iii) in the V2G mode. The activation or not of these three states can be represented by three discrete coefficients, i.e., $A(t)$, $U(t)$and $V(t)$, respectively, which can assume value equal to 0 or 1 at each time step *t*:

- $A(t) \in [0, 1]$, is the recharge availability at time *t*;
- $U(t) \in [0, 1]$, is the use of the vehicle at time *t*;
- $V(t) \in [0, 1]$, is the V2G option at time *t*;

where t, is the time step, expressed in 1 h [0,24].

Defining:

- $p \in [0, 1]$, as the probability for a vehicle of being idle and
- $p_{min} \in [0,1]$, as a minimum threshold probability for the vehicle being idle (e.g. at least 60% of probability of the vehicle of being idle in a certain timestep),

then the following can be written:

$$A(t) = \begin{cases} 0 \text{ if } p(t) < p_{min} \text{ or } P_a(t) < 0, \quad \forall U(t), V(t) \\ 1 \text{ if } p(t) \geq p_{min}, \quad P_a(t) \geq 0, \quad U(t) = 0, \quad V(t) = 0 \end{cases} \tag{3}$$

The value of $A(t)$ - expressed by (3) - is a function of the probability that the vehicle is in charge at time *t* and of the fact that the available power at time t, $P_a(t)$, - that is the difference between the maximum contract power, the load and the power required for recharging, as expressed by equation (1) - is greater than or equal to 0.

$U(t)$ assumes value equal to 1 if the vehicle is in use at time *t* (that is, not available for charging), 0 otherwise, as indicated by (4).

$$U(t) = \begin{cases} 0 \text{ if idle vehicle} \\ 1 \text{ if vehicle in use} \end{cases} \tag{4}$$

$V(t)$ is expressed by (5) and identifies the time steps when the vehicle is occupied in a V2G configuration and thus not available for charging (as it is charging the network itself) or when the V2G configuration is not explicitly chosen.

$$V(t) = \begin{cases} 0 \text{ if} \quad \text{V2G option not considered or } C_v(t) < 0 \\ 1 \quad \text{if} \quad \text{V2G option considered and } C_v(t) \geq 0 \end{cases} \tag{5}$$

V(t) depends on whether the difference between the capacity available at time *t-1*, $C(t-1)$, and that required by the network at time $t, C_{V2G}(t)$, is greater than or equal to 0 (equation (6)). Only in the latter case the V2G option is taken into account:

$$C_v(t) = C(t-1) - C_{V2G}(t) \tag{6}$$

where:

$C_v(t)$ is the net capacity of vehicle batteries available at time *t* in the V2G case (expressed in kWh);

$C(t)$ is the charge of vehicle batteries at time *t* (expressed in kWh);

$C_{V2G}(t)$, is the capacity required by the grid at time *t* for V2G (expressed in kWh).

The state of charge of a vehicle $S_c(t)$ can be therefore expressed by (7):

$$S_c(t) = \begin{cases} S(t-1) + \dfrac{A(t) \bullet P_c - U(t) \bullet f(t) \bullet d(t) - V(t) \bullet C_{V2G}(t)}{C_m} & \text{if } 0 \leq S_c(t) \leq 1 \\ 1 & \text{if } S_c(t) > 1 \\ 0 & \text{if } S_c(t) < 0 \end{cases} \tag{7}$$

where

- $S(t)$ is the state of charge of the vehicle at time t (expressed in %);
- $f(t)$ is the specific consumption of the vehicle at time *t* (expressed in kWh/km);
- $d(t)$ is the distance travelled at time *t* (expressed in km);
- C_m is the maximum capacity of batteries (expressed in kWh).

The state of charge at time step *t* is given by the sum of the vehicle state of charge at the previous time step $(t-1)$ plus three terms:

a) the term $\frac{A(t) \bullet P_c}{C_m}$ expresses the vehicle charge, which is executed only if $A(t) = 1$;
b) the term $\frac{-U(t) \bullet f(t) \bullet d(t)}{C_m}$ expresses the electric charge used to move the vehicle, which is function of the distance travelled in timestep *t* and the specific consumption of the vehicle in time step *t*;
c) the term $-\frac{V(t) \bullet C_{V2G}(t)}{C_m}$ expresses the electric charge provided by the vehicle to the grid in time step *t*.

