sustainability

MDPI

Article

Electrification of Motorway Network: A Methodological Approach to Define Location of Charging Infrastructure for EV

Cristian Giovanni Colombo [1], Fabio Borghetti [2], Michela Longo [1,*] and Federica Foiadelli [1]

[1] Department of Energy, Politecnico di Milano, Via La Masa 34, 20133 Milan, Italy; cristiangiovanni.colombo@polimi.it (C.G.C.); federica.foiadelli@polimi.it (F.F.)
[2] Mobility and Transport Laboratory, Design Department, Politecnico di Milano, Via Candiani 72, 20133 Milan, Italy; fabio.borghetti@polimi.it
* Correspondence: michela.longo@polimi.it

Abstract: Environmental issues have reached global attention from both political and social perspectives. Many countries and companies around the world are adopting measures to help change current trends. Awareness of decarbonization in the transportation sector has led to an increasing development of energy storage systems in recent years, especially for ground vehicles. Batteries, due to their high efficiency, are one of the most attractive energy storage systems for vehicle propulsion. As for road vehicles, the growing interest in Electric Vehicles (EVs) is motivated by the fact that they reduce local emissions compared to traditional Internal Combustion Engine (ICE) vehicles. The purpose of the paper is to present a study on how to plan and implement vehicle charging infrastructure on motorways. In particular, a specific road in Italy is analyzed: the motorway A1 from Milan to Naples with a length of about 800 km. This motorway can be considered representative because it passes through some of Italy's most important cities and regions and may represent the backbone of Italy. A useful model for defining the optimal location of electric vehicle charging stations is presented within the paper. Starting with the data on the average daily traffic flows passing through the main nodes of the motorways section, the demand for the potential vehicles needed to define the number and dimension of charging stations and provide an adequate supply is estimated. The analysis was performed considering five-time horizons (year 2022 to year 2025) and four Scenarios involving the installation of 4, 8, 16, and 32 Charging Stations (CSs) in each service area, respectively.

Keywords: motorway electrification; fast-charging; traffic-based model; transportation planning; sustainable mobility

Citation: Colombo, C.G.; Borghetti, F.; Longo, M.; Foiadelli, F. Electrification of Motorway Network: A Methodological Approach to Define Location of Charging Infrastructure for EV. *Sustainability* **2023**, *15*, 16429. https://doi.org/10.3390/su152316429

Academic Editor: Elżbieta Macioszek

Received: 23 October 2023
Revised: 27 November 2023
Accepted: 27 November 2023
Published: 29 November 2023

1. Introduction

With the growing attention towards environmental sustainability policies, various authorities, such as the European Community and the Conference of Parties (COP), have encouraged the governments of many countries to decarbonize the transport sector [1–4]. Today, the transport sector plays a key role in the national economies of various countries, moving goods and people to places of interest, respecting the trends of economic sustainability and accessibility for users. In more developed countries, however, the transport sector is one of the most polluting in terms of Green-House Gases (GHGs) emissions. In fact, the transport sector emits approximately 30% of the total GHG emissions and is second only to the heat and electricity generation sector [5]. In this context, despite the decarbonization policies already launched in recent years by the various Public Transport Operators (PTOs), the sector's Net-Zero Emission target is still far away. This is linked to the fact that in several countries, the most used means of transport is the private car and the rate of motorization is high [6–8]. Following these data, the authorities began to push towards the electrification of private transport, with incentives and awareness campaigns that promoted Electric Vehicles (EVs). Although the EV market is growing, EV users are still a minimal percentage [9–12]. This is due to several factors including range anxiety: the fear of not being able to reach a destination due to the limited autonomy of EVs compared to common Internal Combustion Engine (ICE) vehicles [13,14]. In fact, if EVs represent an optimal solution for urban travel, where it is also possible to exploit regenerative braking, in long haul travel, EVs are not perceived as reliable by users. To address this limitation, the authorities have allocated various funds for the expansion and construction of new high-power Charging Stations (CSs) (150–300 kW), to allow the rapid charging of EVs. Most of these charging infrastructures will be allocated in some spots on motorways to facilitate the long-haul movements of EVs and will be positioned in existing car parks or gas stations.

Following this trend, this paper aims to propose a motorway electrification model, through the use of real data, in order to identify an optimal scenario in which a specific amount of CS is identified. An attempt is made to identify the percentage of vehicles that it will be possible to recharge in addition to the expenditure to be incurred by the decision maker for electrification. The paper will present, in Section 2, a literature review that will serve to contextualize the work done, particularly in the context of the electrification of the private transportation sector. Section 3 will describe the methodological approach taken and what inputs are needed to make the study scalable by considering other types of highways. Section 4 will show the case study analyzed in the paper considering traffic flow, electric vehicles, the present charging infrastructure, and related costs. Section 5 will show at different time horizons whether the charging infrastructure will be reliable based on the number of CS, combined with the highway flow, showing the percentage of private electric vehicles that can be powered in the course of a day. Section 6 will present the conclusions of the case study, suggesting the optimal conditions for the electrification of the sector.

2. Private Transport Sector Electrification Context

The electrification of private transportation is one of the proposed methods in response to environmental challenges and dependence on fossil fuels. The introduction of electric private cars has been a crucial step towards sustainability and the reduction of greenhouse gas emissions. Electric Vehicles (EVs) offer significant advantages, including the reduction of polluting emissions and noise, decreased dependence on fossil fuels, and lower long-term operational costs. However, challenges arise in terms of limited autonomy and the need for an adequate charging infrastructure. In this context, the effectiveness of EVs on motorways is strongly influenced by the availability and accessibility of charging stations. Now, considering the current traffic flows, the motorways charging infrastructure is insufficient to meet the growing demand. Differences in charging protocols and the lack of standardization can further complicate the situation, limiting convenience for users. Efforts to address the charging infrastructure problem include the implementation of global standards for charging connectors, the expansion of fast-charging station networks, and the development of advanced technologies to increase the autonomy of electric vehicles [15–18]. In this framework, Ref. [19] valuates the possibility of integrating various storage methods to decarbonize the sector, assessing the volumes of recharged vehicles. Ref. [20] provides a model for the positioning of charging stations on the motorway's network through an applied methodology. Ref. [21] analyzes user behavior, combining it with the charging needs of vehicles on high-energy days. Ref. [22] works on a cost minimization model for high-power charging infrastructure in the Austrian scenario. Ref. [23] proposes a comparative analysis of control strategies for adaptive supervision based on the state of charge for Plug-in hybrid EVs. Ref. [24] offers a review of an energy management strategy for hybrid and plug-in hybrid electric vehicles. Also, Ref. [25,26] simulate the emissions impacts through the study of the driving behavior and traffic conditions of autonomous driving electric vehicles and a model for the positioning of CSs.

Focused on the vehicle, Ref. [27] proposes optimal charging and driving strategies for Battery Electric Vehicles (BEVs) on short trips using a dynamic approach. Finally, Ref. [28] proposes a high-performance charging model for the electrification of motorway traffic.

Among the issues considered in the field for the location and sizing of charging stations, there is also the correct placement of Electric Sub-Stations (ESSs), enabling the right and resilient power supply of CSs, highlighting a significant infrastructure task [29]. Additionally, the potential impact of the mass electrification of electric vehicles is studied in [30].

Beyond these stationary charging methods, dynamic charging methods on motorways are also extensively studied to minimize range anxiety among users [31–33]. Finally, the integration of renewables, the establishment of green islands, and emissions monitoring in motorway transportation represent topics of interest in the research framework for sustainable mobility [34,35].

Motorways EV Flow Forecast and Market Share Trend

Most of the national vehicle fleet is powered by petroleum derivatives. However, diesel's share is progressively decreasing, to the advantage of less impactful vehicles, i.e., electric, hybrid, gas, LPG. To build the electric vehicles flow, it is necessary to start from the number of EVs and hybrids registered [36,37]. In this case study, 2018 is selected and in that period, they represented only 0.7% (272,665 vehicles) of the fleet. At the same time, only 14 million cars fell into the Euro 5 and Euro 6 categories, with lower emissions. Most of the vehicles were more than 10 years old and, therefore, outdated [38,39].

With the entry of more stringent policies, the charging infrastructure increment and the development of the market, the number of EVs and hybrids increased to 596,000 cars in 2020 [40,41]. This positive trend continued, even if weaker than in other European countries, also in 2022. The market that had the largest share of electric vehicles was the private one, followed by long-term rentals, retailers, and company fleets. Figure 1 shows the percentage of market channels.

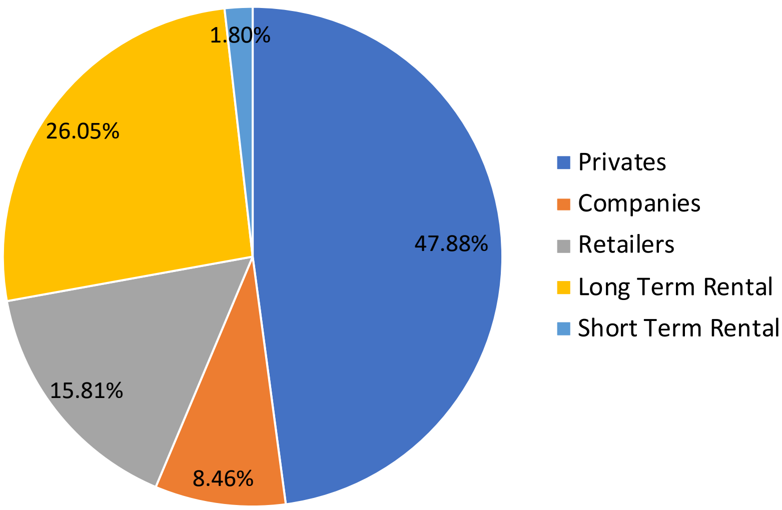


Figure 1. Italian EVs market channel, 2022.

The study carried out will work on Battery Electric Vehicles (BEVs) circulating in Italy, which correspond to 170,428 units. From this analysis it is possible to identify the Italian car fleet composition, reported in Figure 2.

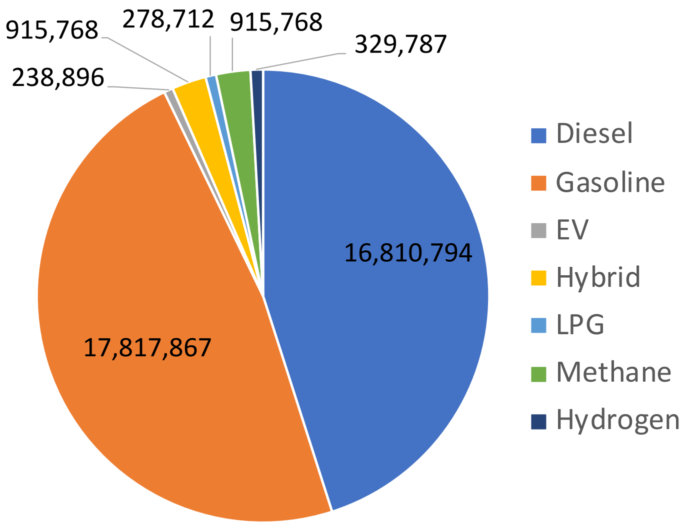


Figure 2. Italian private vehicle fleet by supply, 2021, data in millions of units.

