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Decarbonizing transportation: A data-driven examination of ICE vehicle to EV transition

Cristian Giovanni Colombo [a], Fabio Borghetti [b,*], Michela Longo [a], Wahiba Yaici [c], Seyed Mahdi Miraftabzadeh [a]

[a] Department of Energy, Politecnico di Milano, Via Lambruschini 4, 20156, Milano, Politecnico di Milano, Italy
[b] Design Department, Mobility and Transport Laboratory, Via Candiani 72, Milano, 20158, Italy
[c] CanmetENERGY Research Centre - Natural Resources Canada, Ottawa, Ontario, Canada

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ABSTRACT

Transportation is one of the sectors with the highest CO_2 emissions, accounting for 23% globally and significantly contributing to climate change. To address this challenge, the authorities have proposed new stringent policies that lead to decarbonization. From this perspective, this work proposes a multi-scenario analysis for the electrification of a fleet of private users. The scenarios differ on the type of charging mode adopted: slow charging (charging modes 1 and 2) and fast charging (charging modes 3 and 4). The model aims to identify the percentage of potential users who can shift from Internal Combustion Engine (ICE) to Electric Vehicles (EVs) in different scenarios. Furthermore, the model will highlight the average expenditure of users for charging, highlighting how the cost of energy could be a driver for the electrification of the sector. Finally, the model will allow us to evaluate the savings of up to 220 tons of CO_2/year thanks to the electrification of the sector with Long Range vehicles, in best case scenario. The use of a multi-scenario analysis allowed several possible electrification solutions to be explored, highlighting the strengths and weaknesses of the charging mode used, supported by quantitative results. This data-driven approach allows us to identify optimal locations for public charging stations in region of northern Italy region, where the data was sourced, which will help to encourage the switch to EVs.

1. Introduction

The growing attention towards the issues of Climate Change and urban sprawl led to the revolution of various sectors. Several authorities and associations, such as the European Commission (EU) and the COP (Conference Of Parties), underlined the necessity to change habits, otherwise the damage caused over time will be irreversible. In order to deal with Climate Change, the authorities began to push for a process of change in many sectors. The sectors most involved in the problem, in terms of Green House Gases (GHGs) emissions are the electricity generation sector and the transport sector (IEAa). The power generation sector is the first in terms of CO_2 emissions and is followed by the industry and transport sectors (IEAb). As an example, Fig. 1 shows global transport CO_2 emissions by subsector in the Net Zero Scenario, 2000–2030. The road component plays a significant role. Therefore, following the new stringent policies, these sectors started a decarbonization process (Held and Gerrits, 2019). If there are various strategies in the power generation and industry sectors, in transportation the decarbonization process mainly passes through the electrification of circulating vehicles. Fig. 2 shows the stock of electric cars in the world and Europe over the 2010–2022-time horizon. In particular, the trend of BEVs (Battery Electric Vehicle) and PHEVs (Plug-in Hybrid Electric Vehicle) is shown. During the process, which is still ongoing, several challenges raised, such as the range anxiety linked to EVs (Electric Vehicles), the presence of available CSs (Charging Stations) and charging times. Fig. 3 shows the trend in the number of charging infrastructure over the 2015–2021-time horizon with reference to the United States, Europe, and China. In particular, the trend of publicly available slow and fast chargers is shown.

Today, as illustrated in Fig. 2, the number of EVs in circulation in Europe is around 26 million and it is expected that their number will continue to grow in the coming years (IEA, 2023). To reinforce this prediction, there are the objectives proposed by the authorities such as carbon neutrality for year 2050. Achieving this goal in the transport

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* Corresponding author.
E-mail address: michela.longo@polimi.it (F. Borghetti).

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sector would mark an important turning point in the fight against Climate Change. The theme of urban sprawl is also linked to this. Over the last few years there has been a great centralization towards urban centers.

Most of the activities that move entire nations take place in the major urban centers, causing many people to tend to move towards the highly centralized urban areas. This factor, combined with the modal share on transport, highlights other benefits brought by the electrification of the transport sector. In densely populated places such as large cities, traffic congestion represents a problem that affects citizens in various ways, from stress to air quality. The use of EVs would contribute to the reduction of CO_2 emissions and the reduction of noise pollution, improving the quality of life of citizens. For these reasons, it is important to push towards the electrification of the sector. However, the existing barriers to electrification in the sector remain. Range anxiety, that is the fear of not having enough range to reach a destination, is still a barrier to EV adoption for many conventional vehicle users. At the same time, as the number of EVs on the road increases, users will need more CSs with higher power ratings, to guarantee CS availability and limit charging times. Therefore, to ensure the adequate electrified development of the private mobility sector, the implementation of a reliable charging infrastructure is necessary.

The aim of this work is to propose a multi-scenario impact analysis of electrification strategies, taking into consideration both the perspective of EVs and that of CSs. This work will start from the analysis of a dataset of 200 private users in northern Italy, which will allow to identify user behaviors and cluster them. In this way it will be possible to evaluate the shift from Internal Combustion Engine (ICE) vehicle to EV. The multi-scenario impact analysis will consider the charging possibilities with low-power domestic CSs, high-power public CSs and their combination. Through the evaluation of these scenarios, the savings related to charging vehicles rather than their refueling will be highlighted. Furthermore, the comparison of the scenarios highlights the possibility of saving up to 220 tons of CO_2 per year. Finally, thanks to a data-based approach, points of interest are identified where new CSs can be positioned, following user traffic.

The main contribution of this work is to propose a quantitative electrification impact analysis for private transport, mainly following two goals:

Identify users who can shift from ICE vehicle to EV, considering their journeys, resulting consumption and stops;

Identify the best allocation for the installation of public CSs, based on the attractive poles of urban areas.

Following these purposes, the paper is organized as follow. In Section II, an extensive literature review will be presented on the electrification strategies of private transport and the different methodologies used for this goal, analyzing both infrastructure implementation process and impacts. In Section III the methodology that is proposed in this work will be presented. In Section IV the case study will be implemented, where the different electrification scenarios will be defined. Section V will collect the results of the scenarios and discuss the results, providing a comparison between the different scenarios. Then some considerations about the implementation of new public CSs will be provided. Section VI will conclude the work by recalling the global importance of electrification, which will allow to face the climate crisis, also improving the quality of life of citizens.

2. Literature review

Mobility, understood as the movement of goods and people, changed considerably in the last 20 years. Initially mobility was intended as transporting passengers or goods from an origin to a destination; today it is a different concept. Mobility intends to have a holistic approach and rather than being a means, and it is intended as a service. In this new perspective, the individual journey of the user is considered door-to-door and considers the trip from leaving home to reach a destination. In this context, the use of personal vehicles changed too. The modal share changed, and the number of customers using public transport increased. However, private transport remains the most used; Fig. 4 shows the modal split of air, sea, and inland passenger transport in the 27-country European Union (as of 2020) and Italy over the 2012–2021 period. It can be seen that the passenger car mode holds a significant percentage. The shift from ICE vehicles to EVs represents a turning point in various environmental and social aspects. The electrification process of the sector is ongoing and the implementation of a resilient and reliable CSs charging network represents one of the major challenges.

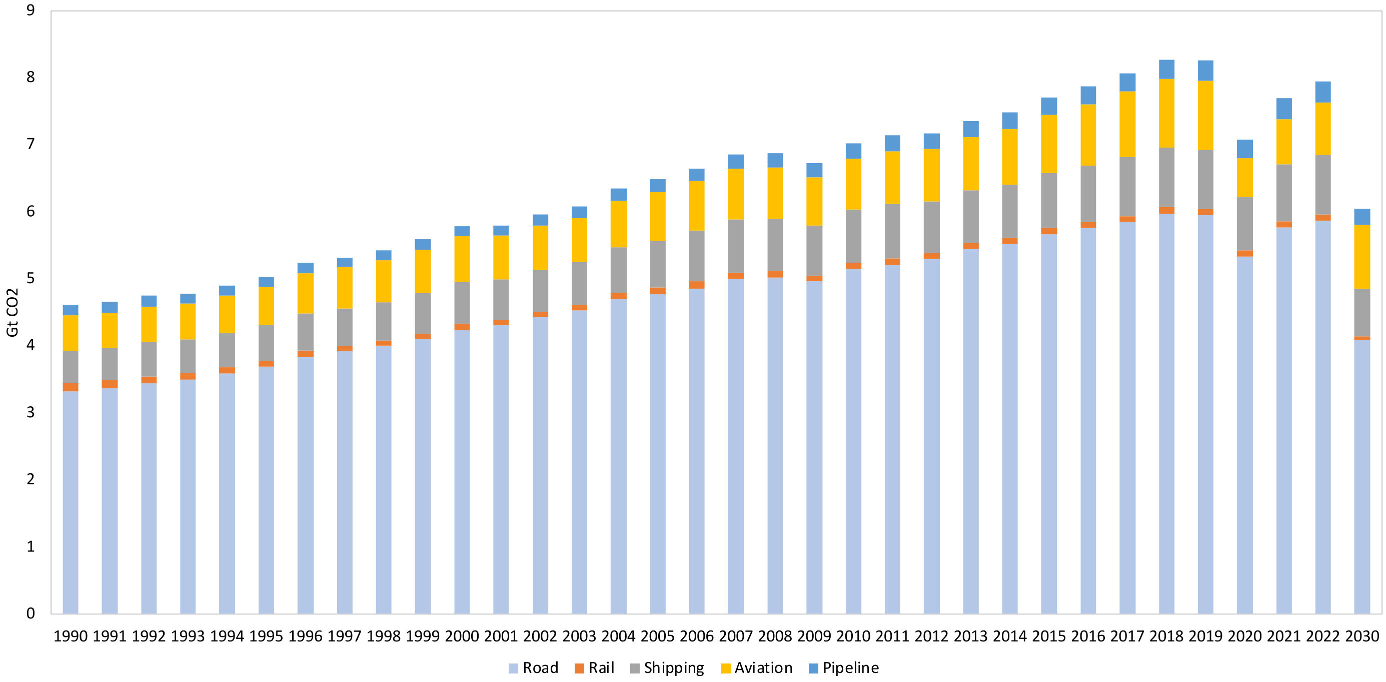

Fig. 1. Global CO_2 emissions from transport by sub-sector in the Net Zero Scenario, 2000–2030.

In this context, numerous studies have been proposed that have offered an electrification perspective. Before showing electrification studies and scenarios, it is appropriate to define the tools available in private mobility context. Fig. 5 shows the different stationary charging technologies available.

There are two types of stationary charging: conductive and wireless. Wireless charging is all that does not include the use of a cable to be plugged into the vehicle. In these recharges it is sufficient for the vehicle to position itself near the charging infrastructure for the vehicle to recharge. The technology mainly studied in the transportation sector is inductive power transfer (Colombo et al., 2022).