If the charge of the vehicle at a certain time step *t* needs to be expressed in kWh, then equation (8) must be applied:

$$C(t) = S_c(t) \bullet C_m \tag{8}$$

In the following paragraphs, conceptual details are provided for the definition of the remaining parameters used in the methodological framework, using the probability p and the power availability at the socket P_a.

Electric charging curve

Once the available time distribution for recharging, its allocation during the day and the charging state are known, the next step is to analyse the load curve for a typical use of the home grid on the base of

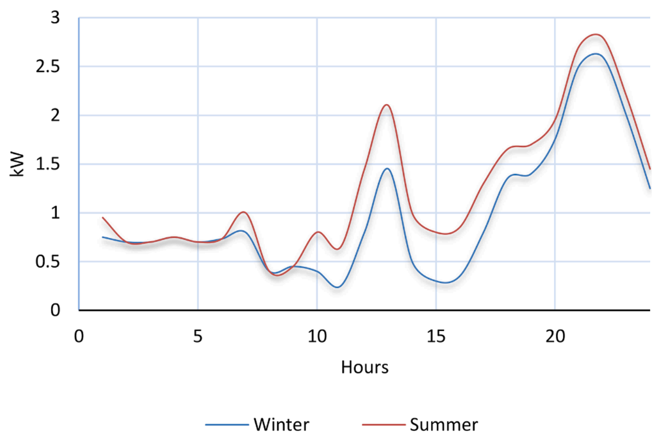

Fig. 4. Load curve for winter and summer use (based on data from (Barsali et al., 2011)).

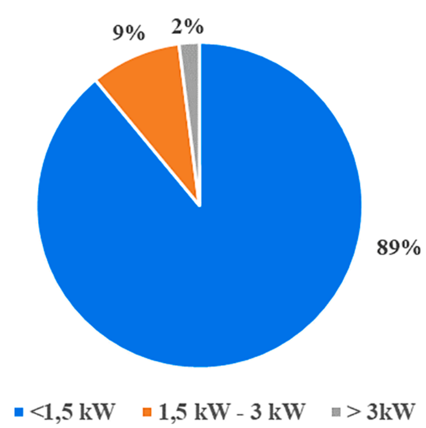

Fig. 5. Distribution of the power meters installed in Italian homes (on data from ARERA, Autorità di Regolazione per Energia Reti e Ambiente, 2018, ARERA-Dati statistici, Available at: www.arera.it/it/dati/elenco_dati.htm, consulted on May 2021.

the vehicle usage. This analysis makes it possible to identify the hours of the day in which the greatest absorption occurs, and the hourly slots in which power is available for domestic vehicle recharge. This means matching the demand and the supply of energy for vehicle use.

The curves shown in Fig. 4 refer to the winter of 2011 on data provided by ENEA (Italian National Agency dealing with Energy) in a study that had the purpose of sizing an electric storage system to limit the absorption peaks of civil use. The summer curve was created by the authors as an average over a four-year period. The two curves differ in the presence of a higher load in the summer, due to the use of air-conditioning systems. Considering the increasing use of these appliances in homes, it was decided to take this aspect into account in the present study. To adopt a conservative approach, only the summer curve was considered later in the calculations.

Power at the domestic socket

Recharging of PHEVs/BEVs can take place in the domestic environment, by means of 10A or 16A currents, which correspond to devices with powers of 2.3 kW and 3.7 kW, respectively. The domestic charging modes (Bräunl, 2012) can generally be *Mode 1* or *Mode 2*. Mode 1 is without an ad-hoc mounted socket and safety protocols. For Mode 1, the maximum current rating is 16 A, usually suitable only for small vehicles including PHEVS equipped with small batteries (e.g. 6–12 kWh). Mode 2 (maximum current rating of 32 A) can use a household-type socket-outlet but with an in-cable protection device (control box). This involves slightly higher costs, suitable cabling, but also a significant improvement in safety (Kersten et al. 2021). In the domestic environment it is also possible to install charging units for a faster recharge (e.g., wall-boxes) which are operated in *Mode 3* (allowable current rating up to 63 A) but which involve the availability of a much higher power at the socket in addition to a suitable local grid.

Data provided by the Italian Energy Authority for the year 2016, although conservative in the following years, reveal the availability of power at the sockets for Italian families. The vast majority of meters (89%) had powers that ranged between 1.5 and 3 kW, while only 9% had a greater availability (Fig. 5).