In recent years, the Italian market has seen registrations of EVs rise from 0.75% in 2018 to 1.5% in 2020. Following the most optimistic forecasts, dependent on the agreements submitted with the European Community and the COP, for 2030 it is expected that all the new registrations in urban areas will be electric. Furthermore, due to the objectives of the National Integrated Energy and Climate Plan, the goal for 2030 is to reach 4 million BEVs and 2 million PHEVs. It is, therefore, possible to trace a trend of electric vehicles to 2040 through a projection of the trend following the market indices (Figure 3) [42].

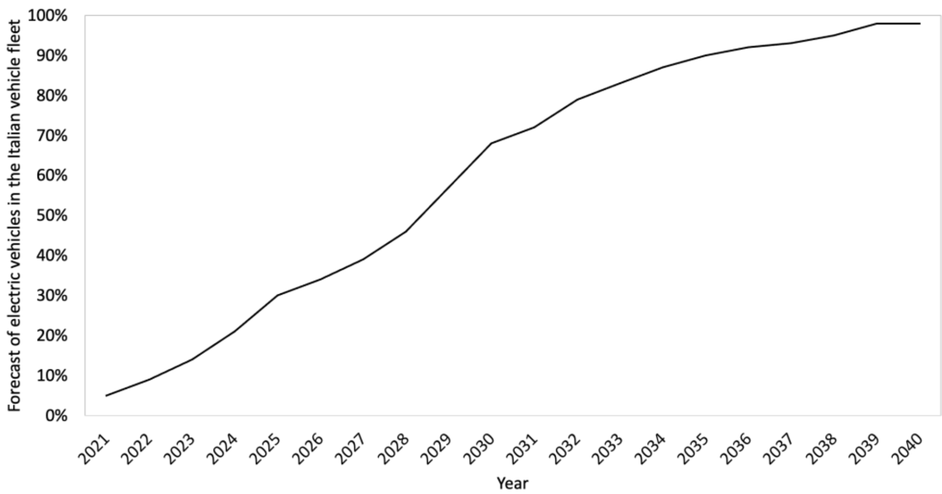


Figure 3. Percentage forecast of electric vehicles in the Italian vehicle fleet. Data are estimated following the market trend shown in [42].

3. Methodological Approach

Since it is impossible to carry out an in-depth study of the proposed methodology on a national scale, one exemplary route was selected to be used as case study. Once the analysis has been carried out on this route, it will be sufficient to form a scalability process involving other motorways for which input data are available.

With the aim of identifying the optimal strategy for the positioning of charging infrastructures, this work is structured with a swimlane diagram, shown in Figure 4. The process begins with unique inputs, which combined in the process can return a reliable average forecast of EV-traffic flow on a defined stretch of motorway. The inputs used to initialize the process are descriptive, i.e., they reflect the real and current situation. The descriptive data are derived from reports provided by some of the stakeholders in the mobility market: decision makers, infrastructure managers, and motor operators. The data used for the study are:

- National new vehicle registration: useful for knowing the national per capita motorization rate;
- Traffic framework in a specific motorway section: necessary to define the flow of users in a specific area;
- EV national market share: useful for characterizing the electricity market trend.

Once the descriptive data of the work have been acquired, they are processed in the second phase of the study. In this phase, the data used are predictive, i.e., resulting from calculations and estimates obtained by combining or developing the input data. It is possible to obtain an estimate of the traffic flow and define a forecast of the trend of the national EV market. The combination of these two results will allow to identify the flow forecasts of EVs, allowing to return information regarding the strategic positioning of CSs.

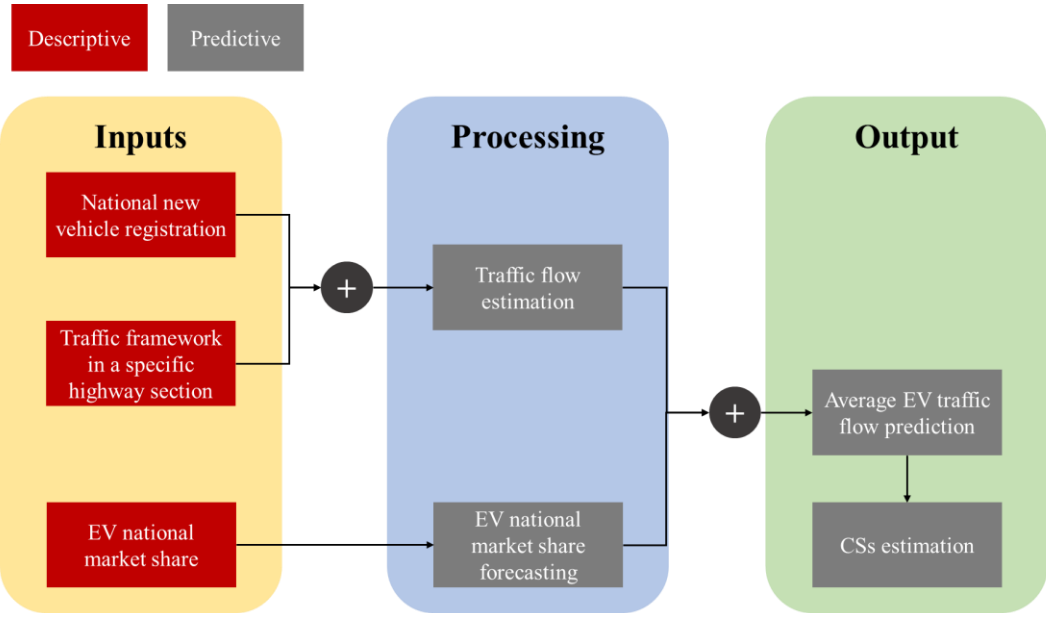


Figure 4. Outline of proposed approach for forecasting EV traffic flows and CS for the future.

4. Case Study: The Italian Motorways

The road identified is one of the longest and busiest at a national level and connects five of the major Italian cities crossing almost the entire peninsula, reaching a length of approximately 800 km (Figure 5). With the aim of carrying out an analysis as detailed as possible, the route examined was divided into four sub-sections:

- Sub-section 1: Milan–Bologna (approximately 215 km);
- Sub-section 2: Bologna–Florence (approximately 119 km);
- Sub-section 3: Florence–Rome (approximately 273 km);
- Sub-section 4: Rome–Naples (approximately 225 km).

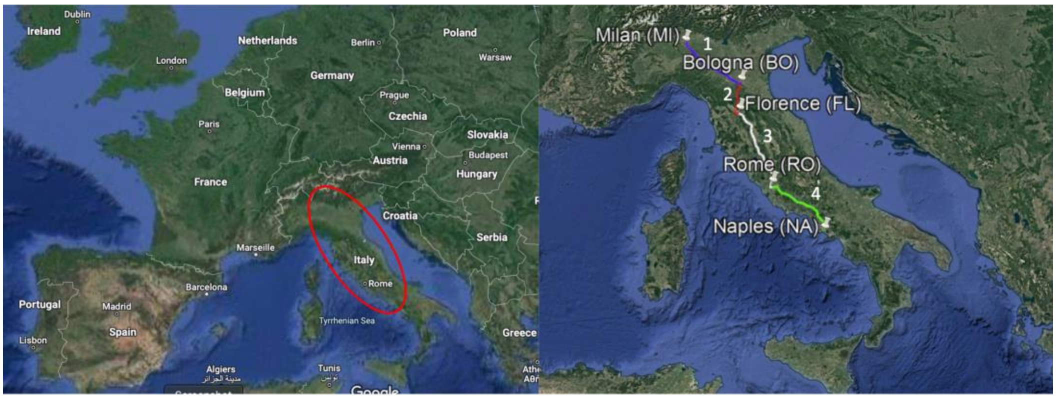


Figure 5. Route identification in Italy—A1 and four Sub-Sections.

4.1. A1 Motorway Traffic Flow

This work processes the 2019 average daily traffic data on the Italian A1 motorway, which connects the city of Milan with the city of Naples. The choice of data from January 2019 to December 2019 will allow us to study traffic in ordinary conditions, neglecting the polarizations of external agents that do not directly involve mobility. In this section, the data are clustered into five categories depending on the vehicle class. The vehicle categories, or classes, specified by the infrastructure manager are shown in Figure 6 [36,37].

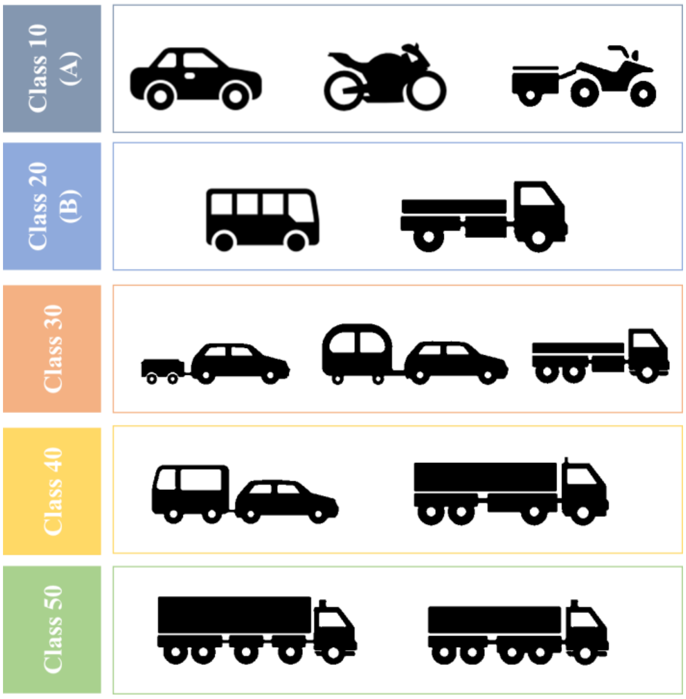


Figure 6. Vehicle classes.

Once the vehicle categories involved in the study have been identified, it is appropriate to identify their distribution on the four sub-sections of the identified route. Figure 7 shows the distribution of vehicle categories in the specific sub-sections. As expected from the national motorization rate, Class 10 vehicles are those with the highest percentage of use in each of the sections of the A1 motorway. The Milan–Bologna sub-section is the busiest, with more than 200,000 Class 10 vehicles, despite not being the longest sub-section. The sub-sections connecting Florence–Rome and Rome–Naples represent the sub-sections with intermediate traffic with more than 150,000 Class 10 cars. Finally, the Bologna–Florence sub-section appears to be the one with the lowest flow of the four segments, crossed by more than 80,000 Class 10 vehicles. A high number of users means a high number of vehicles that will need to be charged, leading to a higher power demand. The combination of traffic flows for each section, combined with the national electrification rate, is essential to provide a prediction on the CSs necessary to offer a reliable charging service. By increasing the vehicle class, which means, increasing the number of axles, the circulating fleet is reduced, emphasizing that the majority of motorway users are private vehicles of Class 10. The graph includes vehicles of Class ES, which refers to exceptional transports and deviates from the standard classification, therefore, it may be designated under specific classes. Additionally, vehicles of Class NC are also reported, a category called Non-Classified, as they indicate a vehicle that does not fall into a specific category or is not clearly classified.