Most stationary charging devices, however, are conductive and require the use of a conductive cable to charge the vehicle. Refills of this type can work with two different types of power. AC (Alternating Current) charging is currently the most widespread. All domestic and some public CSs work with this power supply. AC charging is divided into 3 different charging modes, which vary depending on the type of protection system and the power transmitted. The AC charging modes 1 and 2 are used in domestic use, while the charging mode 3 are used in the domestic environment, with CSs reaching a maximum of 7 kW. AC charging is used in charging mode 3 (scenario 3) in public car parks and reaches a power of 50 kW. Finally, DC (Direct Current) charging is used in the public sector and is also called DCFC (DC Fast Charging) due to its ability to recharge vehicles in few minutes. DCFC uses another type of current and reaches much higher powers (up to 350/400 kW) and uses cables with specific standards. Today, DCFCs are not yet as widely spread as other CSs, but their number is increasing due to diverse funding. The introduction of these infrastructures can be a significant push towards the electrification of the sector, since it contributes to reduce users range anxiety (Sanguesa et al., 2021; Miraftabzadeh et al., 2024).

Considering these available tools, in several studies were analyzed the impacts of national electrification strategies and the projections of the EV market. In (di Foggia, 2021) the drivers and challenges of integrating EVs into a company fleet are analyzed. Still with a view to corporate electrification, (Bragatto et al., 2022) studies the transition to EVs in a company vehicle fleet. The case study highlights that company managers painlessly adopt EVs in their fleets. (Sachan and Singh, 2022) offers a study on the current state of vehicle electrification in India, identifying challenges for the future, including the development of a resilient charging network. Similarly, (Ren et al., 2022) carries out a case study in Beijing with a prediction of charging behaviors for private EVs. The results prove that most EVs dispense with charging in the chain during one-day trips and users generally hold moderate range psychology before departure. For charging patterns, the longer people travel, the more inclined they are to adopt the fast-charging strategy. Still focused on charging patterns, (Li et al., 2023) proposes an empirical analysis in EVs context, depending on their daily travel. Remaining on the topic of charging demand, (Thingvad et al., 2021) studies the possibility of users to rely on public CSs. In the study, they assess the potential of destination charging at existing shared parking facilities to reduce the public charging demand. Furthermore, they study the optimal location for the implementation of new public chargers. (Perera et al., 2020) also works on the planning and management of public CSs, using an urban community as a case study. In the case study a lifecycle thinking-based multi-period infrastructure-planning framework is proposed to develop sustainable public EV CSs in an urban context. This framework consists of a temporal model to find the dynamic EV CS demands, a stochastic model to obtain travel distances, and a multi-objective optimization model to select the best desirable capacities and locations for potential EV CSs. The case study framework can be used to estimate multi-period public recharging demands, minimize lifecycle costs, maximize service coverage and infrastructure utilisation, and ensure reasonable paybacks compared to conventional planning approaches. (Jahn et al., 2020) analyses a methodology to identify charging strategies for urban private vehicles based on traffic simulations. The charging methods used are charging at home, at work and during leisure activities. The work identifies when different charges are suitable for the vehicle's operation. Differently, the approach used in (Newe et al., 2019) is vehicle centered rather than user centered. The work reports the characteristics of EV charging and reproduces them with the relevant components for a charging process. Although most of the case studies are focused on urban settings and involve charging modes 1, 2 and 3 illustrated in Fig. 1, several urban studies have also been carried out. Electrification studies in extra-urban areas mainly involve the DCFC (charging mode 4). (Colombo et al., 2023) proposes a case of electrification in a motorway in the European context. The case study, thanks to the analysis of the market trend, offers 4 possible motorway electrification scenarios, where the number of CSs and their type varies. With this method, combined with motorway traffic, it is

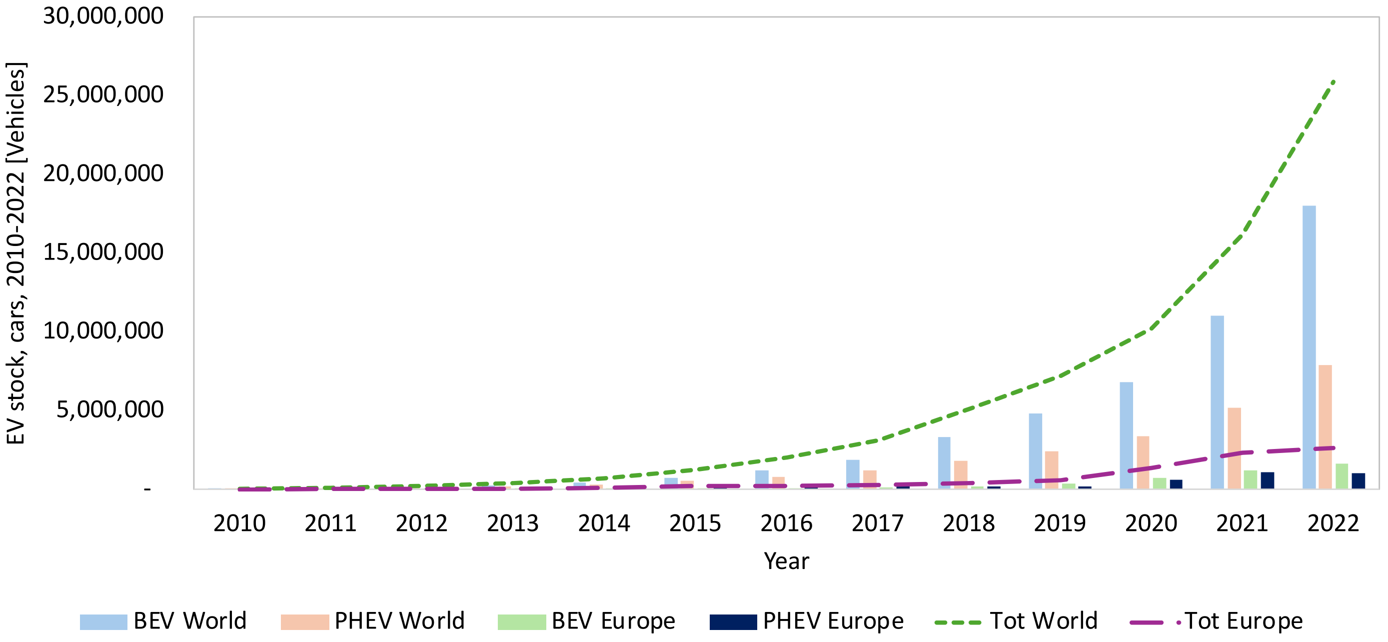

Fig. 2. World and Europe electric car stock, 2010–2022.

possible to understand whether future charging demand will be satisfied. Still in the extra-urban context, but in a US context, (He et al., 2019) proposes an optimal location model of DCFC for completing long haul trips with EVs. Similarly (Saldarini et al., 2022) evaluates the charging infrastructure on motorways by considering several factors that affect the deployment of EVs. Using several scenarios, it evaluates the impact on time and queues for different CSs placed along a motorway route. Ref. (Kong et al., 2019) proposes an optimal location planning method for the installation of new DCFC. The model considers operators drivers, vehicles, traffic flow and power grid. Apart from this, (Ronanki et al., 2019) proposes an extensive review of DCFC systems, highlighting their relevance for future development in mobility. However, the appropriate mix between AC charging and DCFC must be considered, as the power quality and resilience of the system could be affected (González et al., 2019). Ref. (Zinnari et al., 2022) studies the potential electrification of ICE vehicles and, on the basis of acquired data, evaluates its success. Furthermore, through a real-world dataset it evaluates the real charging demand and studies the optimal placing for the CSs. In addition to the technical studies that use the CSs and charging modes shown in Fig. 1, it is important to monitor the impacts that the electrification process has on the market and on citizens. (Phung Thanh, 2022) studies the impacts of the green bond on the Asian market. The electrification of private vehicles is also considered among the actions of the green bond, which will bring benefits in rural areas. The analysis proposed by (Liang et al., 2023) is also effect based. This analysis shows the effects of expanding vehicle charging infrastructure in California, with a specific focus on the housing market. (Liang et al., 2019) proposes an atmospheric chemistry model to evaluate the air quality impacts from multiple scenarios by considering various EV penetration levels in China. Among the benefits, it turns out that by electrifying 27% of private vehicles and a larger proportion of certain commercial fleets it is possible to reduce the annual concentration of Particular Matter (PM), nitrogen, dioxide and summer concentrations of ozone, significantly reducing the number of premature deaths. Finally, among the studies for future electrification studies, the impact of dynamic charging will be considered, which on long-distance journeys will allow the vehicle to be recharged while in motion (Nguyen et al., 2022). This technology will incredibly facilitate the diffusion of EVs, eliminating the range anxiety that afflicts EV drivers. Following the framework proposed by the literature review, this work will propose future electrification scenarios, using the stationary charging technologies analyzed. From this analysis an impact evaluation of the shift to EV will be provided. The data-based methodology will allow us to identify the customers most accustomed to the shift towards electric. Furthermore, the model will help to propose the installation of new CSs in urban contexts, thanks to the user-centered model. This model will be able to produce a wider range of results than existing models. This is due to the fact that the model is a combination of a data-driven process and a multi-scenario process, making it possible to monitor the different outcomes depending on the electrification scenarios. The model will use empirical data to examine vehicle utilisation and combine it with user behaviour and parking space utilisation. This approach aims to provide a comprehensive and rigorous framework for evaluating the transition to EVs by incorporating technical, behavioural and economic dimensions.

3. Methodology

Following the structure of the works present in the literature, this paper will work using a multi-scenario approach. The methodology of the work is linear and presented in Fig. 6.

The work starts from the collection of data regarding the vehicles in circulation (fleet). Each of the vehicles is tagged and begins sampling data. 200 sample vehicles are used in this work. The most relevant data are those that allow to know the journeys travelled and the stops made. Therefore, the sampling positions over time through Global Positioning System (GPS) and the instantaneous speed at which the vehicles move are processed. Through this preliminary data processing, each vehicle is positioned on a route. This allows us to develop a new dataset that considers: i) the distance travelled by each vehicle, ii) the timestamps of the beginning and end of the journey, iii) the positions at the beginning and end of the journey, iv) the speed and the type of journey (urban or extra-urban). Subsequently, users are clustered depending on the ranges travelled and the parking periods. Through this method, it is possible to carry out a vehicle replacement for users, from ICE vehicle to an electric one, depending on: autonomy, capacity, and consumptions. Thus, through the use of CSs, it is possible to implement three specific scenarios, which are different in terms of charging time. The three scenarios will be characterized by the types of CSs present in the area: AC charging (Scenario 1), DCFC (Scenario 2) and hybrid scenario (mix between AC and DCFC). Finally, through the implementation of a sensitivity analysis it will be possible to provide a deep result discussion, identifying the characteristics of the proposed solutions.

3.1. Preliminary data processing

In the first phase of the applied methodology, it is appropriate to collect useful data through systems integrated into the vehicle, such as accelerometers and GPS. Through these tools, each of the vehicles identified will provide a dataset of timely information for each journey. The data collected are.