The Italian energy market reform, which entered into force in 2017, foresees the possibility of modulating the power available at domestic meters, varying the range by as much as 0.5 kW. The cost per kWh of electricity for private use oscillates in Italy between approximately € 0.18 and € 0.25, which makes electric charging nearly 1/3 to 1/5 less expensive than travelling with a private light vehicle using traditional oil-derived fuels. Fast and rapid charging for public use was available in 2020 from 0.45 €/kWh to 0.79 €/kWh. In this case, recharging may become more expensive than refuelling, given the same amount of driven km. Given P_{max} the maximum power at the socket equal to 3.3 kW, it is possible to calculate the power availability P_a, that is, the parameter that allows the possibility of domestic charging of a vehicle. It should be noted that, although energy supply contracts in Italy have a

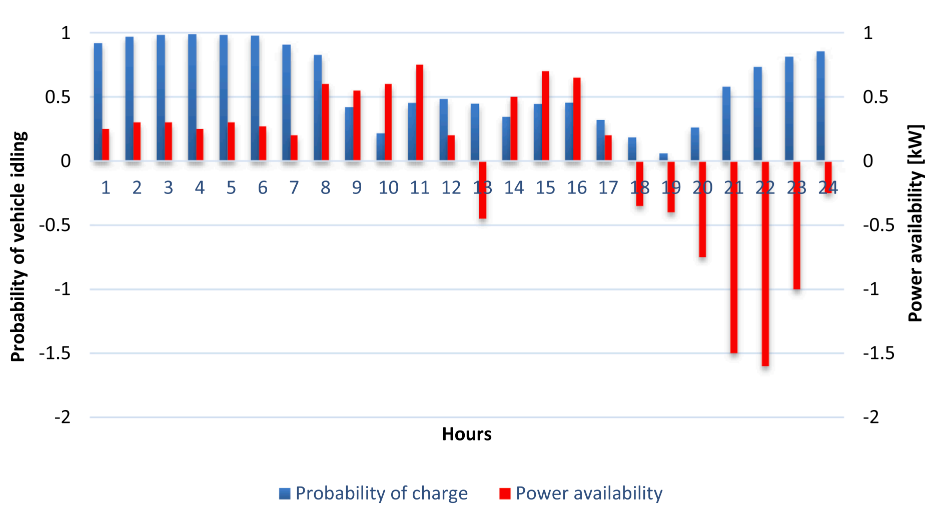

Fig. 6. Power availability versus probability of charging (because the vehicle is idle).

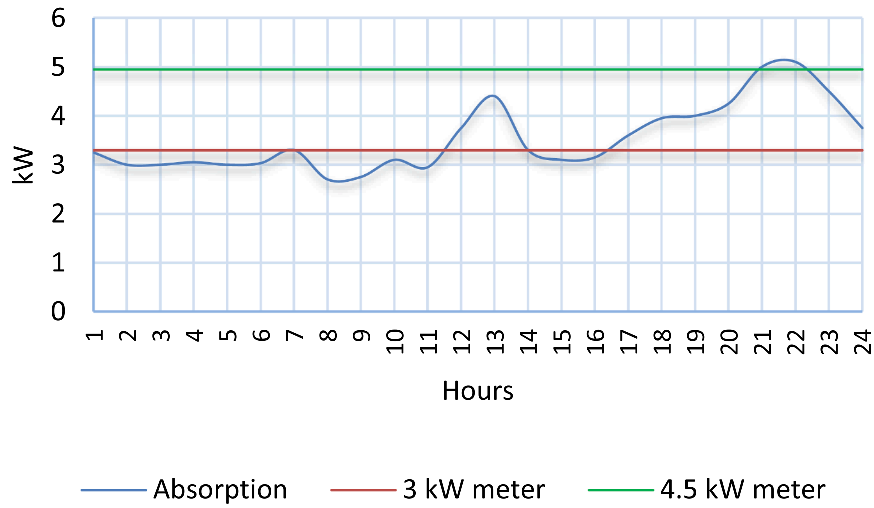

Fig. 7. Summer household profile with BEV/PHEV plugged in and two levels of meter capacity.