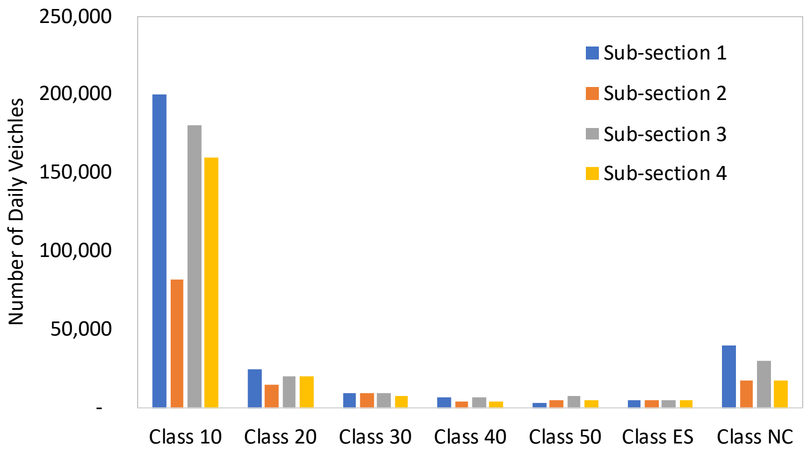
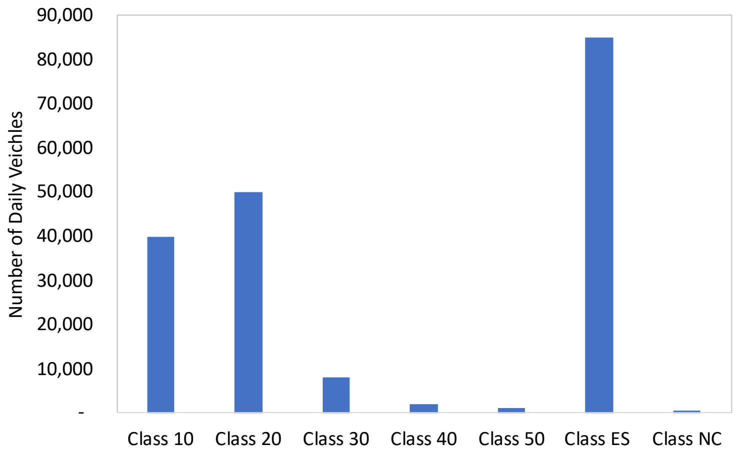
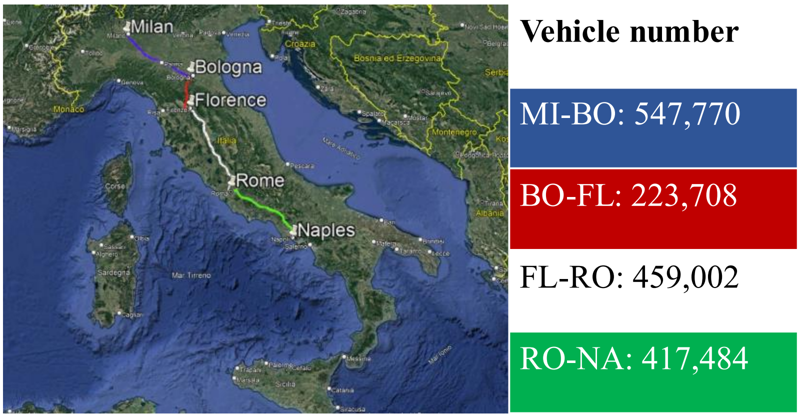


Figure 7. Number of daily vehicles in A1 motorway in the four sub-sections.

To make an in-depth estimate, it was considered that vehicles can move between two adjacent destinations, but also towards a different city from the next. Therefore, the traffic flows of the individual motorway sections were not added together, but the maximum value in each of the sections was identified. Subsequently, the vehicle classes were identified. Based on this process, Figure 8 shows the estimated daily number of vehicles traveling along the A1 motorway following the Milan–Naples direction considering all sub-sections. Overall, traffic was identified along the Italian motorway A1 in the four sub-sections, as shown in Figure 8b, considering the totality of the vehicle classes estimated for the Milan–Naples direction and vice versa.



(**a**)



(**b**)

Figure 8. Daily vehicle estimation in A1 Milan–Naples (**a**) direction and (**b**) direction and vice versa.

The response of European countries [38] shows a tendency towards a decrease in new vehicles, linked to the fact that these are able to offer an adequate public transport system, encouraging citizens to take collective transport. Furthermore, the model requires knowledge of the vehicle market trend at the national level. The market shows that the trend of recent years has peaks and valleys continuously; therefore, following these considerations the forecasts on the number of electric vehicles do not have a monotonous positive trend (Figure 9).

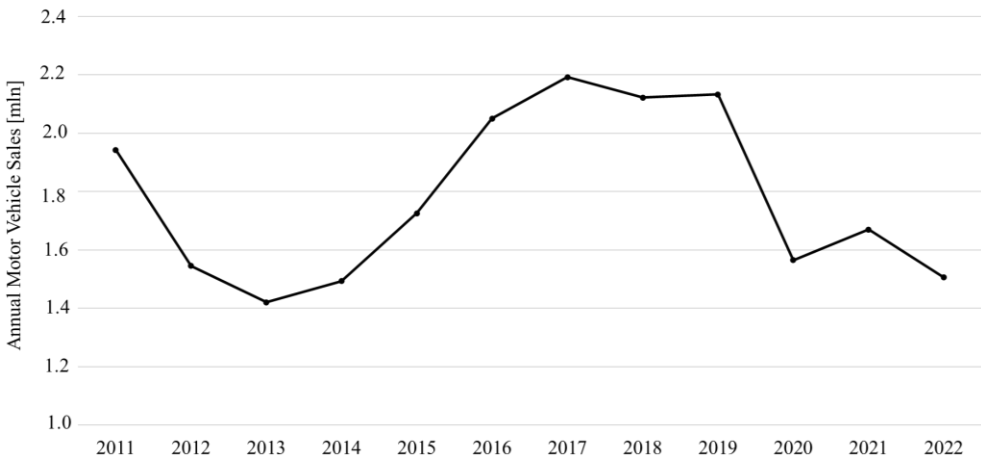


Figure 9. Italian annual motor vehicle sales (2011–2021).

Following these considerations, the predicted traffic on the A1 motorway will be considered constant in the coming years within the work. For the replicability and scalability of the project, it is worth analyzing these data every year to provide an update and have more precise results [37].

4.2. EVs Flow Forecast on A1 Motorway

Finally, with the traffic flow data on the A1 motorway from Milan to Naples and combining them with the forecasts of the national EV market, it is possible to identify the forecast of the flow of electric and internal combustion vehicles along the motorway. Assuming constant vehicle traffic, thanks to the constant private motorization ratio, the increase in EVs on the route would follow the growth trend shown in Figure 10. The market inflection point will be expected between 2028 and 2031, thanks also to government pushes [42–44]. It remains to be specified that this market curve may not respect the complete European trend where some countries are further ahead in the development of the electric vehicle market [45]. However, following what has been shown by [10], a reliable and efficient charging system is only one of the elements that would push the EVs market, such as the achievement of climate targets. Following these considerations, the vehicle traffic forecast curve by type (ICE or EVs) on the A1 motorway in the Milan–Naples section is reported (Figure 10).

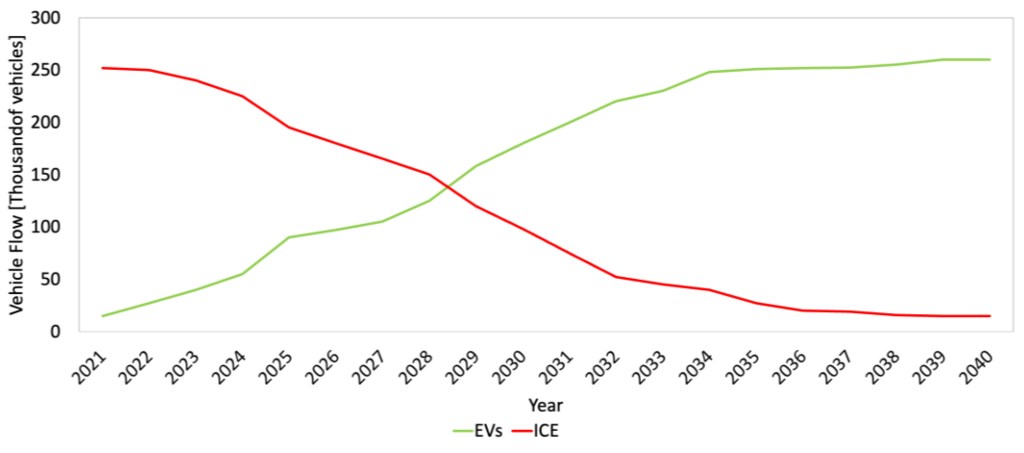


Figure 10. Vehicle traffic flow on A1 motorway, Milan–Naples direction. Data are estimated following the market trend shown in [42].

The study carried out would then be easily scalable using the flow data on the four sub-sections into which the route is divided. Figure 11 analyzes the traffic flow for each sub-section.

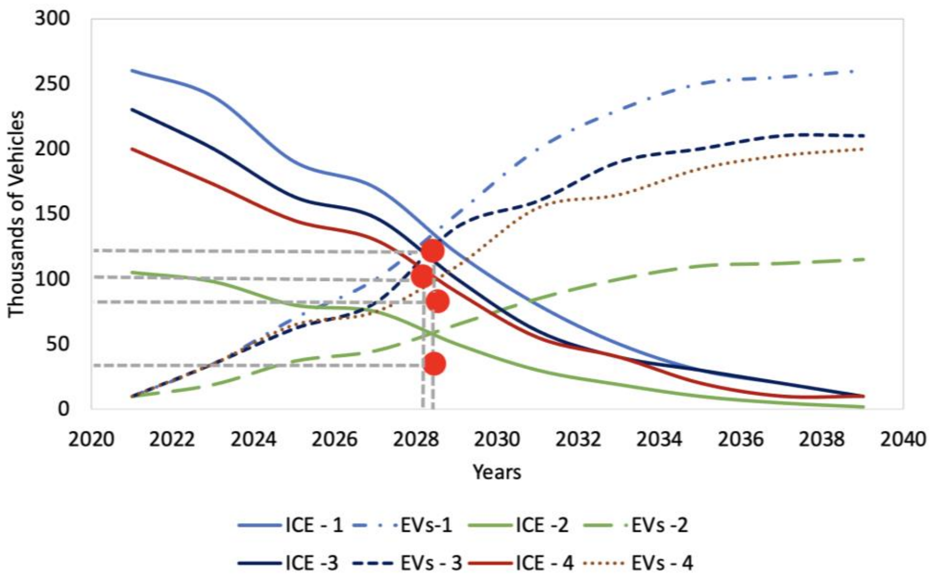


Figure 11. Vehicle traffic flow on A1 motorway divided by sub-sections. Data are estimated following the market trend shown in [42].

