Developing the charging infrastructure for electric cars. Northwestern Italy facing European targets

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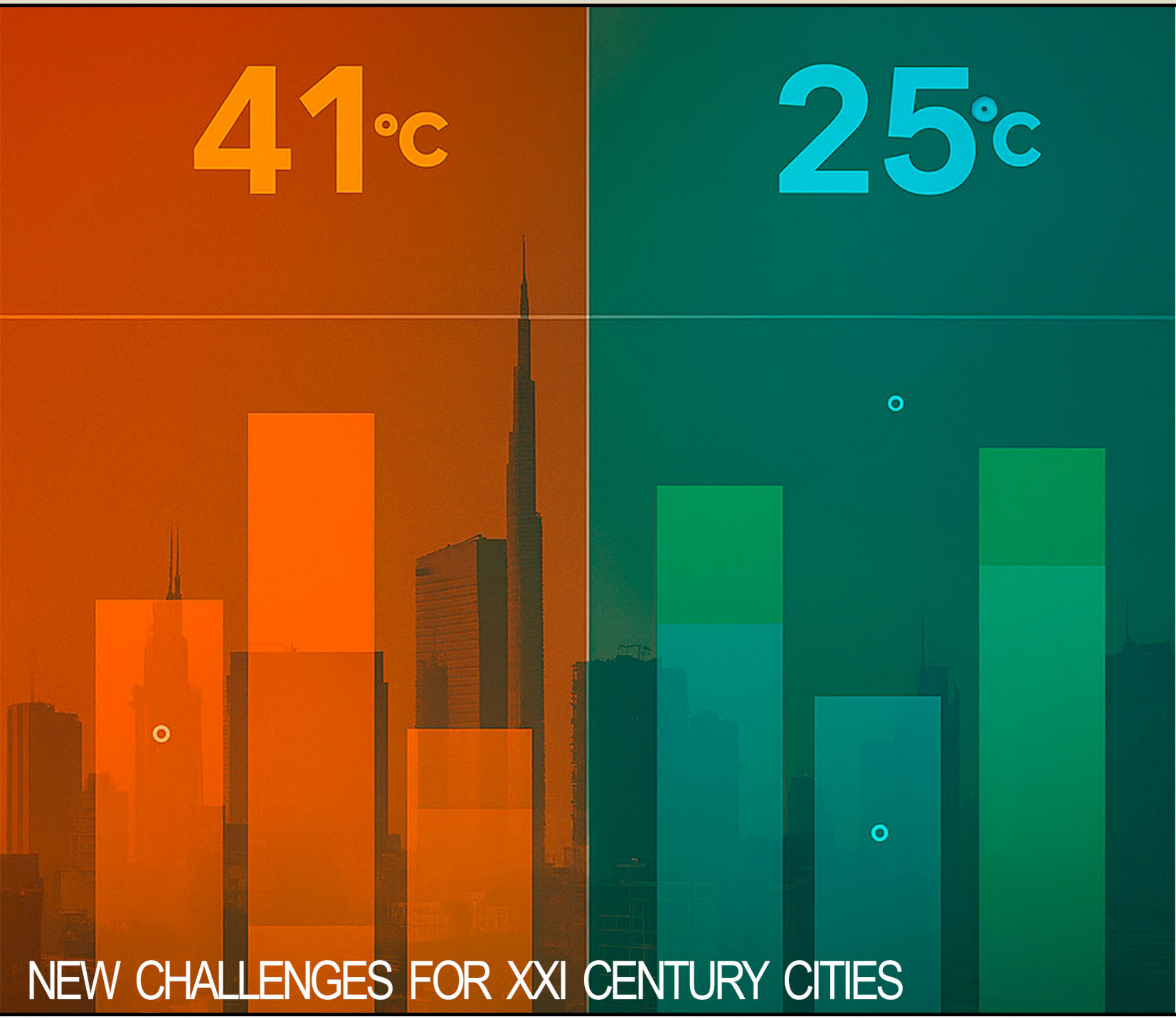