nominal power of 3 kW, the Italian law foresees a tolerance of 10% on extra power required at the socket (ARERA, Autorità di Regolazione per Energia Reti e Ambiente, 2018, ARERA- ARERA-Consumatori elettricità, Available at: www.arera.it/it/consumatori/consumatori_ele.htm, consulted on May 2021). P_a is defined as in (9):

$$P_a[kW] = P_{max} - (L + C) \tag{9}$$

where L is the power absorbed for domestic recharging and which can be inferred from the charging curve in Fig. 4, and C is the power required for a vehicle to be charged. If positive, parameter P_a indicates the possibility of carrying out a recharge. If negative, it indicates the impossibility of recharging as a result of an insufficient availability of power. In Fig. 6, P_a is represented by red bars, and was calculated for the case in which the recharging of a vehicle takes place with an absorbed power of 2.3 kW. The probability of a vehicle being idle, and therefore available for recharging (blue bars), is also shown in the same graph. This result makes it possible to qualitatively identify the hourly slots in which it is not possible to recharge, due to a lack of power, and those hours in which power is available. The statistical probability of the vehicle being idle is low. The threshold of usability for this probability can be set according to realistic utilisation patterns of the electrified vehicle.

Role of an increase in power available at the socket

The evaluation of P_a, and therefore the identification of the time slots in which it would be possible to recharge a vehicle, cannot be performed without considering the power size of domestic meters. In Fig. 7, the red and green curves represent the available power for 3 and 4.5 kW meters, respectively (including tolerance for 10% extra power). The blue curve, on the other hand, indicates the absorption of the two kind of powers - i. e., domestic load and recharging - over a period of 24 h, where recharging is assumed to be 2.3 kW.

From Fig. 6 and Fig. 7 it emerges that it is not possible to recharge a vehicle, unless it is after 24:00. This is due to heavy power consumption in the evening hours when energy-intensive household appliances are typically run to take advantage of the dual hourly rates. This behaviour would change if it were possible to have 4.5 kW available at the socket, while still recharging at 2.3 kW.

Definition of recharging scenarios and modelling assumptions

Different scenarios can be defined that combine the type of domestic meter available and the type of vehicle recharging. The considered scenarios are summarised in Table 3.

Table 3
Features of the analysed scenarios.

Scenario ID	Charging Power [kW]	Available Power [kW]	Simulation time [h]	Place of charging
1	2.3	3.3	24	Home
2	2.3	3.3	24	Home
3	2.3	4.5	24	Home
4	3.7	4.5	24	Home
5	2.3/3.7	3.3/3.7	48	Home/ Workplace

The adopted model foresees the temporal time step of an hour, as the considered recharging has been assumed to be of a Mode 2 type, given the vast majority of existing contracts in Italy (89%, less than 3 kW), and with a low power and a recharging speed of the order of a few hours. The model foresees the evaluation of the recharging level of a vehicle on an hour-by-hour and architecture-by-architecture basis. Recharging begins as soon as power is available and continues until the first slot is reached where the power is no longer sufficient. When the recharging process restarts, it is assumed that the battery pack is completely discharged again. This is obviously a very conservative hypothesis, but it allows the subsequent simulations to be developed realistically. The State of Charge (SOC) of the batteries is calculated, at each hourly step, in each scenario and for each of the different architectures, on the basis of their installed capacity (see Table 2) and the power of the charger, according to Eq.(10):

$$SOC[\%] = \frac{P \cdot H}{C} \tag{10}$$

where P is the recharging power (kW), H is the available recharging hours and C is the total capacity of the batteries (kWh).

Scenario No.1 considers a vehicle with an absorption of 2.3 kW, which is completely discharged at 24:00 and begins the recharging phase as soon as a constant power is available over time.

Scenario No.2 introduces the assumption that the recharging hours at a domestic recharging post can only take place if power is available and there is a probability greater than 60% that the vehicle is idle. This makes the simulation more realistic and reduces the field to night hours only, which is reasonably compatible with the use of private vehicles. Scenario No.3 foresees an increase in available domestic power up to