4.3. A1 Motorway Charging Stations' Current Situation

This subsection will report the charging infrastructure currently operating on the motorway considered in the Milan–Naples direction. In Table 1, the charging stations currently available in this section are reported [46].

Table 1. Existing CS on A1 Milan–Naples.

Location	km of Positioning	Charging Type
S. Zenone Ovest	15.1	HPC 300 kW + fast-charging 64 kW
Arda Ovest	73.3	HPC 300 kW + fast-charging 64 kW
Secchia Est [1]	165.5	HPC 300 kW + fast-charging 75 kW
Give Ovest	481.1	HPC 300 kW + fast-charging 75 kW
Flaminia Est [1]	509.1	HPC 300 kW
Teano Ovest	708.4	HPC 300 kW + fast-charging 64 kW

[1] CS with Est in the name are in the Naples–Milan direction and HPC—High-Power Charging.

In addition to those reported, 21 new installations are currently under construction in various Italian service areas, of which only four are located on the A1. The CSs are always operational and can deliver 300 kW, providing the ability to recharge the vehicle in 15 min. The target set by the infrastructure manager is to have a CS every 50 km, and 100 of them are planned, estimating a cost of EUR 75 million. Considering the CS power, the expected cost for a recharge will be 0.69 EUR/kWh [47,48].

4.4. Cost Estimation Settlement

To carry out the correct analysis of labor, certain costs have been considered:

- Investment costs: equipment and installation costs;
- Operation cost: security, energy consumptions.

Table 2 reports the investment costs for the CSs' implementation [47,49].

Table 2. Investment cost for CSs.

Investment Type	Cost
DC charger unit	EUR 40,000
DC charger Installation	EUR 64,000
Remaining capital expenditure	EUR 46,000
Level 1 [1] charger unit	EUR 1500
Level 1 charger installation	EUR 3000
Level 2 [2] charger unit	EUR 6500
Level 2 charger installation	EUR 12,700
Fast charging	0.5 EUR/kWh
Slow charging	0.3 EUR/kWh

[1] Level 1—type of current in AC and Slow (11–20 h); and [2] Level 2—type of current in AC and Fast (3–8 h).

On the other hand, the operation costs consist of O&M (Operation and Maintenance) costs for the supply equipment and network fees, which involve charges for electricity, site rental or lease, station management, billing, software subscriptions, and preventive and corrective maintenance.

The annual electricity consumption cost is determined through the electricity rate measured in EUR/kWh and the power consumption: average commercial electricity rates are in the range of 0.08–0.15 EUR/kWh [47–49]. The consumption depends on:

- The number of vehicles which use the EV charging station;
- The power output of the charging station;
- The vehicle power acceptance rate;
- The climate;
- The amount of time the vehicles charge.

DCFC (DC Fast Charging) EVSE charging cost is considered 0.5 EUR/kWh. In the operating costs, connectivity is included for communication issues and this fee varies from

EUR 100 to EUR 900, depending on the CS. Finally, the last costs involved are related to incentives and rebates linked to CS installations, software, and soft costs [47–49].

Starting with this information and combining it with the number of CSs available in each scenario studied, it will be possible to identify the capital expenditure for each of the scenarios in different time horizons. Capital expenditure will take into account the cost of DCFC EVSEs and DCFC CSs.

4.5. Simulation Setup

First it is necessary to set some initial information for the study and its parameters. In addition to what is specified in Tables 1 and 2, the presence of 60 gas stations and 30 parking areas at the moment should be mentioned. Finally, the length of the route (1456 km considering the two directions) and the presence of four CSs, which can load up to eight vehicles simultaneously, for each station are considered as the input data. With these data, various time horizons will be developed, which can satisfy the charging demand depending on the traffic. As explained in the previous sections, the traffic flow is studied thanks to the electricity market forecasts combined with the flow of users along the route. The objective will be to electrify the 60 gas stations and the 30 parking areas, and upgrade the 7 existing CSs. There will be five time horizons presented and they are presented in Table 3. In addition to the time horizon number, the table also shows the year in which the time horizon is expected to occur and the percentage of available areas out of the total (97).

Table 3. Case study time horizons presentation.

Time Horizon Number	Year Prevision	% of Available Areas
Horizon 0—H0	2022	7% (actual situation)
Horizon 1—H1	2024	20%
Horizon 2—H2	2028	50%
Horizon 3—H3	2030	70%
Horizon 4—H4	2035	90%

The choice of time horizons is closely related to the curve depicting the increase in the modal share of electric vehicles (Figure 3). Considering 2022 as the current scenario (H0) and 2035 as the long-term time horizon (H4) for the electrification process, in compliance with European standards, intermediate time horizons to monitor the electrification process are selected: short-term (H1), short–medium-term (H2), and medium–long-term (H3) [3,18]. In this sense, the intermediate time horizons used serve as interim monitoring in the electrification process. The selection of dates is also around the inflection points of the curve in Figure 3, where a significant increase in the electrification rate of the vehicle fleet is forecasted.

5. Analysis and Discussion of Results

In this section, the results obtained from time horizon one to time horizon four in different situations will be described. Specifically, four possible scenarios are studied for the time horizons. The scenarios differ in the number of CSs allocated to each of the identified spots. In the first scenario, four CSs are positioned for each spot. In the second scenario, eight CSs will be positioned for each spot, while in scenarios 3 and 4, 16 and 32 CSs will be available, respectively, per spot.

5.1. Scenario 1

In scenario 1, four CSs are considered for each of the selected spots. As mentioned, time horizon zero is the as-is scenario, where the seven CSs already present are located. The presence of four CSs allows the charging of eight vehicles simultaneously. Figure 12 shows the growing trend of the charging infrastructure available in the different time horizons. This representation shows an electrification trend based on the existing infrastructure. First, those that already exist are considered and gradually, considering the space available in the areas used for the refueling service and the existing car parks, the CSs increase over the years, in compliance with the electric vehicle market.

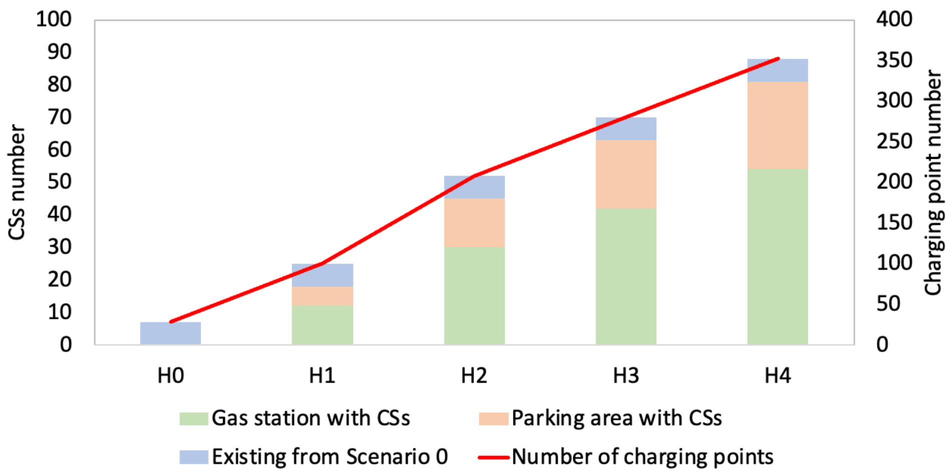


Figure 12. Spots and charging point estimation in scenario 1.

In the graph, the maximum number of columns considered will be 88 (90% of 97), to protect against the possibility that some infrastructures are not built in time. Figure 12 also shows the number of charging points for each scenario.

Next, it is of interest to evaluate the charging power that the different points can provide. Figure 13 shows the different charger types.

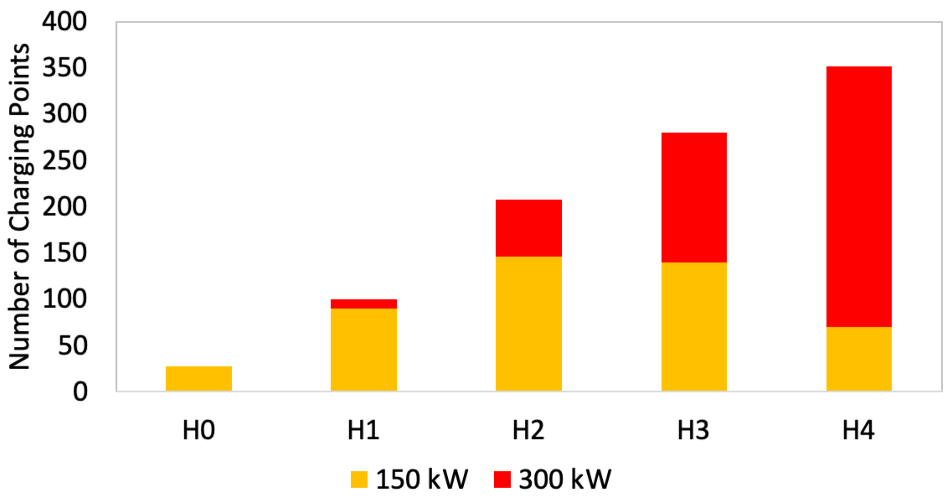


Figure 13. Charging type estimation, scenario 1.

In all scenarios, as in this case, it is estimated that the number of CSs for which the power is 150 kW will decrease in favor of 300 kW columns. This is linked to the installation of new points and the replacement of CS with more performing ones, thanks to the technological development that will progress over time horizons. This replacement investment is considered in the calculation of the Capital Expenditure, in compliance with the costs highlighted in Table 2. Considering the almost electrified time horizon, 4352 charging points are considered, split into 70 charging points for which the power is 150 kW, and 282 for which the power is 300 kW. Following these considerations, Figure 14 shows the maximum capacity of the cars that can be charged in a day, considering CSs always operating with 20 min as the standard charging time for each vehicle. Following this assumption, and considering a CS is always operating, there are 72 time slots of 20 min per day, and in every slot, it is possible to charge one vehicle. The number of rechargeable vehicles in a day are reported in the green column of Figure 14.