Multilevel scientific approach to impacts of global warming on urban areas, energy transition, optimisation of land use and emergency scenario

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Developing the charging infrastructure for electric cars. Northwestern Italy facing European targets

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Abstract

This paper analyzes the development of charging infrastructure for electric light-duty vehicles in northwestern Italy in relation to the targets set by EU Regulation 2023/1804. This regulation introduces two types of requirements for Member States: fleet-based targets, related to the number of registered electric and hybrid vehicles, and distance-based targets, which require adequate coverage along the TEN-T road network. Using data from national and European platforms, the study assesses the degree of alignment with these targets at the provincial levels. The results reveal a strong regional variation in infrastructure adequacy: while some provinces exceed the required power output, others - particularly in rural or mountainous areas - remain underpowered. Regarding the distance-based dimension, 71% of the TEN-T core network and 54% of the comprehensive network already meet the 2027 EU targets. The paper applies a Greedy optimization algorithm to propose cost-effective upgrade strategies for existing charging pools, showing that full compliance is achievable with limited interventions. The discussion highlights the critical role of policy incentives and governance, emphasizing the need to empower regional authorities and rebalance funding between vehicle acquisition and infrastructure development. The study concludes by offering policy recommendations to foster equitable and sustainable deployment of electric mobility infrastructure.

Keywords

Charging infrastructure; Electric light-duty vehicles; TEN-T road network

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1. Introduction

As repeatedly stated in the *Review notes* section of this Journal about "International Regulations and Legislation for the Energy Transition" (see, for example, Martinelli, 2024, 2025), electric vehicles (EVs) are increasingly recognized as a key component in the transition toward urban sustainability. By eliminating tailpipe emissions, EVs directly address the pressing need to mitigate climate change and reduce pollution-related health issues in densely populated areas (Aijaz & Ahmad, 2022).

However, their actual sustainability depends on several critical factors (De Vos, 2024; Tilly et al., 2024). For example, the environmental impact of battery production raises concerns about resource extraction and energy-intensive manufacturing processes (Ahmadzadeh et al., 2025). Second, coupling the adoption of EVs with a transition to clean and renewable energy sources is essential to maximize environmental benefits; in regions where electricity is predominantly produced from fossil fuels, the net reduction in emissions achieved by EVs may be less significant (Jansen & Petrova, 2023). In addition, the integration of EVs into existing transport systems needs to be approached with broader, multifaceted urban mobility strategies in mind. Over-reliance on private EVs without complementary investments in public transport and active mobility solutions may not effectively address issues such as traffic congestion and urban sprawl (Hensher, 2021; Orsi, 2021).

Moreover, the adoption of EVs is intricately linked to the availability and accessibility of charging infrastructure. This relationship is often characterized as a "chicken-and-egg" dilemma: is it the development of charging stations that drive EV uptake, or the increase in EV ownership that stimulates the expansion of charging networks? Consumers are reluctant to adopt EV technology without adequate charging infrastructure, and companies are reluctant to invest in such infrastructure without a sufficient numbers of EV in operation. This problem can hinder the diffusion of EVs and prolong the timeframe over which the existing fossil fuel technology system remains locked-in (Brozynski & Leibowicz, 2022).

A robust charging infrastructure alleviates range anxiety (a primary concern for potential EV buyers) by ensuring that drivers have reliable access to charging facilities (Viola, 2021). Empirical studies have demonstrated a positive correlation between the density of charging stations and EV adoption rates. For instance, research conducted in Sweden indicates that municipal expansion of charging infrastructure effectively increases the share of EVs. The study suggests that public charging points in rural municipalities should be strategically placed along high-traffic routes to mitigate range anxiety, while in urban areas, chargers should be placed close to residences to compensate for limited home charging options (Egnér & Trosvik, 2018).