- Status: divided in ignition, motion and turn-off;

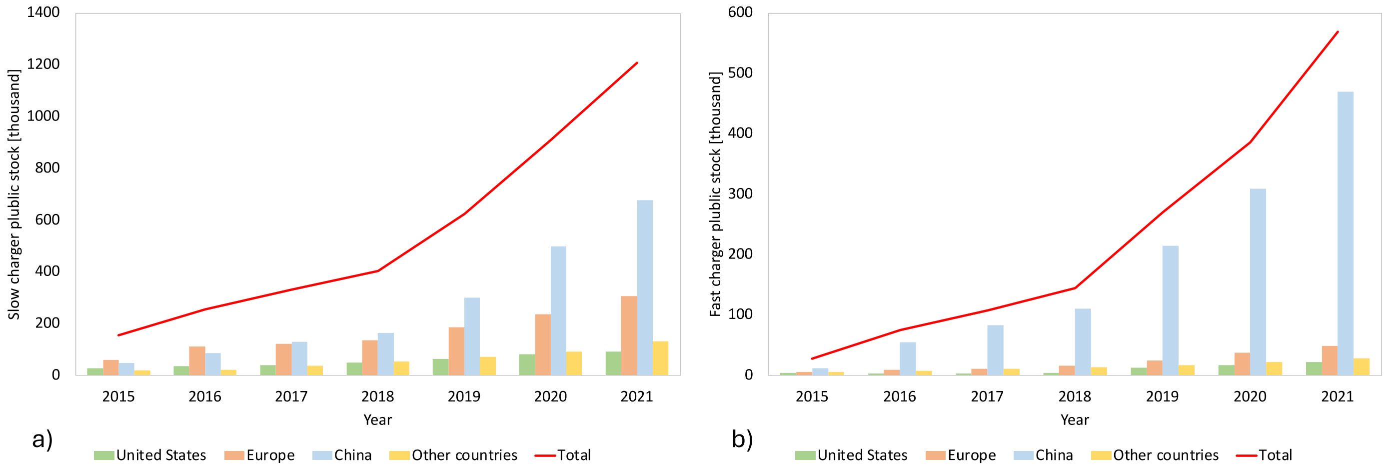

Fig. 3. a) Slow and b) Fast publicly available chargers, 2015–2021.

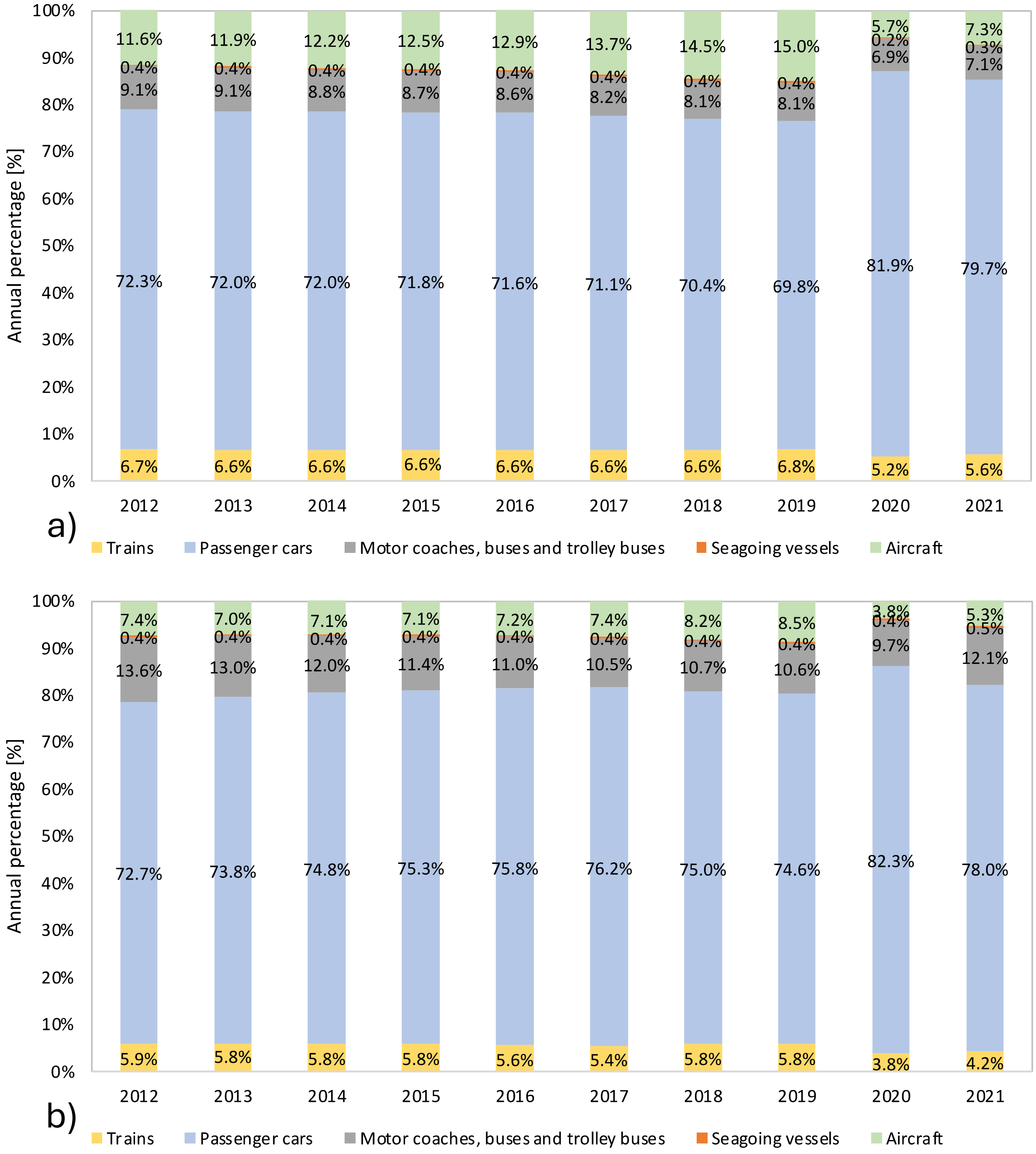

Fig. 4. Modal split of air, sea, and inland passenger transport in a) European Union - 27 countries (from 2020) and b) Italy.

- Real time position;
- Sampling time;
- Sampling distance;
- Instant speed;
- Temperature;
- Road type.

By processing this data, and combining the status with real time positions, it is possible to reorganize the dataset. The dataset will now have the different trips separated. For each trip we can now also know.

- Distance travelled;
- Travel time duration;
- Mean speed.

Furthermore, the duration of the stops was calculated through the difference between two consecutive turn-off and ignition statuses. In this way it will be possible to know the position and duration of the parking of the specific vehicle.

3.2. Data processing for the implementation

In the second data processing the electrification procedure begins. In the initial phase of fleet electrification, three EV models (cars) are identified. The choice of the three models serves to satisfy users' mobility requests. Considering these needs, the vehicles are chosen based on the distance to travel. The EVs, clustered by range of distances to travel, ranges in km, capacity of the traction batteries the average consumption in kWh/km are reported in Table 1.

Subsequently, it is identified through a real model which agents can affect consumption. Therefore, in addition to nominal consumption, coefficients are identified that correct the estimate towards actual con-

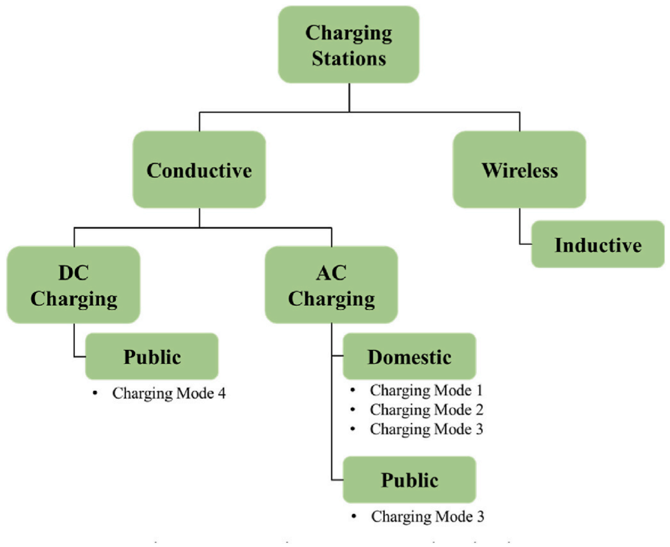

Fig. 5. Stationary CS technologies.

sumption. The model used is represented in (1).

$$c_i' = c_{n_i} \bullet \tau_i \bullet \sigma_i \left[\frac{kWh}{km}\right] \tag{1}$$

where:

c_i' is the new estimated consumption of the i^{th} vehicle;

c_{n_i} is the nominal consumption of the i^{th} vehicle;

τ_i is the temperature coefficient of the i^{th} vehicle, related to the consumption increment due to the use of HVAC (Heating Ventilation Air Conditioning);

σ_i is the speed coefficient of the i^{th} vehicle, related to the consumption increment due to different average speed of the journey.

The temperature coefficient τ_i is evaluated following temperature thresholds, thus three temperature ranges are considered: low, medium, and high temperatures (Evtimov et al., 2017). A similar process was used to identify σ_i. Five different speed ranges have been identified that cause the coefficient to vary. The speed coefficient has a decreasing parabolic trend in the motion phases up to medium/low speeds (20 km/h) (Badin et al., 2013). Beyond this threshold, the coefficient begins to grow, corresponding to the increase in rolling and aerodynamic resistance.

Then, a similar process is applied for the tank-to-wheel CO_2 estimation. The model used for the CO_2 estimation is reported in (2).

$$e_i' = e_{n_i} \bullet \sigma_{CO_2 i} \left[\frac{g_{CO_2}}{km}\right] \tag{2}$$

where:

e_i' is the CO_2 emissions estimated;

e_{n_i} is the nominal CO_2 emissions;

$\sigma_{CO_2 i}$ is a corrective CO_2 emissions coefficient which depend on the speed.

The speed-dependent correction coefficient $\sigma_{CO_2 i}$ is calculated at different speed levels and also has a parabolic trend with increasing speed (Anas and Timilsina, 2015). In addition to this, it should be specified that those produced by users will be considered CO_2 emissions for which it will not be possible to switch to EV. Using the average consumption of the selected vehicles, the average speed and the geographical position in which they work, it is possible to study consumption and with-it CO_2 emissions and performing an economic evaluation knowing the price per CSs. The CSs selected for the implemented case study are reported in Table 2.