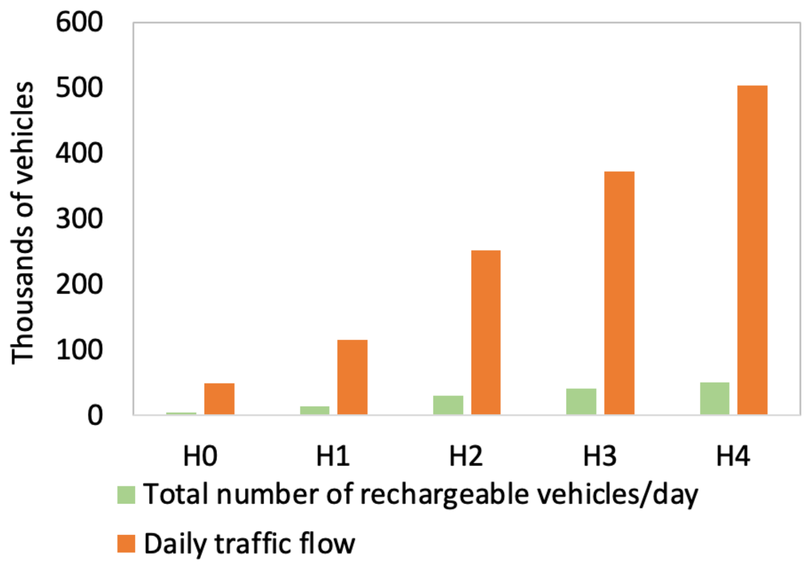


Figure 14. Daily rechargeable vehicle and traffic flow estimation.

From what has been estimated, this model would be able to support approximately 10% of the traffic circulating on the A1 motorway, making it an inefficient model. Finally, following the assumptions made, the capital expenditure statement for the implementation of the infrastructure was calculated (Figure 15).

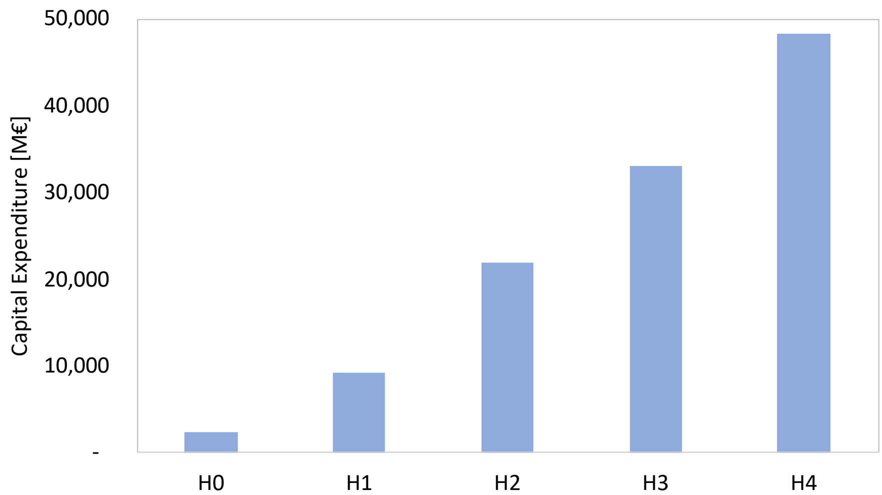


Figure 15. Capital expenditure for each time horizon in scenario 1.

5.2. Scenario 2

In scenario 2, eight CSs are considered for each of the selected spots. As mentioned, time horizon zero is the as-is scenario, where the seven CSs already present are located. The presence of eight CSs allows the charging of sixteen vehicles simultaneously. Figure 16 shows the growing trend of the charging infrastructure available in the different time horizons.

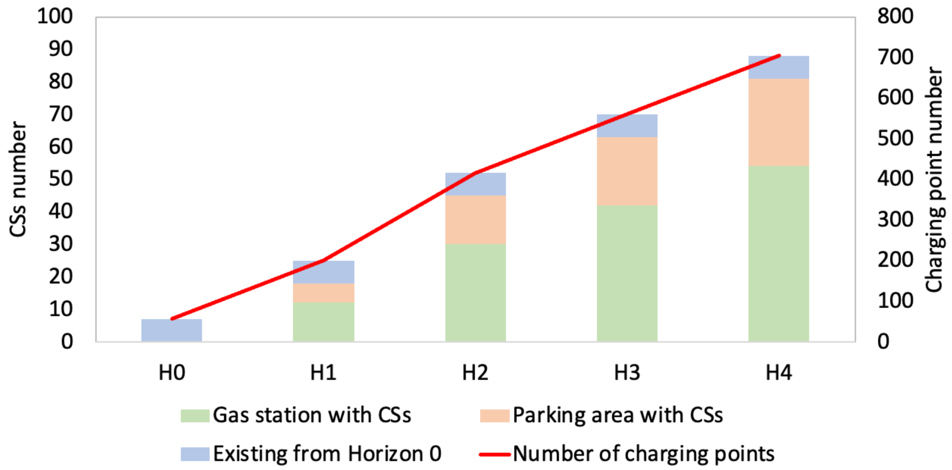


Figure 16. Spots and charging point estimation in scenario 2.

As in scenario 1, the maximum number of columns considered will be 88 (90% of 97), to protect against the possibility that some infrastructures are not built in time. Figure 16 also shows the number of charging points for each time horizon. Then, the charging power that the different points can provide is evaluated. Figure 17 shows the different charger types.

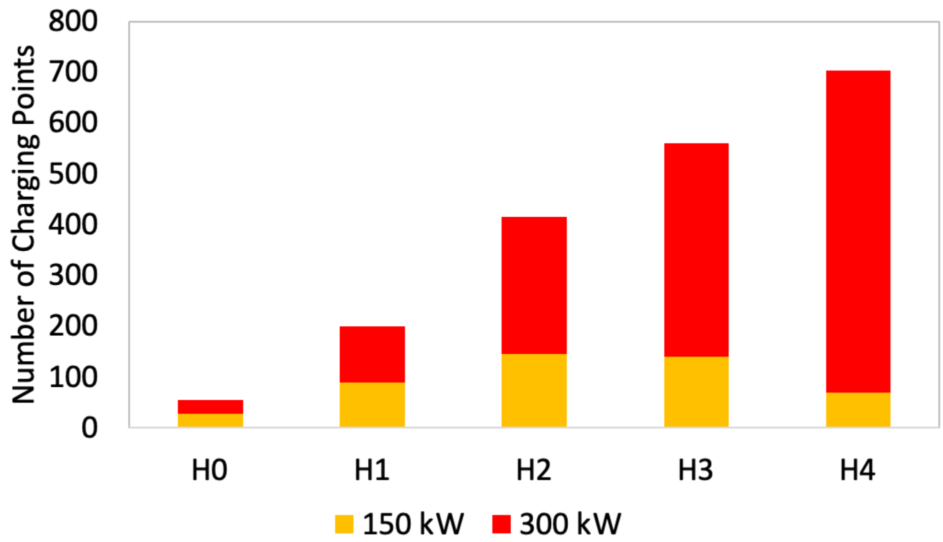


Figure 17. Charging type estimation, scenario 2.

Following the same assumptions made for scenario 1, the amount of rechargeable vehicles in a day is reported in the green column of Figure 18.

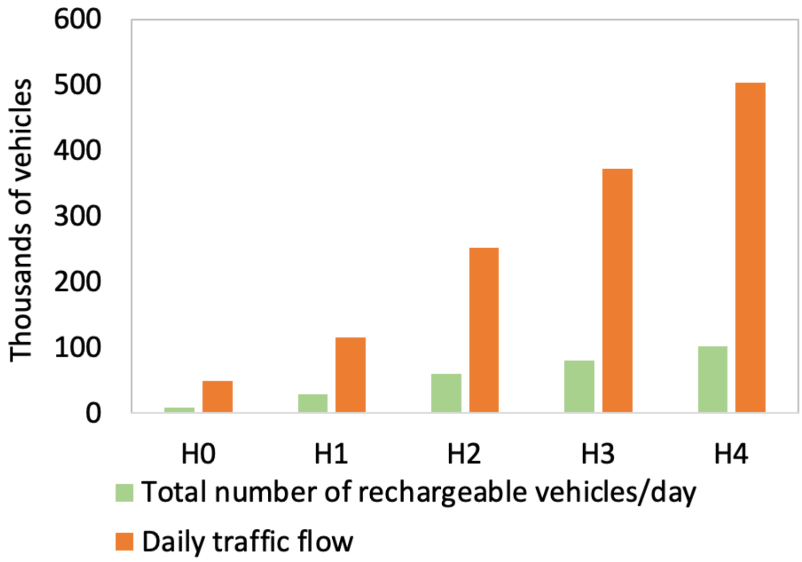


Figure 18. Daily rechargeable vehicles and traffic flow estimation, scenario 2.

From what has been estimated, this model would be able to support approximately 22% of the traffic circulating on the A1 motorway, making it a more efficient model than scenario 1, but still unreliable. Finally, following the assumptions made, the capital expenditure statement for the implementation of the infrastructure was calculated (Figure 19).

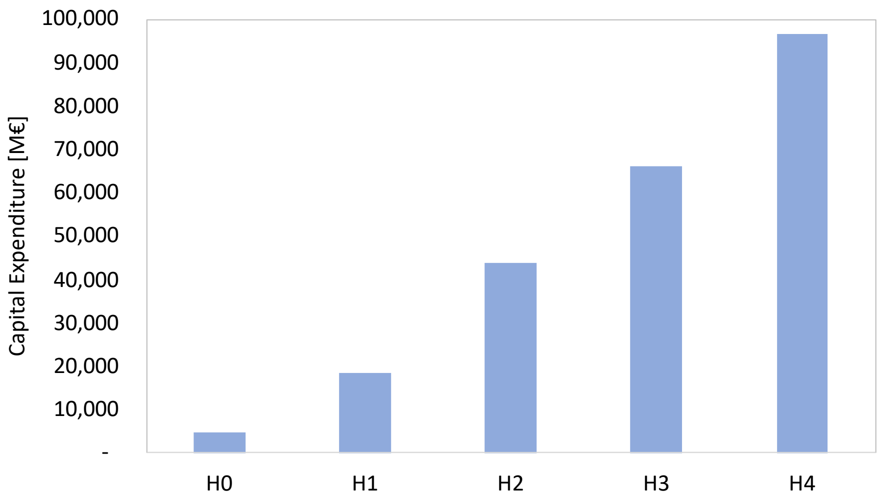


Figure 19. Capital expenditure for each time horizon in scenario 2.

5.3. Scenario 3

In scenario 3, 16 CSs are considered for each of the selected spots. As mentioned, time horizon zero is the as-is scenario, where the seven CSs already present are located. The presence of 16 CSs allows the charging of 32 vehicles simultaneously. Figure 20 shows the growing trend of the charging infrastructure available in the different time horizons.