Conversely, the proliferation of EVs can spur the development of charging infrastructure. As the number of EV users increases, so does the demand for accessible charging solutions, prompting the public and private sectors to invest in expanding the charging network.

A study that analyzed data from 95 Chinese cities between 2018 and 2022 found a bidirectional relationship between EV sales and the construction of public charging pools. The research indicates that while the availability of charging stations positively influences EV adoption, the increase in the number of EVs drives the expansion of charging infrastructure, creating a reinforcing cycle that supports the growth of the EV market (Guo et al., 2024).

The article focuses on one side of this two-sided relationship.

It aims to examine the extent to which the targets set by the European Union to its Member States regarding the quantity and spatial distribution of charging stations for duty-light EVs are already met or still far from being met in northwestern Italy. To develop this analysis, the article is structured in the following order.

First, Section 2 presents the policies and the targets set by the European Union. In Section 3, the aim of the article, the selected case study and the methodology adopted for its analysis are described. Sections 4 and 5 are devoted to the overview and discussion of the results.

2. The policy of the European Union for charging infrastructure dedicated to electric light-duty vehicles

In the 2011 White Paper "Roadmap to a Single European Transport Area. Towards a Competitive and Resource Efficient Transport System", the European Commission committed to reducing greenhouse gas emissions from transport by 60% by 2050 (compared to 1990 levels); this target was to be achieved by pursuing a 10% market share target of renewables in transport fuels such as electricity, hydrogen, biofuels, natural gas etc. However, until then the lack of a harmonized Union-wide infrastructure for alternative fuels had hindered the market introduction of vehicles using these alternative fuels. A coordinated policy framework from all Member States proved necessary to provide the long-term security needed for private and public investment to build-up the infrastructure for these vehicles. Therefore, in 2014 the European Union adopted Directive 2014/94/EU specifically to commit each Member State to define a national policy framework for the development of the alternative fuel market in the transport sector and the deployment of related infrastructure. Each State was required to assess the current state and future development of its alternative fuels infrastructure in the transport sector; based on this assessment, the State was supposed to set national targets and objectives for the deployment of the alternative fuels infrastructure, as well as measures to achieve them.

However, Directive 2014/94/EU did not propose a clear common methodology for setting these targets and adopting measures within the national policy frameworks of Member States. This has resulted in large differences in the level of ambition among Member States, and a consequent uneven development of charging and refueling infrastructure across the Union. In addition, meanwhile, the Renewable energy Directive 2023/2413 had raised the market share target for renewable fuels in transport to 29%.

In order to overcome the fragmented level of supply of alternative fuel infrastructure within the Union, and at the same time pursue the higher market share recently set for these fuels, a new Regulation (2023/1804) was adopted in 2023. This Regulation explicitly set mandatory national targets for the implementation of sufficient alternative fuel infrastructure in the Union for road vehicles, trains, ships and stationary aircraft.

In this article, the focus will be on light-duty EVs[1]. In this case, the targets set by the Regulation are twofold: national fleet-based and distance-based. National fleet-based targets should ensure that uptake of light-duty EVs in each Member State is matched by the deployment of sufficient (in terms of total power output[2]) publicly accessible charging infrastructure. Distance-based targets should ensure full coverage of charging pools[3] along the Union's TEN-T (TransEuropean Network - Transport) road network and thus the ability to travel easily and seamless throughout the Union. The goal is to ensure that these pools are deployed proportionally to the uptake of the EVs and that they provide sufficient power output.

Regarding the national fleet-based target, the Regulation requires each Member State to cumulatively provide, through publicly accessible charging pools, at the end of each year starting in 2024, a total power output of

1 "Light-duty vehicle" means a Category M1 (motor vehicles designed and constructed primarily for the carriage of passengers and their luggage, with not more than eight seating positions in addition to the driver's seating position and without space for standing passengers, regardless of whether the number of seating positions is restricted to the driver's seating position) or a Category N1 (motor vehicles designed and constructed primarily for the carriage of goods, with a maximum mass not exceeding 3,5 tonnes) motor vehicle as described by Regulation (EU) 2018/858. They can be battery electric vehicles or plug-in hybrid vehicles. Battery electric vehicle means an electric vehicle that runs exclusively on the electric motor, with no secondary source of propulsion. Plug-in hybrid vehicle means an electric vehicle with a conventional combustion engine combined with an electric propulsion system which can be recharged from an external electric power source.