Through this methodology it will be possible to implement three different electrification scenarios. In these scenarios, however, it will be

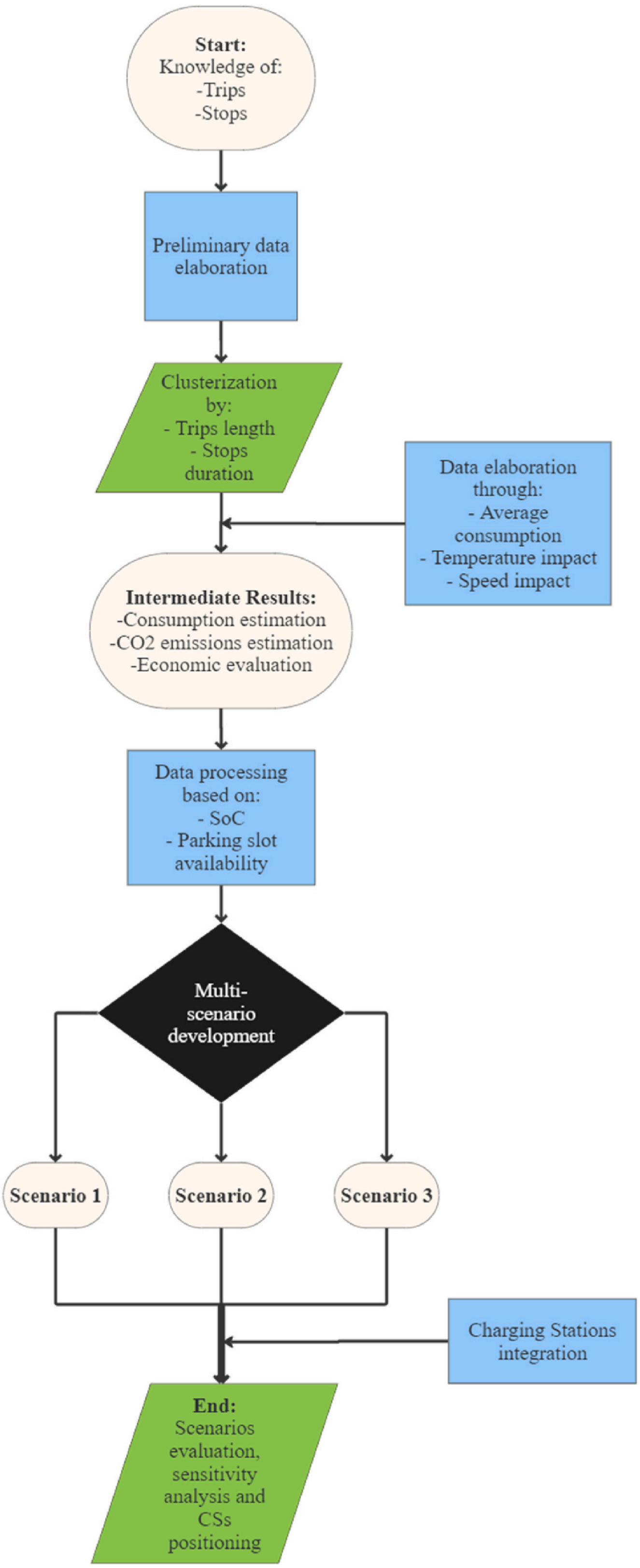

Fig. 6. Methodology description for electrification scenarios identification based on user.

Table 1
Clusters of EVs, autonomy, capacity and consumption of the case study.

EV type	Autonomy [km]	Capacity [kWh]	Consumption [kWh/km]
Short range EV	242	40	0.17
Medium range EV	395	52	0.13
Long range EV	454	72.5	0.16

Table 2
Type of CSs considered in the electrification case study.

Scenario	Charging Mode #	Power [kW]	Price (taxes included) [€/kWh]
1	Charging mode 1/2	3.3	0.20
2	Charging mode 3	50	0.50
3	Charging mode 4	250	0.30

appropriate to identify controllable variables that facilitate the analysis of the scenarios. As a result, a preliminary cost analysis is calculated. This evaluation can only be carried out on users who have switched to EV. The calculation is made on the average expenditure of energy used to recharge the EV and the average expenditure to refuel an ICE vehicle. If the costs for charging the EV are reported in Table 2, the costs for the fuel of the assumed ICE vehicle are 1.6 €/l. The calculation made for the charging cost follows (3). In (4), however, the cost of refueling the ICE vehicle is proposed.

$$CoC = CoE \bullet \frac{1}{n}\sum_{i=1}^{n} \kappa_{EV_i} \left[\frac{€}{year}\right] \tag{3}$$

$$CoR = CoF \bullet \frac{1}{n}\sum_{i=1}^{n} \kappa_{ICEi} \left[\frac{€}{year}\right] \tag{4}$$

where:

CoC and *CoR* are respectively the Cost of Charging for an EV and Cost of Refueling for a ICE vehicle in €/year;

CoE and *CoF* are the Cost of Electricity in €/kWh and the Cost of Fuel in €/l;

κ_{EV_i} and κ_{ICEi} are the consumptions of EV in kWh/year and the consumption of the ICE vehicle in l/year.

It is worth to notice that the analysis that is carried out following this methodology is taking into account only the operating costs. Specifically, the cost of the car and the installation of the domestic CSs are not considered. Furthermore, maintenance costs are not even considered. In order to clarify the type of vehicle suitable for the user, controlled variables are identified which determine the suitability of the user by combining vehicles with the behaviour shown by the data collected.

3.3. Controlled variables definition

Before implementing and simulating electrification scenarios it is advisable to identify the new control variables of the system. The State of Charge (SoC) of the vehicle represents the optimal quantity, as it allows us to know how much autonomy the vehicle has left, maintaining control over all the energy quantities involved. The SoC of the vehicle is evaluated using (5).

$$SoC_i(t) = \frac{C_i(t)}{C_{ni}} \tag{5}$$

where:

SoC_i is the SoC of the vehicle;

C_i is the vehicle capacity;

C_{ni} is the nominal vehicle capacity.

In the case study performed it is assumed that SoC is variable between SoC = 100% down to SoC = 20%, to make the case study more plausible, even if for most of the time the SoC will be between 20% and 80%, to optimize the charging and discharging cycles of the batteries (Colombo et al., 2024).

Finally, the last part of the methodology consists in scenario modelling. In the scenario where AC charging is predominant, the user is considered to recharge the car daily. On the other hand, in the scenario where DCFC is predominant, the user's behaviour will be similar to that of an ICE vehicle driver and a consumption model on a weekly basis will be used. It should be noted that in the simulation it is possible that there are days in which the Depth of Discharge (DoD) is higher than 80%. DoD, is evaluated as the ratio between the vehicle consumption and the vehicle capacity through (6).

$$DoD_i(t) = \frac{c_i'(t)}{C_i(t)} \bullet 100 \tag{6}$$

However, before designating the user as unsuitable for the use of an EV, a time threshold is identified in which the vehicle exceeds this DoD. Therefore, in the scenarios the time threshold will be underlined, to verify the progress of the designated users. The choice of the threshold derives from the fact that it cannot be overlooked that the user can use other vehicles other than his own. The selected thresholds aim to ensure that the user can maintain their behaviour with the vehicle 99% of the time over the year. This means that the potential user recharges the vehicle more than once a day per week or use an alternative. Following this consideration, it is worth to consider the daily autonomy A_i as a parameter to understand if the user is suitable for the EV (7).

$$A_i = SoC_i(t) - \frac{c_i'(t)}{C_i(t)} \bullet 100 = SoC_i(t) - DoD_i(t) \tag{7}$$

Vehicle charging must then be included in this context. Considering a charged vehicle (SoC = 100%) that is unloaded and subsequently recharged the SoC will vary dynamically following (8).

$$SoC_i(t+1) = SoC_i(t) - DoD_i(t) + E_r(t) \tag{8}$$

where, $E_r(t)$ represents the percentage of recharged energy, calculated following (9).

$$E_r(t) = \frac{P \bullet \Delta t}{C_i} \bullet 100 \tag{9}$$

where *P* is the power of the CSs and will depend on the charging mode and Δt is the time interval used for the charging phase.

4. Scenarios implementation

4.1. Scenario 1

The electrification process in Scenario 1 is organized by filters, as depicted in Fig. 7. Scenario 1 will mainly use CSs with charging modes 1, 2 and 3, and they are largely deployed for the service.

The process starts from the number of vehicles assigned to users. The first filter process exploits the daily DoD, highlighting that the SoC must not go below 20% for more than 10 days, identified as time threshold. Therefore, if the SoC is below the 20% acceptability threshold for more than 10 days a year, the driver will not be considered suitable. Subsequently, users who have their own parking available were filtered.

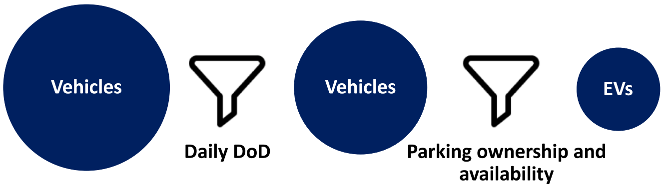

Fig. 7. Scenario 1 flow chart.

Scenario 1 approximates that about 70% of users have private parking available. Through this process, users who are suitable for using an EV have been identified.

4.2. Scenario 2

In the Scenario 2, DCFC CSs are large-scale deployed. The electrification process is organized by filters also in this case (Fig. 8). This time the filters used will be different as home charging will not be used. It is assumed that the majority of DCFC CSs will be installed on highways, while a smaller percentage will be located in urban areas.

To carry out the analysis of the Scenario 2, the behaviour of users is evaluated with respect to their weekly DoD. In this sense, the time threshold considered in this scenario instead of being ten days will be three weeks a year. This hypothesis underlines the desire of drivers not to recharge their car more than once a week, similarly to what is done with an ICE vehicle. This hypothesis, although challenging, is also quite realistic, since if an EV driver does not have a CS near their home, it is unlikely that they will leave the vehicle charging for a long time. The Scenario 2 three weeks in which users cannot use the vehicle correspond to those in which it is possible to use an alternative for travel, are the respective of the 10 days of Scenario 1. In this case, the SoC estimate will be on a weekly basis rather than daily as in Scenario 1.

4.3. Scenario 3

Finally, Scenario 3 combines the two previous scenarios, considering the appropriate mix of AC charging and DCFC. Initially, the analysis works with AC CSs, exactly as in Scenario 1. In addition, the percentage of users who are not eligible to use an EV due to the parking slot is considered. This is because by integrating the DCFC CSs of Scenario 2, the catchment area will be wider and there will be no limitation on private parking as high-power public charging will be possible. This will allow for short recharges, which will facilitate users who were filtered out in Scenario 1. Also in this case, the consumption of motorway trips is excluded from the case studies, since the work is carried out with an urban perspective.

5. Results and discussion

As explained in Section 4, the electrification process follows a logic based on filters. The first filter relates to DoD (Depth of Discharge) thresholds. If among the elements considered there is one that exceeds the defined thresholds, this will be filtered and eliminated from the dataset of potential EV users. The described process is visible in the graph represented in Fig. 9, where the vehicle's DoD is calculated for each day of the year. The dotted red line represents the maximum acceptable DoD threshold.

In the graph, one of the users is tested for the three different types of vehicles, to understand if the driver could be a potential user. The short-range EV examined exceeds the maximum acceptable DoD threshold 18 times a year. This implies that the user will need another car with a higher capacity, if possible, otherwise it will not be suitable for the electrification process. On the other hand, the repeated test with a medium range EV ensures that the threshold is exceeded only 9 times, making the user suitable for both electrification scenarios. In these remaining days, the user will have to make a recharge. A similar process is done for each of the drivers.