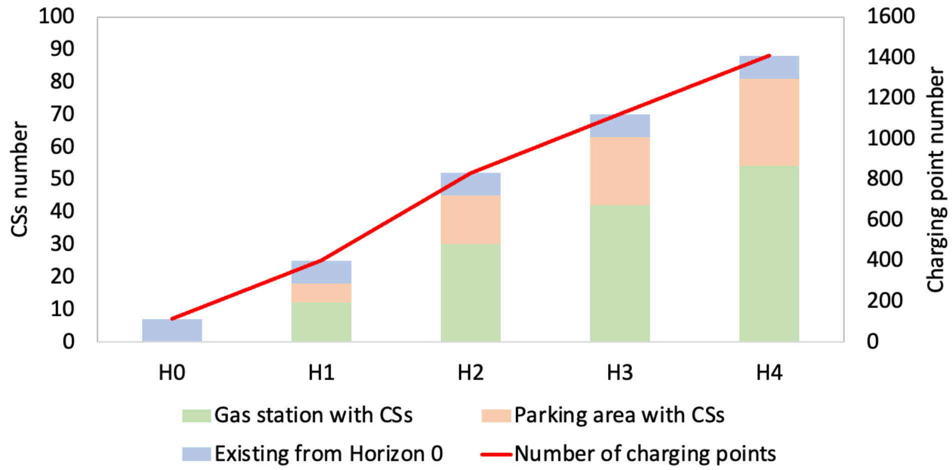


Figure 20. Spots and charging point estimation in scenario 3.

As in the previous scenarios, the maximum number of columns considered will be 88, to face the possibility that some infrastructures are not built in time. Figure 20 also shows the number of charging points for each time horizon. Then, the charging power that the different points can provide is evaluated. Figure 21 shows the different charger types.

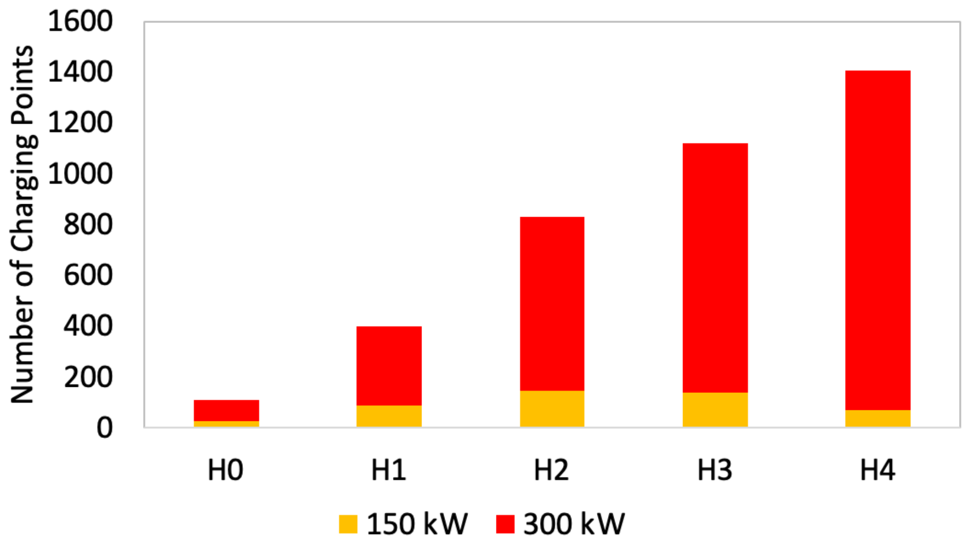


Figure 21. Charging type estimation, scenario 3.

Following the same assumptions made for scenario 1, the amount of rechargeable vehicles in a day is reported in the green column of Figure 22.

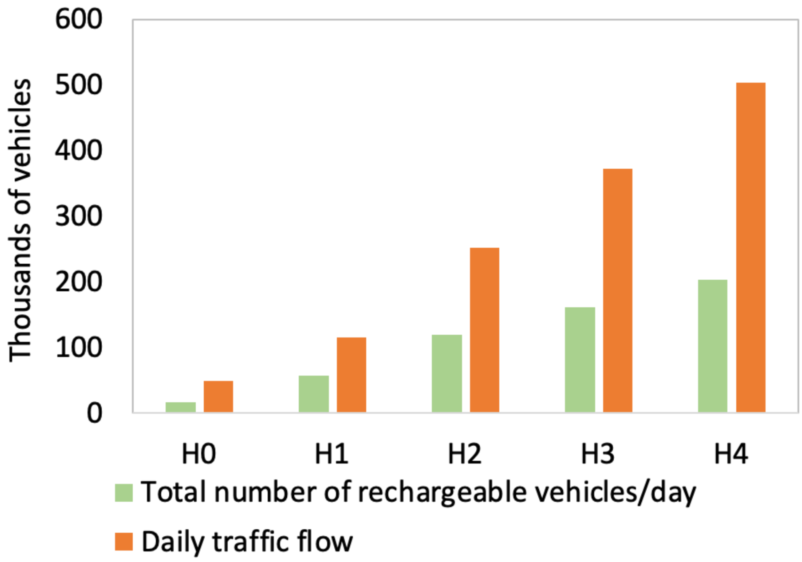


Figure 22. Daily rechargeable vehicle and traffic flow estimation, scenario 3.

From what has been estimated, this model would be able to support approximately 43% of the traffic circulating on the A1 motorway, making it efficient. Finally, following the assumptions made, the capital expenditure statement for the implementation of the infrastructure was calculated (Figure 23).

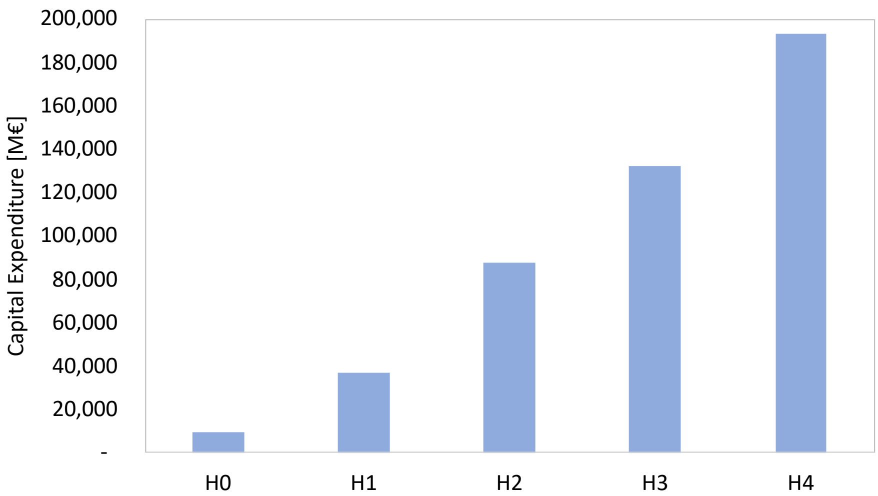


Figure 23. Capital expenditure for each time horizon in scenario 3.

5.4. Scenario 4

In scenario 4, 32 charging stations (CSs) are considered for each of the selected spots. As mentioned, time horizon zero is the as-is scenario, where the seven CSs already present are located. The presence of 16 CSs allows the charging of 64 vehicles simultaneously, making this scenario the one with the most aggressive electrification time horizons. Figure 24 shows the growing trend of the charging infrastructure available in the different time horizons.

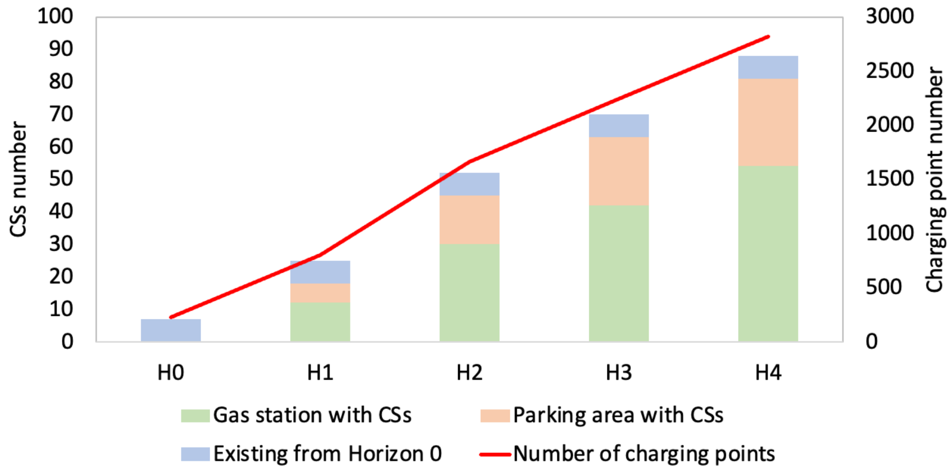


Figure 24. Spots and charging point estimation in scenario 4.

As in the previous scenarios, the maximum number of columns considered will be 88, to face the possibility that some infrastructures are not built in time. Figure 24 also shows the number of charging points for each time horizon. Then, the charging power that the different points can provide is evaluated. Figure 25 shows the different charger types.

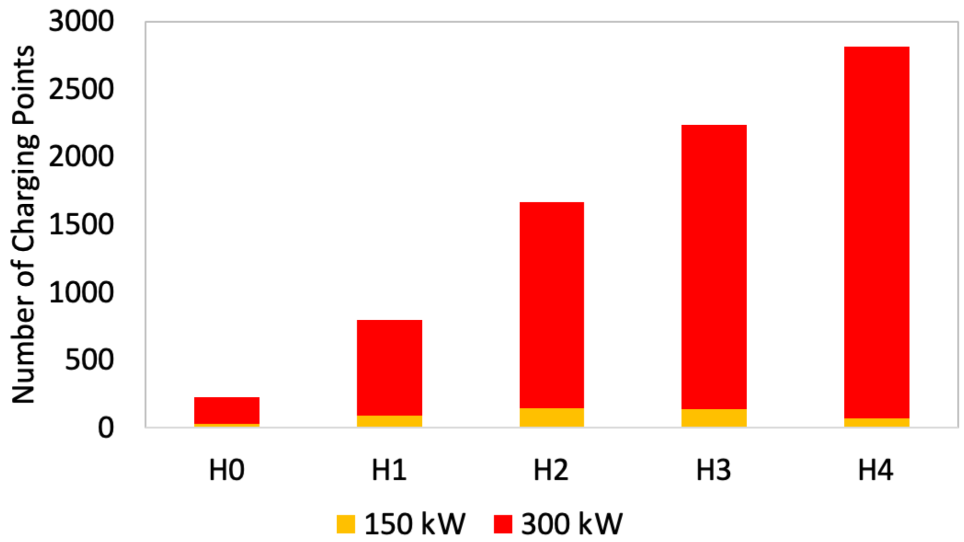


Figure 25. Charging type estimation, scenario 4.

Following the same assumptions made for the previous scenarios, the amount of rechargeable vehicles in a day are reported in the green column of Figure 26.