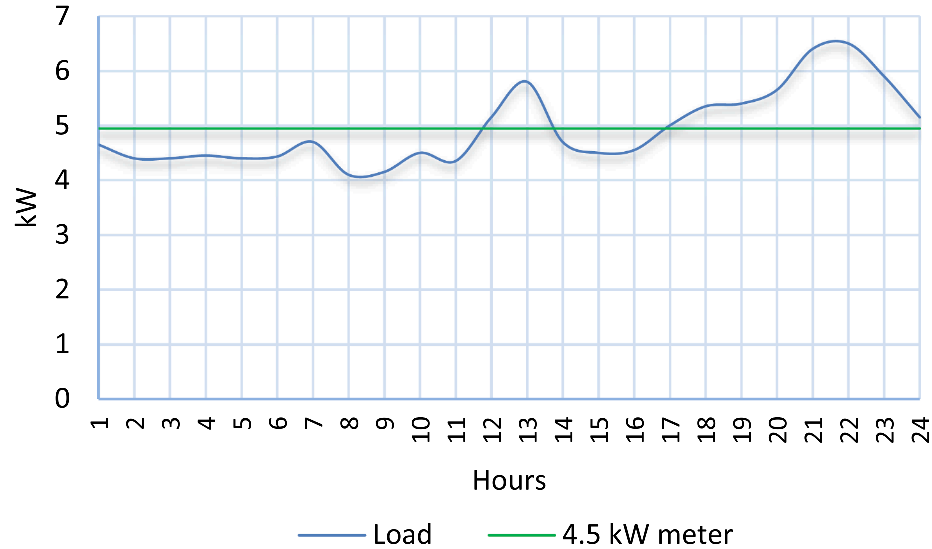

Fig. 8. Summer household profile with BEV/PHEV plugged in and a 3.7 kW recharging capacity.

Table 4
Results of scenario 1 (3.3 kW Meter, 2.3 kW recharging capacity, dead batteries at the beginning of the day): percentage of recharging reached at the end of the recharging time, according to the various architectures.

H	PHEV 25	PHEV 50	PHEV 75	BEV 150	BEV 200	BEV 300
1	0.37	0.26	0.17	0.14	0.08	0.06
2	0.74	0.52	0.33	0.29	0.15	0.13
3	1.00	0.78	0.50	0.43	0.23	0.19
4	1.00	1.00	0.67	0.58	0.31	0.26
5	1.00	1.00	0.83	0.72	0.38	0.32
6	1.00	1.00	1.00	0.86	0.46	0.39
7						
8	0.37	0.26	0.17	0.14	0.08	0.06
9	0.74	0.52	0.33	0.29	0.15	0.13
10	1.00	0.78	0.50	0.43	0.23	0.19
11	1.00	1.00	0.67	0.58	0.31	0.26
12						
13						
14	0.37	0.26	0.17	0.14	0.08	0.06
15	0.74	0.52	0.33	0.29	0.15	0.13
16	1.00	0.78	0.50	0.43	0.23	0.19
17	1.00	1.00	0.67	0.58	0.31	0.26
18						
19						
20						
21						
22						
23						
24						

4.5 kW, keeping the charging power constant at 2.3 kW (according to the chosen mode) and, consequently, increasing the hours available for recharging.

Assuming the possibility of exploiting a potential increase in power at the socket, through a variation in the electricity supply contract, Scenario No.4 simulates the case of a 3.7 kW recharge at 4.5 kW available power. Fig. 8 shows the total absorption curve (domestic use plus vehicle recharging) and the available power at the socket throughout the day. A comparison with the curves in Fig. 7 shows that the increase in absorbed power as a result of the faster recharging – with times that are reduced by about 36% – cancels out the benefits of an increase in available power.

In the last scenario (No.5), a more complex case has been simulated, which foresees the possibility of recharging at both domestic and workplace sockets. In this simulation, the domestic recharging takes place at 2.3 kW, while at the workplace the recharging takes place at 3.7

Table 5
Results of scenario 2 (3.3 kW Meter, 2.3 kW recharging capacity, dead batteries at the beginning of the day and probability of the vehicle being idle greater than 60%): percentage of recharging reached at the end of the recharging time, according to the various architectures.

H	PHEV 25	PHEV 50	PHEV 75	BEV 150	BEV 200	BEV 300
1	0.37	0.26	0.17	0.14	0.08	0.06
2	0.74	0.52	0.33	0.29	0.15	0.13
3	1.00	0.78	0.50	0.43	0.23	0.19
4	1.00	1.00	0.67	0.58	0.31	0.26
5	1.00	1.00	0.83	0.72	0.38	0.32
6	1.00	1.00	1.00	0.86	0.46	0.39
7						
8	0.37	0.26	0.17	0.14	0.08	0.06
9						
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kW, presuming there is a dedicated line for the recharging of vehicles. The vehicle is charged at home from 1:00 until 7:00, and then undergoes a Worldwide harmonized Light vehicles Test Cycles (WLTP) cycle to reach work, where it is connected to a recharging column from 8:00 till 17:00. A double WLTP cycle has been modelled for the trip home for a total distance of 46 km. From 19:00 onwards, the vehicle reconnects to the domestic grid, in a V2G configuration, supplying power to the grid when the power absorbed by a domestic user exceeds the limit of 1.5 kW. This helps to reduce the evening peak. Simulation of Scenario No. 5 was performed over two days: this made it possible to analyse the situation in which a vehicle is not completely discharged at the beginning of the second day.