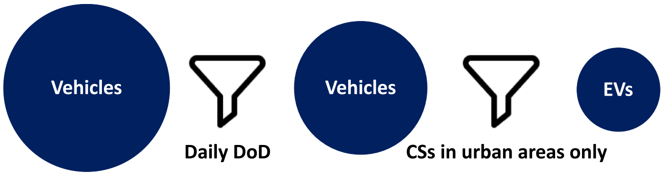

Fig. 8. Scenario 2 flow chart.

5.1. Scenario 1 output evaluation

Within the Scenario 1, the use of AC charging modes is considered predominant. The main charging strategy will be overnight charging of vehicles with a 3.3 kW domestic CSs, for a $\Delta t = 8$ hours. Using this charging strategy, the daily SoC estimation is calculated using (9). A model used as an example for this charging strategy is presented in Fig. 10. The dotted red line represents the SoC threshold.

Through this strategy, the graph shows the daily SoC after overnight charging, and before the impact of consumption. The SoC is shown exclusively at the beginning of the day: therefore, when the vehicle is not fully charged, it is due to the previous day's incidence. However, this is not the only possible solution. For example, you may not charge your vehicle every night. In this case, it is optimal to choose to define an SoC threshold that will trigger charging when it is exceeded. One possible situation would be to set this charging threshold to $SoC = 20\%$. The daily SoC profile will vary as shown in Fig. 11.

Using this strategy, however, there are two days a year in which the daily SoC drops below 0%, thus rendering the vehicle unusable. You can see that in this strategy there are days for which $SoC < 20\%$, unlike the scenario where users recharge every day. Therefore, for the user who does not want to use home charging 8 h every night, it becomes necessary to use a public CSs during the day. If he did not do so, the user would remain with the vehicle unloaded during use. In this case scenario, DCFC public charging are not considered, which involve multiple factors, such as:

- Stop time due to recharging;
- Distance from CSs;
- DCFC CSs availability;
- Driver behaviour.

These factors make the study of the SoC more dynamic and unpredictable, as it causes multiple variables to cooperate. From a massive analysis of the datasets, it is highlighted that from 64% to 88% of drivers could shift from an ICE vehicle to an EV of the 3 selected categories (see Table 1). The differences are linked to the consumption coefficients and the autonomy of the vehicles. However, these data must be adjusted with the amount of people who have private parking available (70% in this case study). The result of the analysis is shown in the graph in Fig. 12.

Subsequently, the CO_2 emission savings of Scenario 1 are highlighted in Fig. 13. The emissions are calculated before and after the filter of the user's parking availability. For the calculation before the filter, the emissions produced are those generated by users identified as non-suitable. For the calculation following the available parking filter, a selection of unsuitable profiles was added, so as to estimate the emissions produced by those who were unable to make the shift to the EV. The comparison of these two amounts is in turn reported to the emissions of the case in which all users have an ICE vehicle. The vehicle under consideration has a nominal CO_2 emission coefficient of $e_{n_i} 117 \left[\frac{g_{CO_2}}{km}\right]$.

Subsequently, the economic analysis of Scenario 1 is carried out, considering all users eligible for travel. Using formulas (3) and (4), which make up Fig. 14, it is clear that the use of an EV allows us to reduce operating costs, which strictly depend on travel. However, as mentioned, this analysis does not consider the purchase costs of domestic vehicles and CS.

Comparing the results in Fig. 14, it is evident that Long Range EVs provide the highest results in terms of CoC. This result is linked to the greater distance that users can travel with this vehicle. It is clear that greater autonomy implies a greater number of potential users, which

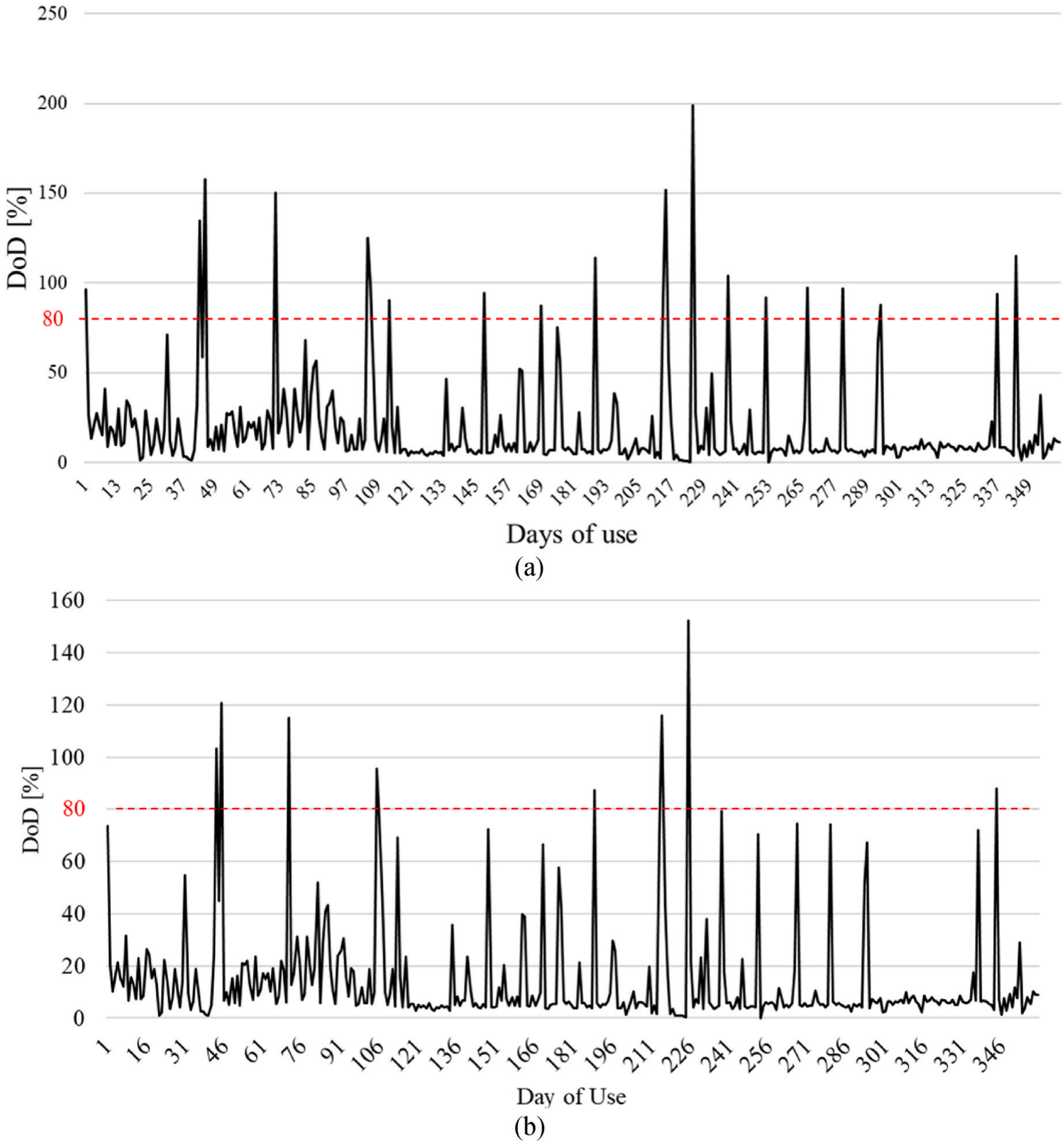

Fig. 9. Driver suitability test for EV following the DoD filtering process. (a) Driver not suitable with short range EV, (b) Driver suitable with medium range EV.

raises the value of average consumption, and thus that of expenditure per user.

5.2. Scenario 2 output evaluation

Differently from Scenario 1, Scenario 2 does not consider AC charging modes 1 and 2, but only charging mode 3 and DCFC. Furthermore, Scenario 2 suitability thresholds are set to three weeks instead of ten days, as in the Scenario 1. Instead, the type of vehicles and the assessments that will be carried out will be the same as in Scenario 1. Moreover, this scenario, takes into account only urban environment. Therefore, the highway DCFC are not considered in the results. Following this consideration, the daily SoC represented in Fig. 7 will be similar and will be calculated by defining a threshold and recharged with DCFC when the vehicle allows it. However, it should be specified that most DCFCs will be installed on motorways, therefore it is of interest to add a new hypothesis. This new hypothesis consists in the consumption assessed on the motorway in the preliminary processing are neglected. The choice to neglect consumption on the motorway also comes from the fact that users do not need to make dedicated trips in search of DCFCs on motorways, where the CSs are already present. This simplification is follows the assumption that users travelling on a motorway section will recharge thanks to the DCFCs that will be present, automatically fulfilling the need for recharging. However, this simplification, in the worst case, could lead to an underestimation of the energy demand of users who use the motorway frequently and who do not necessarily always recharge when entering or leaving the motorway. In this scenario, users who do not need to recharge more than once a week are considered suitable. The choice to neglect consumption on the motorway provides a better overview of the charging needs of EV users. Following these considerations, it is clear that the number of users suitable for shifting to the EV is lower with respect to Scenario 1 if motorways consumptions are considered. On the other hand this difference is less evident if motorways consumptions are neglected, as

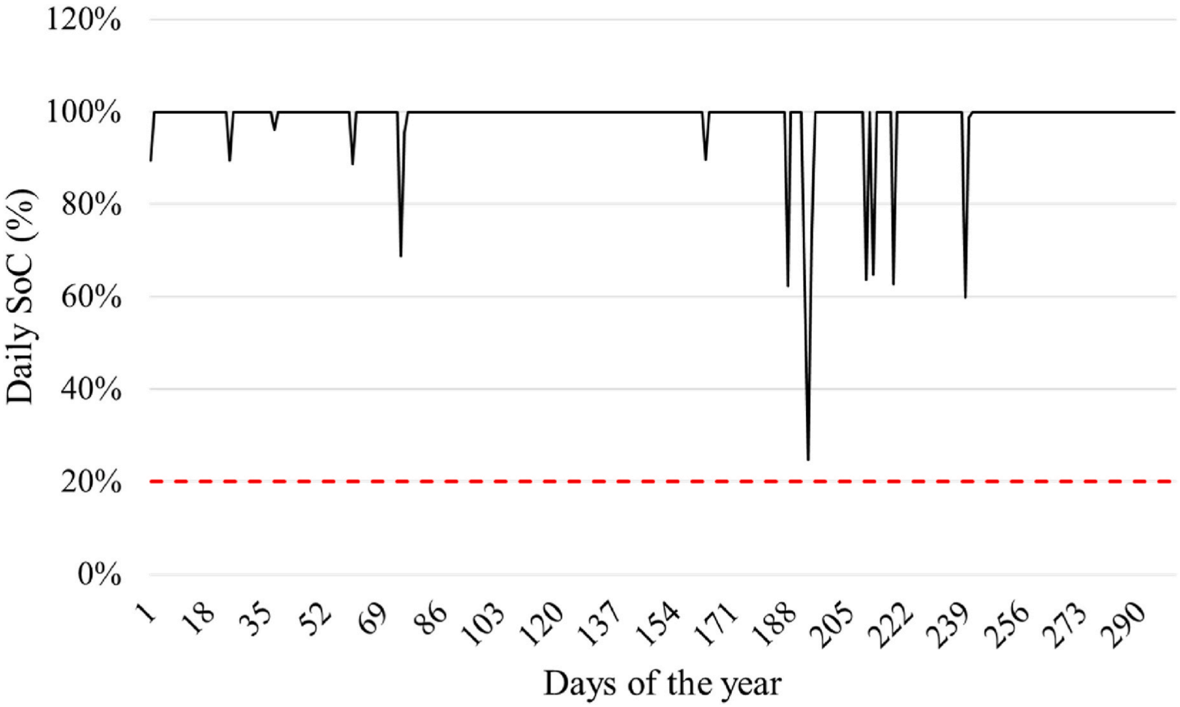

Fig. 10. Daily SoC considering daily 3.3 kW overnight charging.