2 "Power output" means the theoretical maximum power, expressed in kW, that a charging point, station or pool can provide to vehicles connected to that charging point, station or pool.

3 "Charging pool" means one or more charging stations at a specific location. A charging station is a physical installation at a specific location, consisting of one or more charging points. A charging point is defined as a fixed or mobile, on-grid or off-grid interface for the transfer of electricity to an electric vehicle which, although it may have one or more connectors to accommodate different connector types, is capable of charging only one electric vehicle at a time, and which excludes devices with a power output less than or equal to 3,7 kW the primary purpose of which is not the charging of electric vehicles.

at least 1.3 kW for each light-duty battery EV registered in its territory, and a total power output of at least 0.80 kW for each light-duty plug-in hybrid vehicle[4].

Regarding the distance-based target, according to the Regulation Member States must ensure a minimum coverage on the TEN-T road network in their territory through an appropriate spatial distribution of charging pools. The targets are differentiated for the entire TEN-T road network and for its core section[5]. Along the core network (i.e., located on the TEN-T road network or within 3 km driving distance of the nearest exit of a TEN-T road), accessible charging pools must be provided publicly in each direction of travel with a maximum distance of 60 km between them. Each pool has to offer:

- by 31 December 2025, a power output of at least 400 kW, including at least one charging point with an individual power output of at least 150 kW;
- by 31 December 2027, a power output of at least 600 kW, including at least two charging points with an individual power output of at least 150 kW.

Along the TEN-T comprehensive road network, in each direction of travel with a maximum distance of 60 km between them, charging pools have each to provide:

- by 31 December 2027, a power output of at least 300 kW, including at least one charging point with an individual power output of at least 150 kW along at least 50 % of the length of the TEN-T comprehensive road network;
- by 31 December 2030, the same target has to be extended to the whole network;
- by 31 December 2035, a power output of at least 600 kW, including at least two charging points with an individual power output of at least 150 kW.

3. Aim, case study and methodology

3.1 Aim and case study

The article aims to analyze what is the current supply of charging infrastructure for light-duty EVs in the northwestern part of Italy, compared to the targets set by the European Regulation 2023/2413. As mentioned earlier, this Regulation introduced equal targets throughout the European Union, which therefore can be more or less difficult to achieve in the coming years depending on the 2023 starting level.

In this sense, Italy is an interesting case. It is the penultimate State in the European Union in terms of the number of charging points per capita (9.2 per 10,000 inhabitants); only Spain does worse (8.9), while the Netherlands come in at 101, Norway at 55, Belgium, at 64, France at 23, Germany at 18. If the number of charging points is weighted by the fleet of battery EVs, Italy performs better (it is fourth in the EU with 19.25 charging points per 100 battery EVs, after the Netherlands with 33.8, Belgium with 26.3 and Spain with 23.4), but only because it is the last country in terms of the share of battery light-duty EVs in the entire fleet (0.54%) (Motus-E, 2025). In this context, the northwestern regions of Italy (Valle d’Aosta, Piedmont, Liguria and Lombardy) offer a - relatively - rich charging infrastructure. They are home to 35.5% of the total national charging points and 34.2% of the total national light-duty EVs, compared to 25.7% of the total light-duty vehicles registered in Italy and 27% of the total Italian population.

[4] The Regulation specifies that, if the share of light-duty battery electric vehicles compared to the total fleet of light-duty vehicles registered in the territory of a Member State reaches at least 15% and the Member State demonstrates that the implementation of the requirements set out for the total power output can have the adverse effect of discouraging private investments, that Member State may submit to the Commission a reasoned request for authorization to apply lower requirements.