Results obtained for the different scenarios

The model presented in Section 2 allows the calculation of the recharge percentages of each type of vehicle for each hour. These values populate a matrix using a chromatic scale varying from red (vehicle completely discharged) to green (vehicle charged). The first column of Tables 4–8 reports the hours of the day, while the remaining columns provide the percentage of recharging reached at the end of each hour, for the different types of vehicles. The deep red indicates when the SOC is lower than 20%, which is the lowest possible percentage below which the battery goes into early decay. Matrix cells are depicted by orange-yellow when the SOC is about 50%; intense green represents a 100% recharging. Grey cells represent the hours when recharging is not possible, for example because not enough power is available.

Scenario 1: Results

The first scenario provides three blocks of hours (i.e., from 3:00 to 7:00, from 10:00 to 12:00 and from 16:00 to 18:00) in which is possible to recharge the vehicles (Table 4). The percentage of charge at the end of each cycle largely depends on the type of vehicle and, therefore, on the storage capacity installed on board.

All PHEVs vehicles on the market have a battery capacity of indicatively 6–12 kWh, though more frequently 10–12 kWh. PHEVs are able to reach a full charge in a period of time between 3 and 4 h. This makes PHEVs more suitable for frequent use and short distances, as they do not require any particular investments for the charging infrastructure, and it is not necessary to change the electricity supply contract. BEV 200 and 300 vehicles have installed capacities of the order of 30–40 kWh. On the other hand, they have a limited available driving range, due to the small recharging percentages they can achieve. It could be expected that buyers of these types of vehicles will be willing to pay more for accumulators in exchange for greater freedom of movement in the electric mode alone.

Scenario 2: Results

This second simulation introduces a limitation regarding the probability that a vehicle is connected to the charging grid, as the possibility that the vehicle is idle is less than 60%. The results presented in Table 5 show that only night hours remain available for recharging. As in Scenario 1, BEV 200 and 300 vehicles have an insufficient driving range compared to their nominal capacity.

Table 6
Results of scenario 3 (4.5 kW Meter, 2.3 kW recharging capacity, dead batteries at the beginning of the day): percentage of recharging reached at the end of the recharging time (1 h), according to the various architectures.

H	PHEV 25	PHEV 50	PHEV 75	BEV 150	BEV 200	BEV 300
1	0.37	0.26	0.17	0.14	0.08	0.06
2	0.74	0.52	0.33	0.29	0.15	0.13
3	1.00	0.78	0.50	0.43	0.23	0.19
4	1.00	1.00	0.67	0.58	0.31	0.26
5	1.00	1.00	0.83	0.72	0.38	0.32
6	1.00	1.00	1.00	0.86	0.46	0.39
7	1.00	1.00	1.00	1.00	0.54	0.45
8	1.00	1.00	1.00	1.00	0.61	0.51
9	1.00	1.00	1.00	1.00	0.69	0.58
10	1.00	1.00	1.00	1.00	0.77	0.64
11	1.00	1.00	1.00	1.00	0.84	0.71
12	1.00	1.00	1.00	1.00	0.92	0.77
13	1.00	1.00	1.00	1.00	1.00	0.84
14	1.00	1.00	1.00	1.00	1.00	0.90
15	1.00	1.00	1.00	1.00	1.00	0.96
16	1.00	1.00	1.00	1.00	1.00	1.00
17	1.00	1.00	1.00	1.00	1.00	1.00
18	1.00	1.00	1.00	1.00	1.00	1.00
19	1.00	1.00	1.00	1.00	1.00	1.00
20	1.00	1.00	1.00	1.00	1.00	1.00
21	1.00	1.00	1.00	1.00	1.00	1.00
22	1.00	1.00	1.00	1.00	1.00	1.00
23	1.00	1.00	1.00	1.00	1.00	1.00
24	1.00	1.00	1.00	1.00	1.00	1.00

Scenario 3: Results

Scenario 3 foresees an increase of the meter to 4.5 kW under the same assumptions of the previous two scenarios. If the charging current is kept at 10 A, and an energy contract allows the absorption of up to 4.9 kW (including 10% of tolerance), the simulation results suggest that it is possible to recharge a vehicle at any time of the day with the same charging curve. As shown in Table 6, it takes almost 17 h to have a BEV 300 fully recharged.