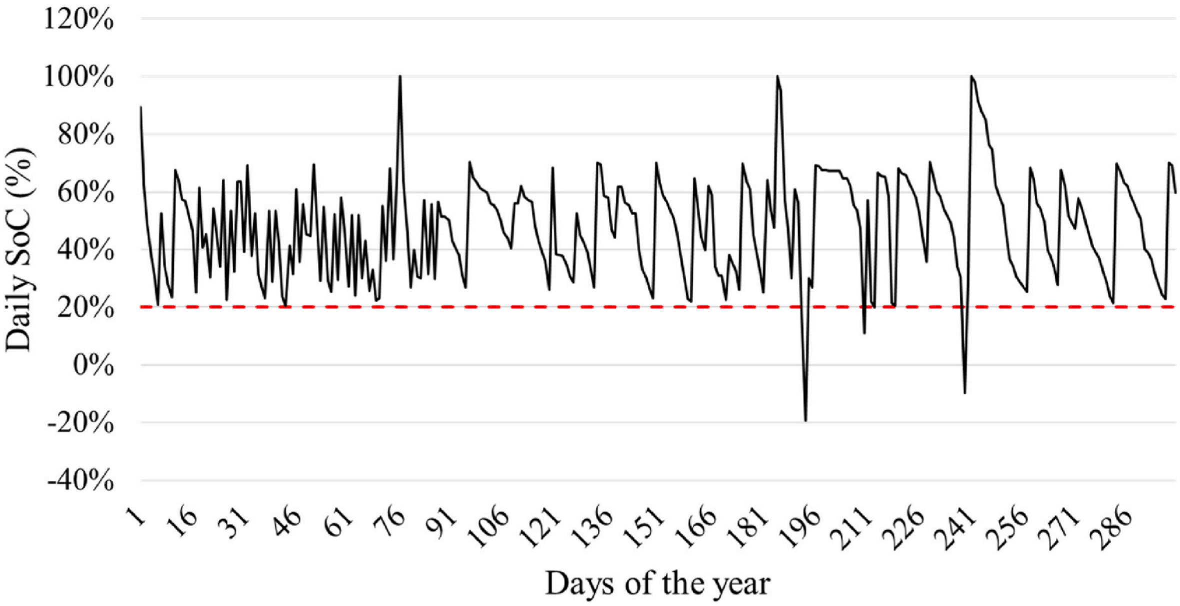

Fig. 11. Daily SoC considering 3.3 kW overnight charging only when SoC<20%.

reported in Fig. 15.

Following the identification of the suitable EV users, it is possible to identify the percentage of CO_2 emissions saved (Fig. 16). As in Scenario 1, the larger the number of EV users, the higher the savings in CO_2 emissions. Similarly, the emissions identified are those produced by non-suitable EV users, who were unable to switch to EV, and these emissions are compared to the sum of those produced by all users if they used ICE vehicles.

Subsequently, it is useful to quantify the economic value of the expenses to be incurred for charging the EV or refueling the ICE vehicle. In Scenario 2, only DCFC are considered for the Long Range EVs, while the Short-Range EV and the Medium Range EV can only charge in charging mode 3. The costs for charging are those hypothesized in Table 2. The results of this economic evaluation are shown in Fig. 17.

In this case the average expenditure per user is not advantageous for EVs. This is linked to the CoE in public charging tariffs. In the Long-Range EV this is less evident since charging mode 3 was supposed to have a higher cost (0.5 €/kWh) than charging mode 4 (0.3 €/kWh). The Short-Range EV has a significant gap due to the distance travelled annually, which on average is lower than other cases. Focusing, however, on the gap between cases that consider and do not consider motorway consumption, if these are not considered, the costs are significantly higher. This impact is since in the second case the average consumptions and average distances travelled by suitable users are

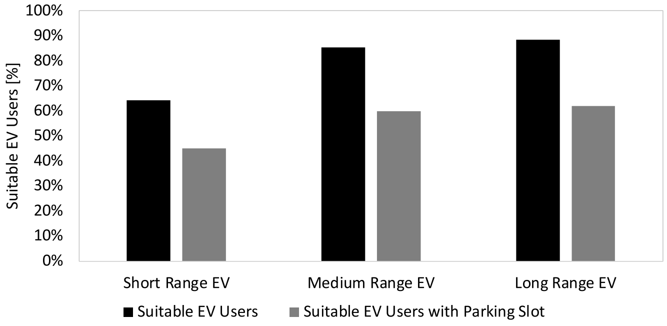

Fig. 12. Scenario 1 evaluation of suitable EV users with and without parking slot.

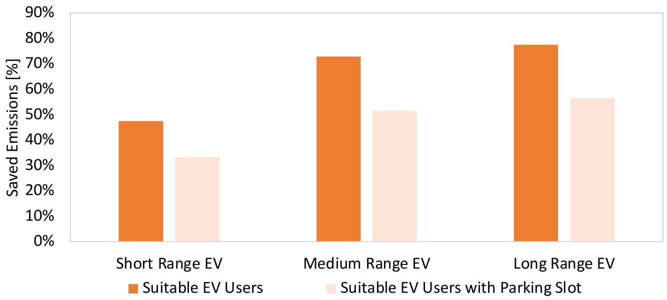

Fig. 13. Scenario 1 evaluation of saved emission with respect to an average ICE Vehicle, calculated for suitable EV users with and without parking slot.

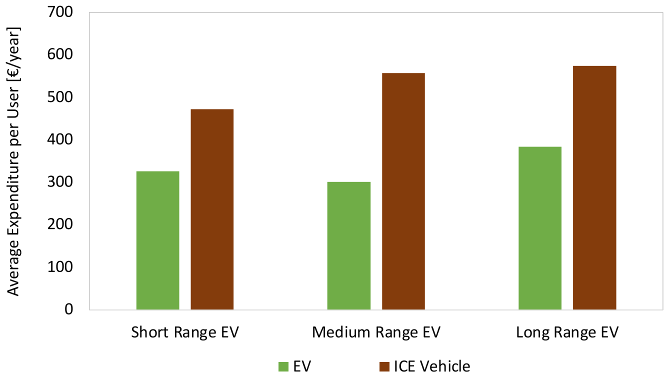

Fig. 14. Scenario 1 Average expenditure per user with respect to an average ICE Vehicle.

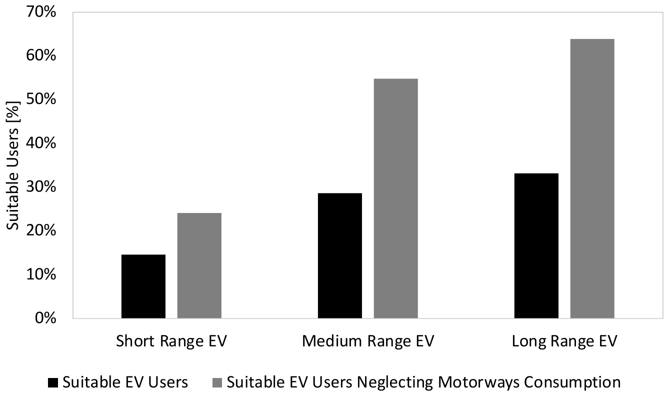

Fig. 15. Scenario 2 evaluation of suitable EV users, considering and neglecting motorways consumptions.

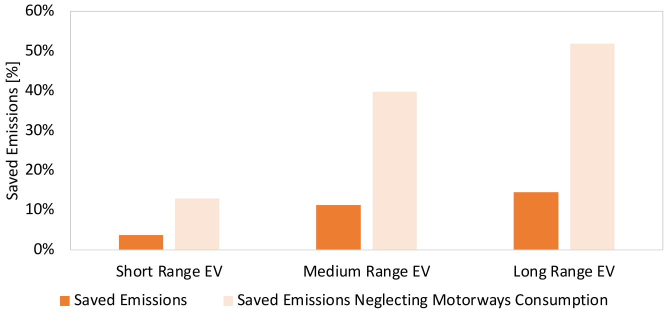

Fig. 16. Scenario 2 evaluation of saved emission with respect to an average ICE Vehicle, calculated considering and neglecting motorways consumptions.

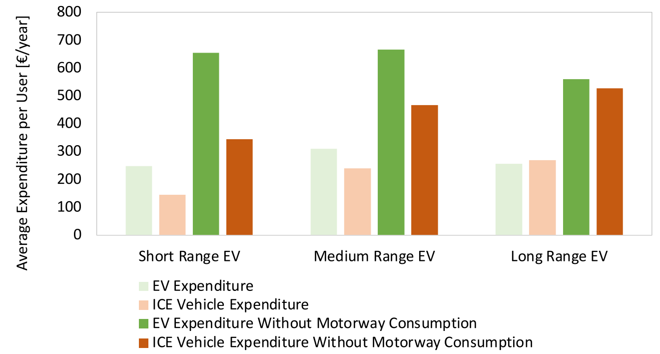

Fig. 17. Scenario 2 average expenditure per user with respect to an average ICE Vehicle both considering and not motorways consumptions.

higher than those of suitable users in the case in which motorways consumption are considered, as evident from Fig. 15.

5.3. Scenario 3 output evaluation

Scenario 3 is a hybrid scenario that considers all charging modes operating. The analysis is initialized with eligible users from Scenario 1, who are subsequently filtered considering parking availability. Following this operation, the hypotheses of Scenario 2 are applied to users who have so far been found to be unsuitable, without considering motorway consumption. Fig. 18 shows the percentage of suitable users for Scenario 3 (see Fig. 19).

The results obtained from Scenario 3 simulation show that the addition of DC and AC fast charging improve the number of eligible users significantly compared to Scenario 1. The same can be said with respect to Scenario 2. With the increase of suitable users, the percentage of emissions saved will be higher. Also, in this case the saved emissions are calculated with respect to a scenario in which all vehicles are ICE.