[5] According to the Regulation 1315/2013, the core network consist of those parts of the comprehensive network which are of the highest strategic importance for achieving the objectives for the development of the trans-European transport network. The Regulation identifies both the comprehensive TEN-T and core section.

3.2 Methodology

Fleet-based targets

To verify the fleet-based targets the number of total, battery and hybrid light-duty vehicles in Italy at the national, regional (NUTS-2) and provincial (NUTS-3) levels was first obtained from the database compiled by the Automobil Club d'Italia. The available data were updated to 31/12/2023. Next, data on the total power output of each charging pool were collected from the so-called PUN (Piattaforma Unica Nazionale), the Italian on-line platform (https://www.piattaformaunicanazionale.it) which allows citizens, companies and public administrations to visualize the location, type of access (public, restricted, private) and power output of each pool (even if not all the pools are included[6]). These data were aggregated at the provincial level to calculate the total power output available for electric and hybrid light-duty vehicles in each province in the study area and compare it with the target set by the European Union.

Distance-based targets

Regulation 2023/1804 set distance-based targets to cover the entire TEN-T road network and its core section through appropriate spatial distribution of charging points. Several academic methodologies have been developed to determine the optimal placement of EV charging points along a road network. Micari et al. (2017) adopt a methodology to calculate the necessary number of EV charging points and to determine their location in a road network using demand (the flow of EVs) and supply (the road network where they will be placed). A multi-criteria approach is proposed by Skaloumpakas et al. (2022) to take into account EV range and investment costs, and by Janjić et al. (2023) to also consider walking distances, site safety, parking access, and capacity of the electrical distribution network. Gopalakrishnan et al. (2016) integrate a Canonical Correlation Analysis to predict demand for charging points at candidate sites with a mixed-packing-and-covering optimization framework to model the competing concerns of the service provider and EV users. Lamontagne et al. (2023) use stochastic discrete choice models optimize the placement of charging points based on user attributes and preferences for station characteristics. Torres Franco (2021) proposes a heuristic algorithm for locating charging stations by considering user preferences and constraints. Based on Lam et al. (2014), who compared four solution methods to address the EV charging station placement problem (EVCSPP), we formulated our problem as a minimum upgrade coverage problem on a road network graph with existing nodes (stations) and varying service levels (charging power). To solve it, we adopted a Greedy approximation approach, which provides a near-optimal solution with significantly less computation (Cormen et al., 2014).

First, we checked whether and how far the EU's targets are already met in the case study (as of 31/12/2023), through this sequence of steps:

1. the motorways included in the comprehensive TEN-T road network and its core section were identified from Regulation 1315/2013 maps; their bi-directional routes were geo-referenced from OpenTransportMap and their carriageways were splitted, so to calculate 60 km spacing in each direction;
2. filling petrol stations currently located along (and accessible from) the motorways of the TEN-T were downloaded from OpenStreetMap;
3. the motorway exits of the TEN-T were downloaded from OpenStreetMap, and an isochrone of 3 km driving (network, not Euclidean) distance around each of these exits was drawn using the Plug in HERE route API (Fig.1);
4. public charging pools located at one of the existing filling petrol stations along the TEN-T road network or within one of the isochrones around the network exits were identified from Data Retrieval Platform

[6] https://www.lautomobile.aci.it/attualita/pun-in-arrivo-i-prezzi-e-possibili-agevolazioni-per-la-ricarica-delle-auto-elettriche/

(https://docs.eco-movement.com/guides/data-retrieval-platform/). For each of them, information was collected about the number of public charging points offered and the power output of each charging point; this information provided insight into whether the pool already met the criteria of the Regulation (e.g., as required by December 2025, a power output of at least 400 kW, including at least one charging point with an individual power output of at least 150 kW);

5. segments of the TEN-T road network between two charging pools (located at a filling petrol station along the network or within a 3-km isochrone around a motorway exit) that meet the standards of the Regulation but are more than 60 km apart in each direction of travel were identified, and their total length was measured in order to calculate the percentage of the core and comprehensive network covered by the service.