Scenario 4: Results

Scenario 4 envisages the adoption of both a 4.5 kW meter and a faster recharging system with an absorption of 3.7 kW. The simulation results show that an increase in recharging power would lead to a further improvement of the available PHEV performances (Table 7).

It is possible to recharge a battery pack of the PHEV 25 in less than 2 h, while it takes 3 h to recharge a PHEV 75 at 80% of the SOC. The use of a BEV 150 becomes completely justifiable, as does that of a BEV 200. BEV 300 vehicles, or vehicles with a greater capacity, are still penalised as they cannot fully express their potentiality in terms of driving range.

Scenario 5: Results

The last scenario analysed regards a simulation conducted over two days, using a vehicle according to WLPT cycles and a connection to the domestic grid in a V2G configuration, depending on availability. The colours of the matrix cells have the following meanings (Table 8):

- Red-green: hours in which the vehicle is under charge;
- White: hours in which the vehicle is in use;
- Blue: hours in which the vehicle releases power to the grid (i.e., V2G mode).

The colours for the numbers of Table 8 highlight other peculiarities of the simulation:

- purple indicates the percentage of charge at the end of an hour of vehicle use;
- red indicates that the charge has dropped below the minimum allowable SOC level.

The results obtained in this case are more complex. It emerges that recharging in large car parks, such as those available at workplaces, is one of the possible solutions to the anxiety problems related to driving range and recharge of vehicles. As shown in the previous scenarios, recharging at home is often not sufficient to completely recharge a BEV, while guaranteed access to a public recharging point almost completely eliminates this problem. Considering a more realistic evaluation over two days and with the use of the vehicle, the most interesting result of this simulation is that even the BEVs with greater capacity are able to complete their recharging on the second day.

Regarding the V2G option, the results show that it is not recommended to carry out recharging if PHEV 25 or 50 vehicles are used, while this is viable when using a PHEV 75. BEVs show a recharging capacity that makes them completely suitable to be used in the V2G context.

Table 7
Results of scenario 4 (4.5 kW Meter, 3.7 kW recharging capacity, dead batteries at the beginning of the day): percentage of recharging reached at the end of the recharging time (1 h), according to the various architectures.

H	PHEV 25	PHEV 50	PHEV 75	BEV 150	BEV 200	BEV 300
1	0.60	0.42	0.27	0.23	0.12	0.10
2	1.00	0.84	0.54	0.46	0.25	0.21
3	1.00	1.00	0.80	0.69	0.37	0.31
4	1.00	1.00	1.00	0.93	0.49	0.41
5	1.00	1.00	1.00	1.00	0.62	0.52
6	1.00	1.00	1.00	1.00	0.74	0.62
7	1.00	1.00	1.00	1.00	0.86	0.72
8	1.00	1.00	1.00	1.00	0.99	0.83
9	1.00	1.00	1.00	1.00	1.00	0.93
10	1.00	1.00	1.00	1.00	1.00	1.00
11	1.00	1.00	1.00	1.00	1.00	1.00
12	1.00	1.00	1.00	1.00	1.00	1.00
13						
14	0.60	0.42	0.27	0.23	0.12	0.10
15	1.00	0.84	0.54	0.46	0.25	0.21
16	1.00	1.00	0.80	0.69	0.37	0.31
17	1.00	1.00	1.00	0.93	0.49	0.41
18	1.00	1.00	1.00	1.00	0.62	0.52
19						
20						
21						
22						
23						
24						

Conclusions

This paper presented a new methodology that allows the comparison of battery recharging scenarios for plug-in road vehicles (hybrid and full electric), with different levels of energy storage. The results regard a national case study and provide relevant insights regarding the operability of different modes of domestic recharging and the role of larger installed structures, on the base of the vast majority of contracts for domestic electric supply.

On a generic single day of simulation, PHEVs result to be much more flexible than the other EVs considered in the study. The simulations show that PHEV recharging times are compliant with the periods of night rest, with the limits of the electric grid and with the most diffused contracts. BEVs require more attention since their charging times are usually four times longer than those of a PHEV charged at home, but they offer the advantage of being able to be connected to the grid in a V2G configuration. A necessary condition for the safe operability of BEVs is the availability of at least 4.5 kW supply contracts and a fast-recharging infrastructure, with suitable local grid and cabling. Alternatively, the availability of recharging spots in workplace parking areas or in public places would be a solution, so as to extend the daytime possibility of recharging in addition to domestic night-time slots.