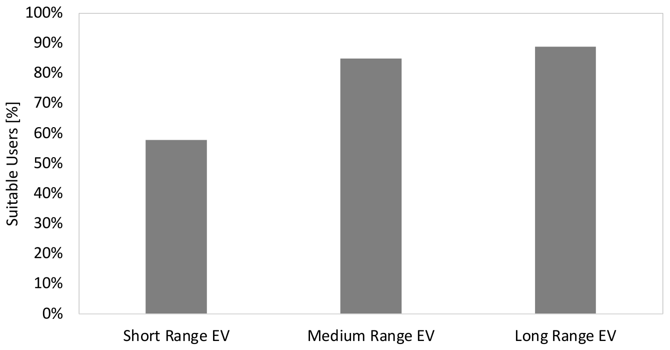

Fig. 18. Scenario 3 evaluation of suitable EV users.

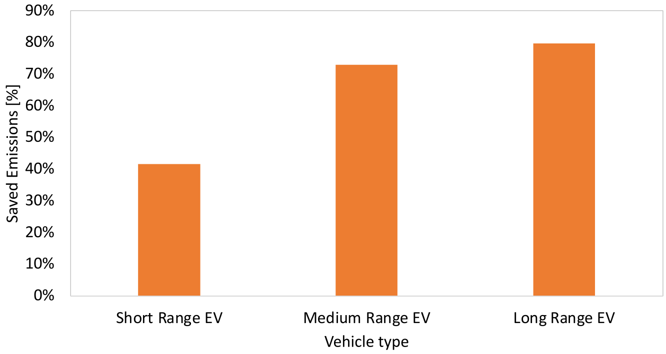

Fig. 19. Scenario 3 evaluation of saved emission with respect to an average ICE Vehicle.

Similarly to the previous scenarios, emissions during the use of vehicles are linked to users who were not suitable for EV shift and continue to use an ICE vehicle. Fig. 15 shows the estimate of emissions saved in percentage clustered by vehicle type.

Also, in this case the Long-Range EV appears to be the one that maximizes the percentage of saved emissions. The reason is linked to the fact that a greater number of suitable users decreases the ICE vehicles in circulation, decreasing CO_2 emissions. Similarly, for the other scenarios, a cost estimation is then performed on the suitable users and is represented in Fig. 16. The charging costs are shown in Table 2 while the CoF is 1.6 €/l.

In Scenario 3, in which slow charging remains predominant, the average expenditure remains lower than the average expenditure that users would have with the ICE vehicle selected as a sample. The increase in average expenditure between the different types of vehicles is linked to higher consumption or the wider distances possible thanks to EVs with larger autonomy.

5.4. Scenarios comparison

In this section of the work the outputs of the different scenarios are compared. In the three scenarios the number of eligible user's changes depending on the underlying hypotheses. Fig. 21 shows the comparison of suitable users for EV of all scenarios and their cases.

It is worth of interest compare Scenario 1, made up mostly for home charging with Scenario 3, which integrates it with fast charging. Scenario 1 showed that around 70% of drivers were suitable to switch to EV. Scenario 3 shows a significant growth in the number of suitable users, highlighting the effect of combined charging modes. This effect also derives from the fact that some users who are unsuitable due to the lack of private parking become suitable users with the installation of rapid CSs. The reduced difference between Scenario 1 (S1-Suitable EV Users) and Scenario 3 (S3) is closely linked to the fact that many of the users suitable for slow domestic charging are also suitable for fast charging, not considering motorway consumption. It is also interesting to look at the difference between Scenario 2, which includes motorway consumption, and the other Scenarios. The considered scenario has significantly fewer suitable users, mainly due to the fact that in Scenario 2 refueling is weekly and not daily. Moreover, taking into account motorway consumption, which is higher due to the length of the journey, and a weekly refill, the number of suitable users is reduced, as there will be more than three weeks per year when users have a SoC below the 20% limit. However, considering that the majority of future DCFCs will be installed on motorways in the future, it is a reasonable assumption to neglect this consumptions as they will be served by the DCFCs in operation. This consideration led to perform the version of Scenario 2 that neglects the motorways consumption.

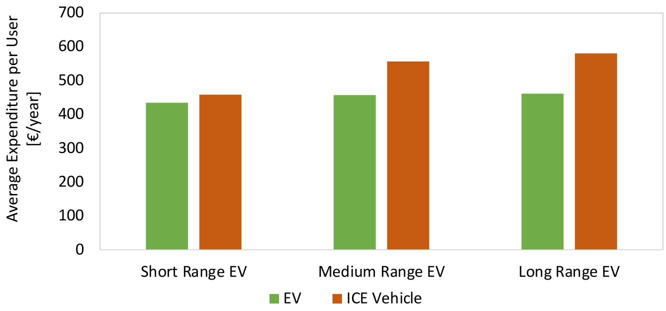

Fig. 20. Scenario 3 average expenditure per user with respect to an average ICE Vehicle.

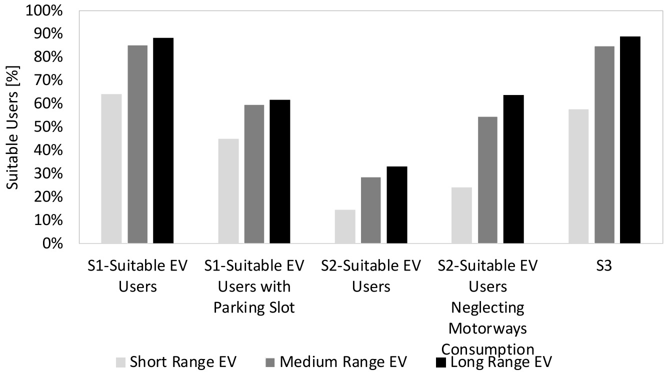

Fig. 21. Scenarios comparison evaluation of suitable EV users considering all cases.

Subsequently, the analysis of CO_2 emissions is carried out. The assumptions followed are the same as those followed in each of the scenarios. The comparison of saved emissions compared to a scenario of only ICE vehicles is presented in Fig. 22.

Through Fig. 18, the percentage of emissions saved through the shift to EVs is highlighted. It is worth remembering that the emissions considered in this case study are Tank-to-Wheel. Moreover, the differences between the cases are due both to the number of users considered and to the distances travelled by users not considered suitable for the shift to EV. Finally, to quantitatively identify the saved emissions, Fig. 23 expresses the data in tons of CO_2/year.

It is worth of interest to compare Scenario 1 also considering the available parking spaces and Scenario 3. Looking at the Medium Range EV, in the first case there are approximately 145 tons of CO_2 saved per year, while scenario 3 saves up to 205 tons of CO_2 per year. The Medium Range EV is an interesting case study since it represents a vehicle with an average autonomy and the difference in the number of suitable users in the scenarios is more highlighted. However, it is clear that the best performance in terms of saved emissions is the Long-Range EV. This

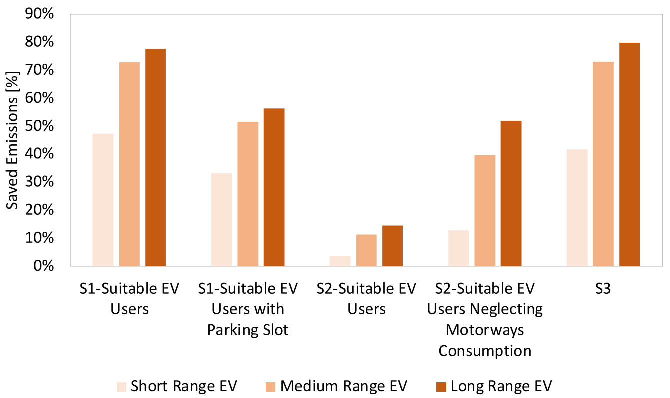

Fig. 22. Scenarios comparison evaluation of saved emission with respect to an average ICE Vehicle.

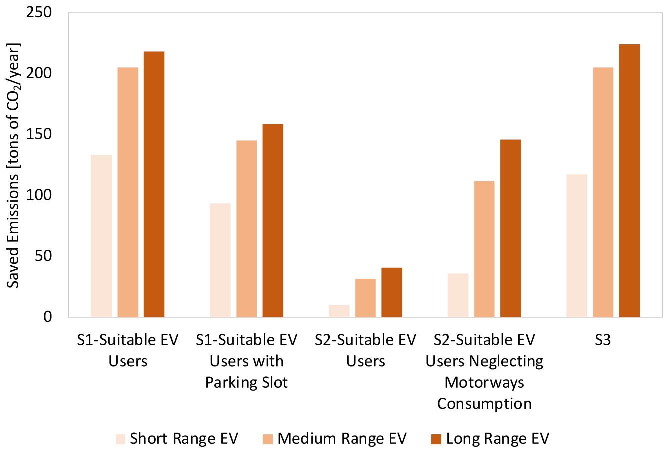

Fig. 23. Scenarios comparison evaluation of saved emission in tons of CO_2/year.

vehicle saves 220 tons of CO_2 per year when compared to a scenario in which everyone uses the ICE vehicle designated for the study. Finally, Fig. 24 shows the aggregate of the average expenditure per user in the case of recharging EVs.

From the analysis of Fig. 24 and combining Figs. 14, Figs. 17 and 20 together, it can be understood how the type of power supply can be a driver towards electric mobility. Considering the difference between home charging and fast charging, it is important to reflect on the origin of consumption. It is clear from Fig. 24 that the Short Range and Medium Range EV have similar average expenditure. The difference with the Long-Range EV is linked to the greater autonomy of the vehicle. However, if we consider fast charging, the situation changes due to the increase in the price of charging, modifying the gap between the average yearly expenditure of EVs. It is also easy to see from Fig. 24 that Scenario 1 is very cost effective. In Scenario 1, charging is mainly domestic and daily but still is less expensive, according to Table 2. In Scenario 2, where motorway consumption is neglected, mainly charging modes 3 and 4 are considered, which are more expensive. On the other hand, Scenario 2 with motorway consumption is very economical as the recharging takes place weekly. However, it should be noted that the number of suitable users is the lowest of the scenarios, as for many users one charge per week would not be sufficient. In this scenario, the suitable users are those who have lower energy consumption and would still spend the lowest price on recharging. This scenario is therefore the one with the fewest suitable users, although it appears to be the most advantageous.

Finally, in this section is proposed a sensitivity analysis to see the impact that the designated inputs have on the identified scenarios. Specifically, it will be interesting to understand how the defined thresholds for user suitability that were identified have impacted. For Scenario 1, where home charging was considered, the threshold for the maximum number of days of vehicle unavailability was 10 days, while for Scenario 2, where fast charging was considered, the threshold was three weeks. Focusing on Scenario 1, a sensitivity analysis is carried out by changing the days of inactivity from 10 to 0 and Fig. 25 shows how the percentages of suitable users vary.