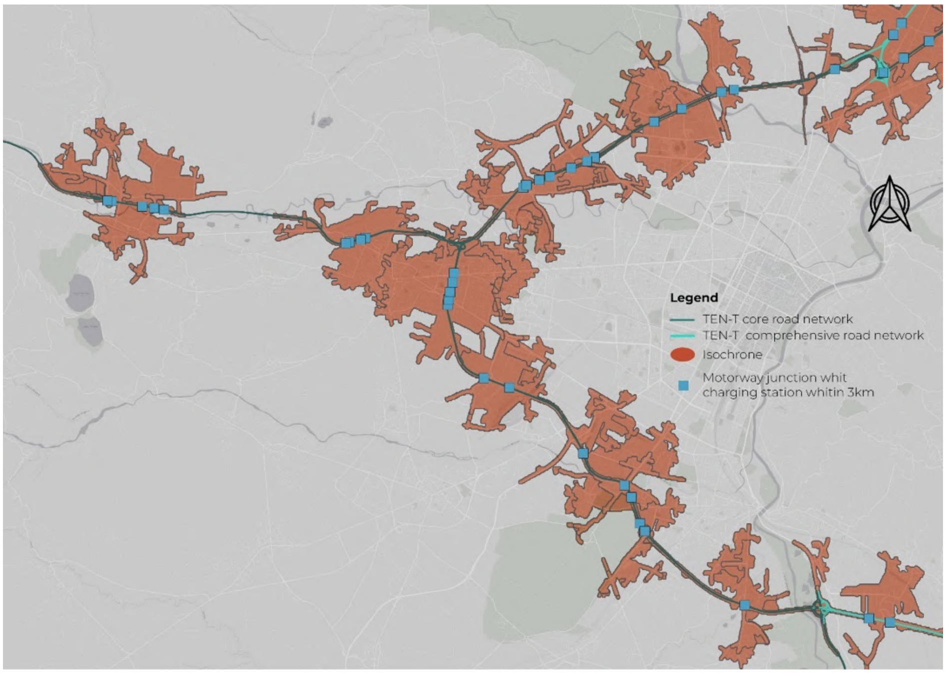

Fig.1 3-km isochrones of the TEN-T motorway exits around the city of Turin

To identify the minimum number of existing charging pools to be upgraded and/or new ones to be placed along the network, the Greedy approximation was applied through this sequence of steps:

1. all unserved segments of the TEN-T road network were identified;
2. for each existing charging pools that does not meet the standards of the Regulation in terms of power output, the number of km of unserved segments it could cover if it were upgraded was calculated;
3. at each filling petrol station and isochrone without a charging pool, the number of km of unserved segments it could cover if it were equipped with a new charging pool was calculated;
4. the existing or new pool covering the greatest number of km of unserved segments was upgraded or installed;
5. this procedure was repeated until all road segments were covered.

In other words, the objective function aims to maximize the additional length of unserved segments covered at each iteration. Formally:

$$\text{choose } p^* = \arg max_{p \in P_{candidates}} \sum_{s \in U} lenghth(s) * 1[p \text{ covers } s] \tag{1}$$

where:

- p = a candidate pool (existing pool to upgrade or new one to install)
- $P_{candidates}$ = set of candidate pools
- U = set of unserved segments

- 1[·] = 1 if true, 0 otherwise
- length(s) = length (km) of segment s

4. Results

4.1 Fleet-based target

At the end of 2023, the light-duty vehicle fleet in Italy consisted of 40,915,229 units. Those battery electric were 219,540, accounting for 0.54% of the total fleet. Those hybrid were 2,211,934, accounting for 5.4% of the fleet. At the regional level, the percentage of electric and hybrid vehicles on the total fleet is much higher: for example, it reaches 23.8% and 18.2% in the Alpine regions of Valle d'Aosta and Trentino Alto Adige; in other regions it is less than 3%, for example in Campania (2.1%) and Molise (2.25%).