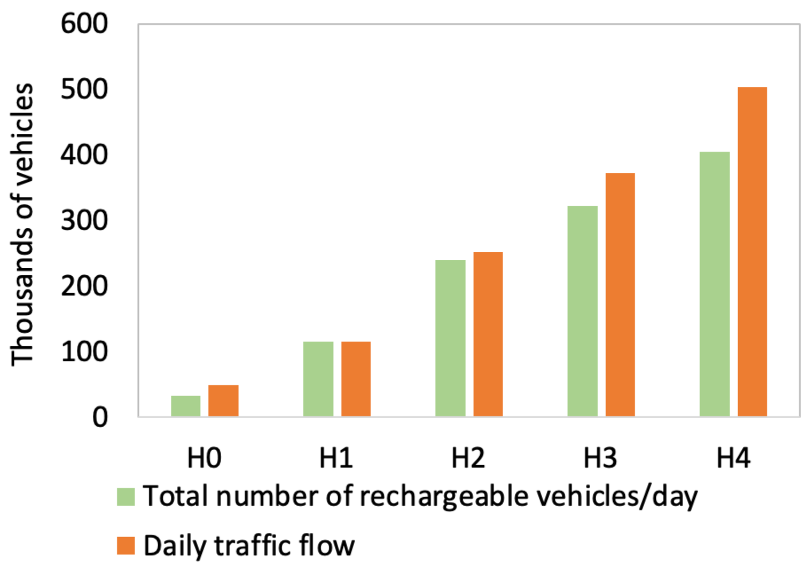


Figure 26. Daily rechargeable vehicle and traffic flow estimation, scenario 4.

From what has been estimated, this model would be able to support approximately 85% of the traffic circulating on the A1 motorway, making it the most effective scenario model. Finally, following the assumptions made, the capital expenditure statement for the implementation of the infrastructure was calculated (Figure 27).

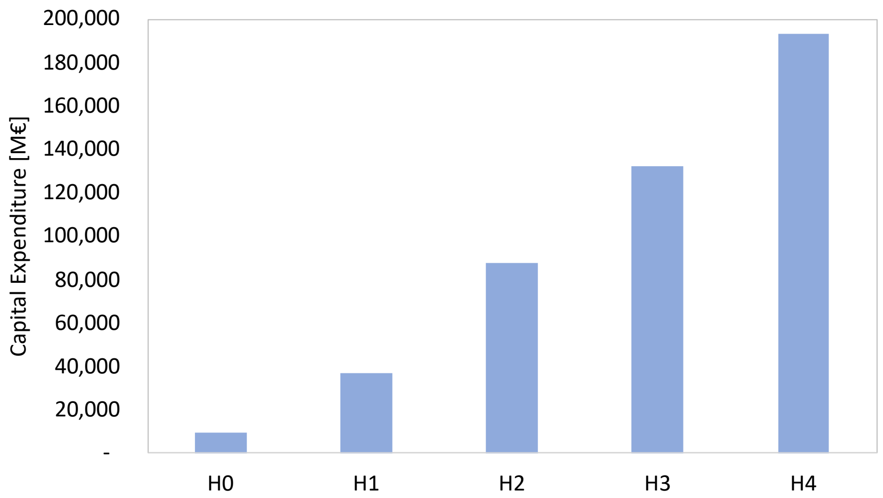


Figure 27. Capital expenditure for each time horizon in scenario 4.

5.5. Discussion

After examining four scenarios of electrification on the A1 motorway connecting Milan to Naples, classified into five time horizons, it is possible to carry out an analysis on the results produced. As reported, the four scenarios differed by the number of CSs for each spot on the motorway:

- Scenario 1: four CSs per spot;
- Scenario 2: eight CSs per spot;
- Scenario 3: 16 CSs per spot;
- Scenario 4: 32 CSs per spot.

Table 4 contains the results provided on the percentage of vehicles in the various time horizons for each scenario.

Table 4. Ratio between daily rechargeable vehicle and traffic flow estimation.

Scenario	Time H0	Time H1	Time H2	Time H3	Time H4
Scenario 1	8.18%	12.52%	11.89%	10.83%	10.86%
Scenario 2	16.36%	25.04%	23.77%	21.65%	20.12%
Scenario 3	32.72%	50.07%	47.55%	43.30%	40.23%
Scenario 4	65.43%	100.15%	95.10%	86.60%	80.47%

Taking traffic into consideration, Scenario 3 appears to be realistic and a good electrification compromise. In fact, it must be specified that cars with high autonomy can travel more than 300 km on a charge, without the need to charge several times on the motorway. Given the autonomy, the driver does not want to recharge, making the service unused by every passing vehicle. Scenario 3 will provide a service to 40.23% of vehicles in circulation by 2035, through 16 CSs for each spot. Similarly, Scenario 4 represents an appreciable solution for users, even if it would require investments of a completely different scale, looking at Figure 28. Therefore, the decision maker could identify it as an oversized solution. However, the identified case study only considers private car vehicles. Scenario 4 could no longer be oversized if the traffic also involved LDVs (Light-Duty Vehicles) or HDVs (Heavy-Duty Vehicles), and it would immediately become the best compromise.

Finally, considering the worst case of always-operating structures, an economic analysis based on the capital expenditure and the facility offered is estimated. Figure 28 offers an aggregate of the capital expenditure of the scenarios divided in time horizons.

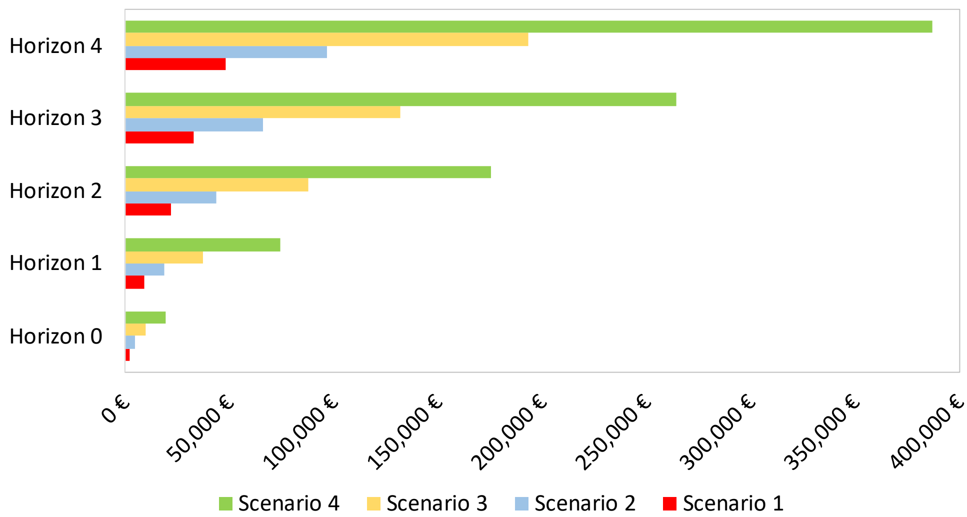


Figure 28. Capital expenditure for each scenario and each time horizon (data in millions of euros).

It should be underlined that the case study carried out is strictly dependent on some factors at a national and international level, such as the dependence of incentives and political strategies. However, several countries comply with the directives of a common body (i.e., European Community) and have similar markets in this area. Despite this limitation, this case study represents a motorway electrification model in order to identify an optimal scenario in which a specific amount of CSs are identified. Moreover, this case study relies on the fact that the grid is able to sustain the high electrification rate development, and the issue of instabilities related to massive electrification is neglected.

6. Conclusions

With the authorities' push towards the decarbonization of vehicles, through the electrification of private transport, it is estimated that the number of electric cars will soon reach a significant percentage of the market and fleet. This will lead to the need to expand the CSs network for these. To cope with these trends, the work proposes a model for the electrification of one of the main Italian motorways, the A1 from Milan to Naples with a length of about 800 km. The model combines descriptive elements, such as the motorway flow and the existing vehicle fleet, with predictive elements, obtained thanks to the global electrification trend. This process ends up proposing four scenarios of electrifications in different time horizons. Observing the Scenarios, it is clear that Scenario 4 is oversized compared to the traffic, also proposing a high expense for the infrastructure manager. In fact, as in the Scenario of ICE vehicles, it is not certain that all vehicles refuel on the motorway. In fact, for shorter journeys, drivers tend to refuel off the motorway as it is cheaper. On the contrary, Scenario 1 starts from modern state-of-the-art scenarios, but turns out to be undersized since, in the worst-case conditions considered, only 10% of EVs can refuel during a day. This result is a scenario that fuels the phenomenon of range anxiety, discouraging people from purchasing EVs, which are considered useful only for short trips. Considering the implementability and necessity of CSs, Scenario 3 seems to be the appropriate compromise for users. Furthermore, considering the market trend of EVs, in 2035, 80% of vehicles will be electric, so CSs will have to be able to keep up with the flow. Therefore, by further improving the charging performance and continuing decarbonization activities, it will be possible to reach the targets set by the authorities.

Author Contributions: Conceptualization, C.G.C., F.B., and M.L.; methodology, F.B., M.L., and F.F.; software, C.G.C.; validation, F.B. and M.L., formal analysis, C.G.C.; investigation, M.L. and F.F.; resources, C.G.C.; data curation, M.L.; writing—original draft preparation, C.G.C. and M.L.; writing—review and editing, F.B. and F.F.; visualization, M.L.; supervision, F.B. and M.L.; project administration, M.L.; funding acquisition, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This study was carried out within the MOST—Sustainable Mobility Center—and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4—D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors' views and opinions; neither the European Union nor the European Commission can be considered responsible for them.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. International Energy Agency (IEA). World Energy Outlook 2022. Available online: https://www.iea.org/t&c/ (accessed on 23 October 2023).
2. Arora, N.K.; Mishra, I. COP26: More challenges than achievements. *Environ. Sustain.* **2021**, *4*, 585–588. https://doi.org/10.1007/s42398-021-00212-7.
3. European Commission. Communication from the Commission, "The European Green Deal", Brussels 11 December 2019. EUR-Lex – 52019DC0640 – EN – EUR-Lex. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed on 23 October 2023).
4. European Commission. Communication from the Commission to the Aprile n Parliament, the Council, the Aprile n Economic and Social Committee and the Committee of the Regions, "Sustainable and Smart Mobility Strategy—Putting European Transport on Track for the Future", Brussels 9 December 2020. Available online: https://transport.ec.europa.eu/system/files/2021-04/2021-mobility-strategy-and-action-plan.pdf (accessed on 23 October 2023).
5. IEA. Transport, IEA, Paris. 2022. Available online: https://www.iea.org/reports/transport (accessed on 23 October 2023).
6. Peyravi, B.; Peleckienė, V.; Vaičiūtė, K. Research on the Impact of Motorization Rate and Technological Development on Climate Change in Lithuania in the Context of the European Green Deal. *Sustainability* **2022**, *14*, 11610. https://doi.org/10.3390/su141811610.
7. Stefaniec, A.; Hosseini, K.; Assani, S.; Hosseini, S.M.; Li, Y. Social sustainability of regional transportation: An assessment framework with application to EU road transport. *Socio-Econ. Plan. Sci.* **2021**, *78*, 101088. https://doi.org/10.1016/j.seps.2021.101088.
8. Maltese, I.; Gatta, V.; Marcucci, E. Active Travel in Sustainable Urban Mobility Plans. An Italian overview. *Res. Transp. Bus. Manag.* **2021**, *40*, 100621. https://doi.org/10.1016/j.rtbm.2021.100621.