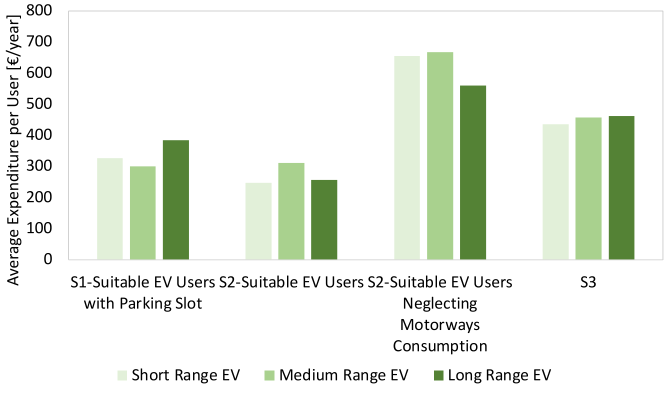

Fig. 24. Scenarios comparison on average expenditure per user.

The same reasoning is applied to Scenario 2. The number of weeks of unavailability is scaled from three to none. In this case unavailability means that the user can exceed the vehicle's autonomy and recharge more than once a week. In this scenario, as shown in Fig. 26, the percentages are halved between three and zero weeks of unavailability. The graph considers Scenario 2 without consumption on motorways.

Following these results, it is clear that as the unavailability time decreases, the number of suitable users also decreases linearly. In conclusion, the model used can be considered solid and allows a quantitative analysis of the impacts in electrification scenarios. However, some intrinsic limitations of the model must be considered. The model uses only three types of EVs and one ICE for the simulations. The validity of the data also lies in how the hypothesized vehicle models are close to other models on the market. This happens even if the assumed vehicles are real, as in this case. It is unreal that 200 users have the same ICE vehicle, however the ICE vehicle used can be considered as a medium performance model on the market. The same considerations are replicable for the EVs selected for the case study. Still, the range of models offered by the market does not undermine the validity of the study. Finally, within this case study there is no algorithm that optimizes charging. Vehicles charge randomly and sometimes daily without control. A future improvement can consider the implementation of an algorithm that can help in the charging management of this fleet. This will allow to face the problem of ensuring the resilience of the network, which will represent a challenge in the near future (Liu et al., 2018; Hussain and Musilek, 2022).

5.5. *Charging stations integrability*

Within the case study, the importance of an effective, accessible, and resilient charging infrastructure was highlighted. Thanks to these features, users can more easily switch to an EV. In compliance with the aim of increasing the electrification rate of the sector, the data obtained from the case study were used to study the strategic positioning of DCFC CSs. Preferred positions for users were identified from the data. It is reasonable to think that a place highly visited by users is a point of interest for many drivers and this can be a place of interest for a CSs. In urban areas, these locations may be restaurants, shopping centers or other areas of interest and offer flexibility to demand. In extra-urban contexts, CSs are mostly used to facilitate long-distance travel. Thanks to the presence of motorway service areas, there is space available for connection to the network. Following these considerations and the case

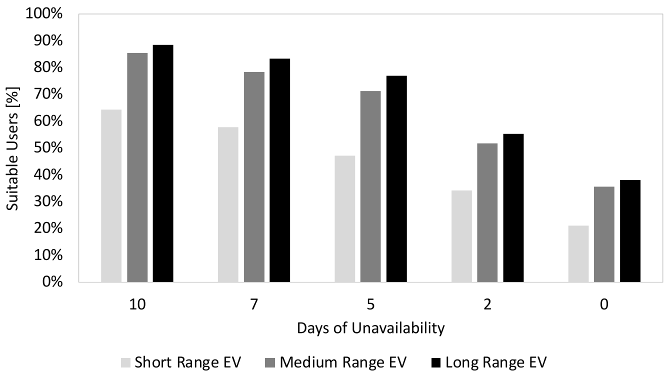

Fig. 25. Scenario 1 sensitivity analysis on suitable EV users considering days of unavailability.

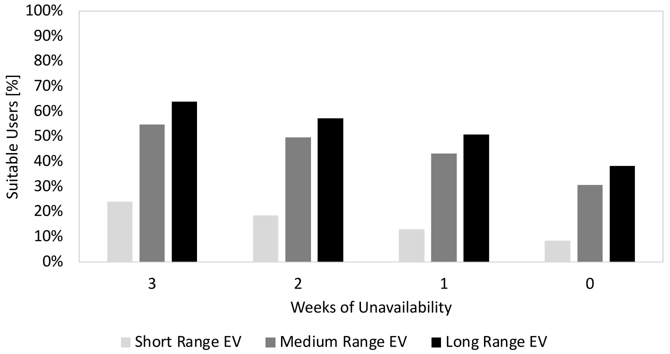

Fig. 26. Scenario 2 sensitivity analysis on suitable EV users considering weeks of unavailability.

study carried out, the model was tested in the Piedmont region (located in northern Italy), where most of the data came from. In this area, 3 cities were studied, based on the number of stops lasting less than an hour. The selected area is close to the cities of Turin, Alessandria, and Vercelli. Fig. 27 offers an overview of the identified areas.

As previously reported, to identify an area of interest it is necessary to count the number of stops around 1 km^2 at a point and consider stops lasting less than an hour. Fig. 28 shows a map where short stops have been considered and the number of stops around the year in the area is highlighted.

From the graph represented in Fig. 28, it can be seen that the majority of stops are made in urban areas, while in extra-urban areas short stops are present, but more sporadic. The points with the greatest number of vehicles to park combined with the high number of stops identify the points of interest for the positioning of new CSs. Through the analysis of stops and user flow, attractive poles for users have been identified and as initially hypothesized, these are shopping centers and places close to the city center.

6. Conclusions

Climate Change represents one of the most important contemporary challenges. Reducing CO_2 emissions in different sectors represents one of the keys to face it, and transportation appear to be one of the major contributors. To address this issue, the authorities (at different levels) began to promote policies aimed at the electrification of the sector. In this context, the proposed work presents a decarbonization case study based on real data. The possibility of switching to EVs was assessed for a pool of ICE vehicle drivers based on their habits and charging possibilities in different electrification scenarios. In the electrification scenarios, massive electrification was evaluated with slow charging (Charging Mode 1 and 2) combined with the availability of parking, and fast charging (Charging Mode 3 and 4). Finally, the two scenarios were combined to highlight the potential penetration rate of EVs. The scenarios will highlight the percentages of suitable users for EVs of different operating ranges. Furthermore, the case study shows the potential for economic savings on users' charging with respect to diesel refueling. Thus, depending on the scenarios developed, from 11 tons in worst case up to 220 tons of CO_2 in best case, can be saved every year. Moreover, the results shows that in a scenario where charging mode 1 and 2 are predominant a suitable user can save from 146 €/year to 190 €/year. On the other hand, when all charging modes are combined, EVs save between 24 €/year and 119 €/year. The scenarios are then compared, underlining the potential of electrification and a sensitivity analysis based on the day of unavailability of the vehicle test the flexibility of the model. Finally, thanks to the data collected, a methodology is proposed for the positioning of the CSs in an area taken as a case study in northern Italy, highlighting some criteria for the strategic positioning of DCFC CSs. In this way the work aims to highlight the benefits of the electrification process of the sector, proposing a strategy for integration for further CSs. The importance of this study lies in providing an empirical basis to promote sustainable mobility through the electrification of transport. The analysis of different electrification scenarios provides key insights for public policy, showing how different charging strategies can influence the uptake of EVs. The ability to adapt the methodology to different contexts allows the scalability, promoting sustainable practices in different urban and rural environments. Data-driven policies and strategies, such as those proposed in this study, can accelerate the transition to a more sustainable future, reducing environmental impacts and improving quality of life in urban context. However, it should be emphasised that the work has limitations due to factors within the study. The number of users in the dataset is limited and may not fully represent the diversity of user behaviour. At the same time, the habits of the users may change over time and the data collected may no longer reflect their lifestyle. It should also be clarified that the economic considerations made do not take into account government incentives or changes in energy prices. Finally, the model does not consider the impact of charging on the local electricity network. In the future, the results of this work can be scaled to other contexts with appropriate adaptation. Therefore, it will be possible to perform power flow studies on the grid through algorithms able to optimize the power demand or the energy cost, improving the CSs service for EV users. This will result in an innovative data-driven model for managing the electric network following the EVs power demand.

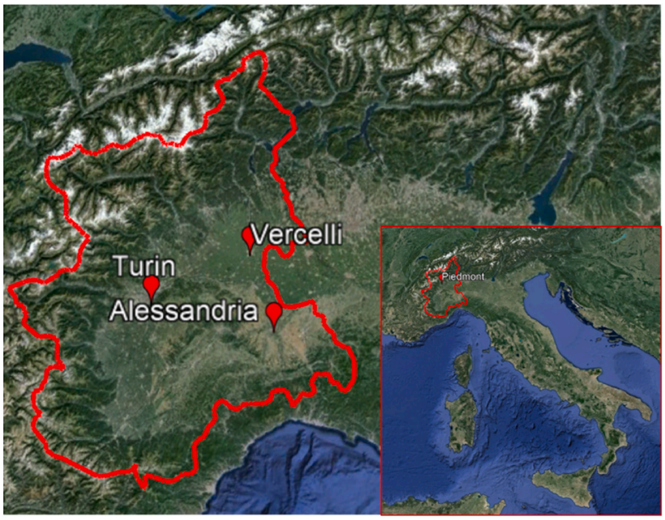

Fig. 27. Area selected for the study of the positioning of public CSs.

CRediT authorship contribution statement

Cristian Giovanni Colombo: Writing – original draft, Methodology, Funding acquisition, Data curation. **Fabio Borghetti:** Writing – review & editing, Investigation, Formal analysis. **Michela Longo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **Wahiba Yaici:** Writing – review & editing, Supervision, Conceptualization. **Seyed Mahdi Miraftabzadeh:** Writing – original draft, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

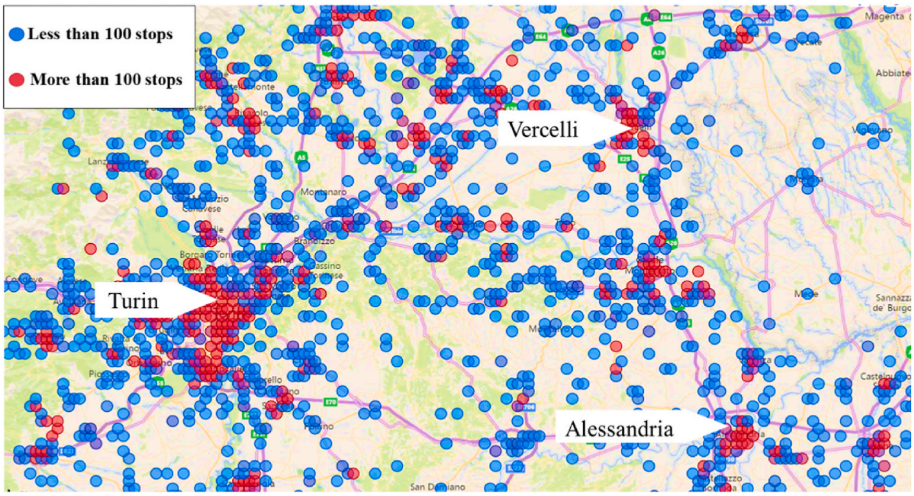

Fig. 28. Common stops area of the study for the positioning of public CSs.

Data availability

The authors do not have permission to share data.

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