The proposed methodology can easily be applied in different national contexts. The implementation of the methodology in a commonly used spreadsheet and the adoption of a colour code are advantageous features for use by a variety of stakeholders, not limited to experts and professionals but broadened to a wider public and, possibly, to decision makers. The results can support decisions on the type of subsidy and investment to be granted with public funding or in private contexts. The optimal choice of a new family car or of a company fleet necessarily require the availability of infrastructures for their usability in a continuous trade-off between cost-optimisation and service-continuity (Gerboni et al., 2017).

As technology improves continuously in the field, new options for recharging and new ranges for EVs become available. However, in order to fully reach the new energy paradigm, a parallel evolution of the wider context - in terms of grid, recharging spots, meters, and connections - is needed. The bottleneck stands in the electric infrastructure, both at home and on a national level. This paper is an attempt to partially fill this gap, i.e., to outline the indispensable role covered by internal combustion engines, while fulfilling local constraints concerning pollution. Plug-in vehicles with electric traction obtained using indicatively 8–12 kWh batteries have resulted to be compliant with the needs of daily urban and suburban mobility users, provided that a recharging of the battery on a regular base is guaranteed.

CRediT authorship contribution statement

Raffaella Gerboni: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Claudia Caballini:** Visualization, Writing - review & editing, Project administration. **Alessandro Minetti:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization. **Daniele Grosso:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Formal analysis, Investigation. **Bruno Dalla Chiara:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Resources, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial

Table 8
Results of scenario 5 (3.3 kW Meter for a morning recharge, 2.3 or 3.7 kW recharging capacity, 2 days with a WLTP cycle during use and the V2G option): percentage of recharging reached at the end of the recharging time (1 h), according to the various architectures.

	DAY1						DAY2					
H	PHEV 25	PHEV 50	PHEV 75	BEV 150	BEV 200	BEV 300	PHEV 25	PHEV 50	PHEV 75	BEV 150	BEV 200	BEV 300
1	0.37	0.26	0.19	0.14	0.08	0.06	0.37	0.26	0.49	0.41	0.74	0.79
2	0.74	0.52	0.38	0.29	0.15	0.12	0.74	0.75	0.65	0.56	0.82	0.85
3	1.00	0.78	0.58	0.43	0.23	0.18	1.00	0.92	0.82	0.70	0.90	0.92
4	1.00	1.00	0.77	0.58	0.31	0.24	1.00	1.00	0.99	0.85	0.97	0.98
5	1.00	1.00	0.96	0.72	0.38	0.30	1.00	1.00	1.00	1.00	1.00	1.00
6	1.00	1.00	1.00	0.86	0.46	0.36	1.00	1.00	1.00	1.00	1.00	1.00
7	0.41	0.61	0.80	0.62	0.35	0.27	0.41	0.61	0.80	0.76	0.89	0.92
8	1.00	1.00	1.00	1.00	0.47	0.37	1.00	1.22	1.00	0.99	1.00	1.00
9	1.00	1.00	1.00	1.00	0.72	0.56	1.00	1.00	1.00	1.00	1.00	1.00
10	1.00	1.00	1.00	1.00	1.00	0.85	1.00	1.00	1.00	1.00	1.00	1.00
11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
16	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
17	0.41	0.61	0.80	0.76	0.89	0.92	0.41	0.61	0.80	0.76	0.89	0.92
18	0.00	0.00	0.60	0.51	0.77	0.83	0.00	0.00	0.60	0.51	0.77	0.83
19	0.00	0.00	0.59	0.50	0.76	0.83	0.00	0.00	0.59	0.50	0.76	0.83
20	0.00	0.00	0.55	0.47	0.75	0.81	0.00	0.00	0.55	0.47	0.75	0.81
21	0.00	0.00	0.47	0.40	0.71	0.78	0.00	0.00	0.47	0.40	0.71	0.78
22	0.00	0.00	0.37	0.31	0.67	0.74	0.00	0.00	0.37	0.31	0.67	0.74
23	0.00	0.00	0.32	0.27	0.64	0.73	0.00	0.00	0.32	0.27	0.64	0.73
24												

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