9. Andoni, M.; Robu, V.; Flynn, D.; Abram, S.; Geach, D.; Jenkins, D.; McCallum, P.; Peacock, A. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renew. Sustain. Energy Rev.* **2019**, *100*, 143–174. https://doi.org/10.1016/j.rser.2018.10.014.
10. Sanguesa, J.A.; Torres-Sanz, V.; Garrido, P.; Martinez, F.J.; Marquez-Barja, J.M. A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities* **2021**, *4*, 372–404. https://doi.org/10.3390/smartcities4010022.
11. Lin, B.; Wu, W. Why people want to buy electric vehicle: An empirical study in first-tier cities of China. *Energy Policy* **2018**, *112*, 233–241. https://doi.org/10.1016/j.enpol.2017.10.026.
12. Husain, I.; Ozpineci, B.; Islam, M.S.; Gurpinar, E.; Su, G.-J.; Yu, W.; Chowdhury, S.; Xue, L.; Rahman, D.; Sahu, R. Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles. *Proc. IEEE* **2021**, *109*, 1039–1059. https://doi.org/10.1109/jproc.2020.3046112.
13. Yang, X.-G.; Wang, C.-Y. Understanding the trilemma of fast charging, energy density and cycle life of lithium-ion batteries. *J. Power Sources* **2018**, *402*, 489–498. https://doi.org/10.1016/j.jpowsour.2018.09.069.
14. Noel, L.; de Rubens, G.Z.; Sovacool, B.K.; Kester, J. Fear and loathing of electric vehicles: The reactionary rhetoric of range anxiety. *Energy Res. Soc. Sci.* **2019**, *48*, 96–107. https://doi.org/10.1016/j.erss.2018.10.001.
15. IEA. Global EV Outlook 2020, IEA, Paris. 2020. Available online: https://www.iea.org/reports/global-ev-outlook-2020 (accessed on 23 October 2023).
16. Unterluggauer, T.; Rich, J.; Andersen, P.B.; Hashemi, S. Electric vehicle charging infrastructure planning for integrated transportation and power distribution networks: A review. *eTransportation* **2022**, *12*, 100163. https://doi.org/10.1016/j.etran.2022.100163.
17. Hamdare, S.; Kaiwartya, O.; Jugran, M.; Brown, D.; Vyas, P. Analysis of EV charging infrastructure and its impact on public adoption: Examining the critical role of charging stations in the acceleration of electric vehicle market growth. In Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments, Corfu, Greece, 5–7 July 2023; pp. 550–556. https://doi.org/10.1145/3594806.3596586.
18. European Alternative Fuels Observatory. Charging Infrastructure Statistics. 2021. Available online: https://www.eafo.eu/alternative-fuels/electricity/charging-infra-stats (accessed on 23 October 2023).
19. Pelosi, D.; Longo, M.; Bidini, G.; Zaninelli, D.; Barelli, L. A new concept of highways infrastructure integrating energy storage devices for e-mobility transition. *J. Energy Storage* **2023**, *65*, 107364. https://doi.org/10.1016/j.est.2023.107364.
20. Napoli, G.; Polimeni, A.; Micari, S.; Andaloro, L.; Antonucci, V. Optimal allocation of electric vehicle charging stations in a highway network: Part 1. Methodology and test application. *J. Energy Storage* **2020**, *27*, 101102. https://doi.org/10.1016/j.est.2019.101102.
21. Wei, W.; Ramakrishnan, S.; Needell, Z.A.; Trancik, J.E. Personal vehicle electrification and charging solutions for high-energy days. *Nat. Energy* **2021**, *6*, 105–114. https://doi.org/10.1038/s41560-020-00752-y.
22. Golab, A.; Zwickl-Bernhard, S.; Auer, H. Minimum-Cost Fast-Charging Infrastructure Planning for Electric Vehicles along the Austrian High-Level Road Network. *Energies* **2022**, *15*, 2147. https://doi.org/10.3390/en15062147.
23. Girade, P.; Shah, H.; Kaushik, K.; Patheria, A.; Xu, B. Comparative analysis of state of charge based adaptive supervisory control strategies of plug-in Hybrid Electric Vehicles. *Energy* **2021**, *230*, 120856. https://doi.org/10.1016/j.energy.2021.120856.
24. Yang, C.; Zha, M.; Wang, W.; Liu, K.; Xiang, C. Efficient energy management strategy for hybrid electric vehicles/plug-in hybrid electric vehicles: Review and recent advances under intelligent transportation system. *IET Intell. Transp. Syst.* **2020**, *14*, 702–711. https://doi.org/10.1049/iet-its.2019.0606.
25. Stogios, C.; Kasraian, D.; Roorda, M.J.; Hatzopoulou, M. Simulating impacts of automated driving behavior and traffic conditions on vehicle emissions. *Transp. Res. Part D Transp. Environ.* **2019**, *76*, 176–192. https://doi.org/10.1016/j.trd.2019.09.020.
26. Ouyang, X.; Xu, M. Promoting green transportation under the belt and Road Initiative: Locating charging stations considering electric vehicle users' travel behavior. *Transp. Policy* **2022**, *116*, 58–80. https://doi.org/10.1016/j.tranpol.2021.11.023.
27. Cussigh, M.; Hamacher, T. Optimal charging and driving strategies for battery electric vehicles on long distance trips: A dynamic programming approach. In Proceedings of the 2019 IEEE Intelligent Vehicles Symposium (IV), Paris, France, 9–12 June 2019; pp. 2093–2098.
28. Pesch, T.; Allelein, H.-J.; Müller, D.; Witthaut, D. High-performance charging for the electrification of highway traffic: Optimal operation, infrastructure requirements and economic viability. *Appl. Energy* **2020**, *280*, 115706. https://doi.org/10.1016/j.apenergy.2020.115706.
29. Jakobsson, N.; Hartvigsson, E.; Taljegard, M.; Johnsson, F. Substation Placement for Electric Road Systems. *Energies* **2023**, *16*, 4217. https://doi.org/10.3390/en16104217.
30. Bischoff, J.; Marquez-Fernandez, F.J.; Domingues-Olavarria, G.; Maciejewski, M.; Nagel, K. Impacts of vehicle fleet electrification in Sweden—A simulation-based assessment of long-distance trips. In Proceedings of the 2019 6th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Krakow, Poland, 5–7 June 2019; pp. 1–7. https://doi.org/10.1109/MTITS.2019.8883384.
31. Wang, T.; Zhang, J.; He, J. Dynamic wireless charging lane reversal for connected and automated electric vehicles in highway. *Sustain. Energy Technol. Assess.* **2023**, *57*, 103206. https://doi.org/10.1016/j.seta.2023.103206.
32. Schwerdfeger, S.; Bock, S.; Boysen, N.; Briskorn, D. Optimizing the electrification of roads with charge-while-drive technology. *Eur. J. Oper. Res.* **2022**, *299*, 1111–1127. https://doi.org/10.1016/j.ejor.2021.08.045.

33. Colombo, C.G.; Miraftabzadeh, S.M.; Saldarini, A.; Longo, M.; Brenna, M.; Yaici, W. Literature review on wireless charging technologies: Future trend for electric vehicle? In Proceedings of the 2022 Second International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART), Cassino, Italy, 23–25 November 2022; pp. 1–5. https://doi.org/10.1109/SMART55236.2022.9990331.
34. Nguyen, V.C.; Wang, C.-T.; Hsieh, Y.-J. Electrification of Highway Transportation with Solar and Wind Energy. *Sustainability* **2021**, *13*, 5456. https://doi.org/10.3390/su13105456.
35. Colombo, C.G.; Longo, M.; Brenna, M. Sustainable Green Island in smart road: Case study applied on Italian highway network. In Proceedings of the 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Prague, Czech Republic, 28 June–1 July 2022; pp. 1–5.
36. Clairotte, M.; Zardini, A.; Martini, G.; European Commission Joint Research Centre. *Phase 1 of the Environmental Effect Study on the Euro 5 Step of L-Category Vehicles: Stocktaking and Data Mining*; Publications Office of the European Union: Luxembourg, 2016.
37. CEIC. Italy Motor Vehicles Sales Growth, 2006–2022|CEIC Data. Available online: https://www.ceicdata.com/en/indicator/April/motor-vehicles-sales-growth (accessed on 23 October 2023).
38. Münzel, C.; Plötz, P.; Sprei, F.; Gnann, T. How large is the effect of financial incentives on electric vehicle sales?—A global review and European analysis. *Energy Econ.* **2019**, *84*, 104493. https://doi.org/10.1016/j.eneco.2019.104493.
39. MOTUS-E. April 2022—The Car Market is Worse than May 2020—MOTUS-E. Available online: https://www.motus-e.org/analysis-di-mercato/Aprile-2022-mercato-peggio-maggio-2020 (accessed on 23 October 2023).
40. Energy Strategy. Smart Mobility Report 2022. 2022. Available online: www.energystrategy.it (accessed on 23 October 2023).
41. Mathilde Carlier. Annual Number of All-Electric Car Registrations in Italy from 2015 to 2021, 21 April 2022, Statista. Available online: https://www.statista.com/statistics/736809/electric-cars-registered-in-italy/ (accessed on 23 October 2023).
42. Rietmann, N.; Hügler, B.; Lieven, T. Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO2 emissions. *J. Clean. Prod.* **2020**, *261*, 121038. https://doi.org/10.1016/j.jclepro.2020.121038.
43. Ministero delle Infrastrutture e dei Trasporti PNire. *Piano Nazionale Infrastrutturale per la Ricarica dei Veicoli Alimentati ad Energia Elettrica*; Ministero delle Infrastrutture e dei Trasporti: Rome, Italy, 2015.
44. Rietmann, N.; Lieven, T. How policy measures succeeded to promote electric mobility—Worldwide review and outlook. *J. Clean. Prod.* **2019**, *206*, 66–75. https://doi.org/10.1016/j.jclepro.2018.09.121.
45. Meade, N.; Islam, T. Modelling and forecasting the diffusion of innovation—A 25-year review. *Int. J. Forecast.* **2006**, *22*, 519–545. https://doi.org/10.1016/j.ijforecast.2006.01.005.
46. Nicholas, M.; Wappelhorst, S. Preparing Italy's Charging Infrastructure for Rapid Vehicle Electrification. 2022. Available online: https://www.governo.it/sites/governo.it/files/PNire.pdf (accessed on 23 October 2023).
47. Jaržemskis, A.; Jaržemskienė, I. European Green Deal Implications on Country Level Energy Consumption. *Folia Oeconomica Stetin.* **2022**, *22*, 97–122. https://doi.org/10.2478/foli-2022-0021.
48. Tsiropoulos, I.; Siskos, P.; Capros, P. The cost of recharging infrastructure for electric vehicles in the EU in a climate neutrality context: Factors influencing investments in 2030 and 2050. *Appl. Energy* **2022**, *322*, 119446. https://doi.org/10.1016/j.apenergy.2022.119446.
49. Lanz, L.; Noll, B.; Schmidt, T.S.; Steffen, B. Comparing the levelized cost of electric vehicle charging options in Europe. *Nat. Commun.* **2022**, *13*, 5277. https://doi.org/10.1038/s41467-022-32835-7.