Province	Number of electric vehicles	Number of hybrid vehicles	Number of electric and Hybrid vehicles	Total power output delivered (kW)	Total power output required by Reg 2023/1804
Alessandria	1,021	15,411	16,432	30,348	13,656
Aosta	4,343	62,677	67,020	20,062	55,788
Asti	554	6,732	7,286	7,116	6,106
Bergamo	4,840	40,915	45,755	44,946	39,024
Biella	439	7,404	7,843	13,390	6,494
Brescia	6,483	43,061	49,544	50,558	42,877
Como	3,213	31,745	34,958	20,238	29,573
Cremona	1,345	13,382	14,727	10,740	12,454
Cuneo	2,004	22,111	24,115	18,145	20,294
Genova	1,544	29,857	31,401	21,053	25,893
Imperia	377	6,280	6,657	8,207	5,514
La Spezia	555	7,598	8,153	10,273	6,800
Lecco	1,538	14,681	16,219	7,461	13,744
Lodi	742	8,102	8,844	3,763	7,446
Mantova	1,325	12,715	14,040	16,357	11,895
Milano	14,474	164,448	178,922	111,689	150,375
Monza e della Brianza	3,921	42,388	46,309	28,619	39,008
Novara	1,304	15,508	16,812	22,245	14,102
Pavia	1,489	21,475	22,964	14,227	19,116
Savona	536	9,510	10,046	18,570	8,305
Sondrio	675	6,013	6,688	8,412	5,688
Torino	8,332	125,111	133,443	93,340	110,920
Varese	4,260	45,891	50,151	21,321	42,251
Verbano-Cusio-Ossola	431	5,781	6,212	10,780	5,185
Vercelli	497	6,776	7,273	7,007	6,067

Tab.1 Electric and hybrid light-duty vehicle fleet and total power output delivered and required in northwestern Italian provinces

In the regions of northwestern Italy, which are the case study of these paper, the regional percentage is always above 6.5%. If we consider the provinces in these regions, the percentage of electric and hybrid vehicles varies approximately from 5 to 10% (except for Valle d'Aosta, where the regional and provincial boundaries coincide). Relating the total power output delivered in each province to the target set by the

European regulation (1.3 kW per electric vehicle plus 0.8 kW per hybrid vehicle; see Tab.1), the situation is very different, as shown in Fig.2. In the Piedmont provinces of Alessandria and Biella and the Ligurian province of Savona, the current power output is more than double the target. In contrast, in Valle d'Aosta output is a third of the target; in the Lombard provinces of Lodi and Lecco it is close to half.

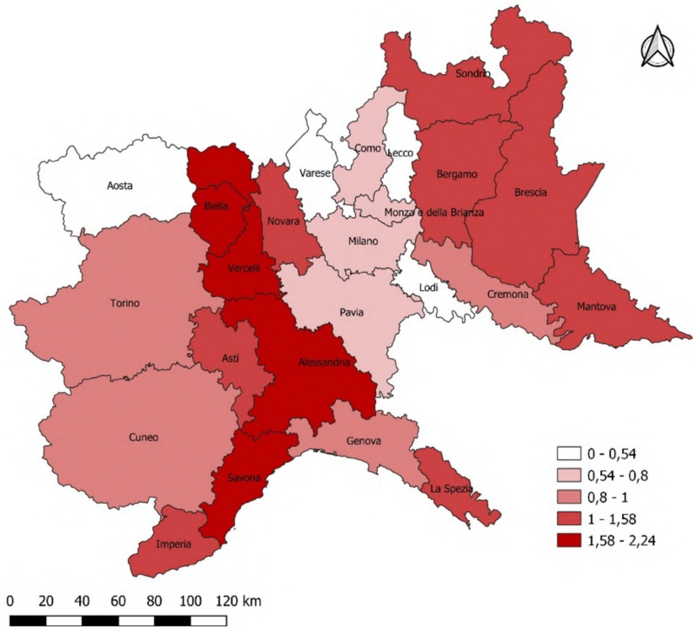

Fig.2 Ratio between total power output currently provided and the target set by the European Regulation

4.2 Distance-based target

The TEN-T road network located within the study area is 2,039 km long in its core section and 1,649 km in the rest of its comprehensive length (Fig.3).

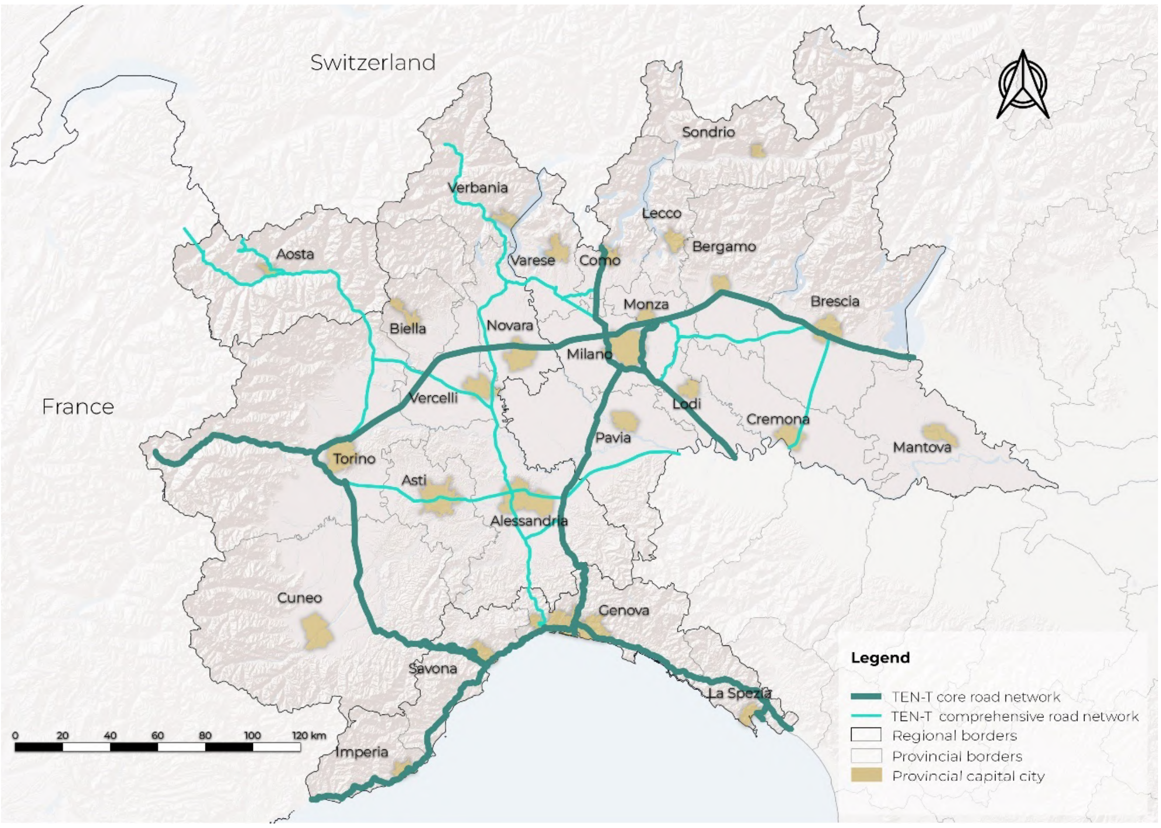

Fig.3 TEN-T core and comprehensive road network. Source: elaboration by the authors

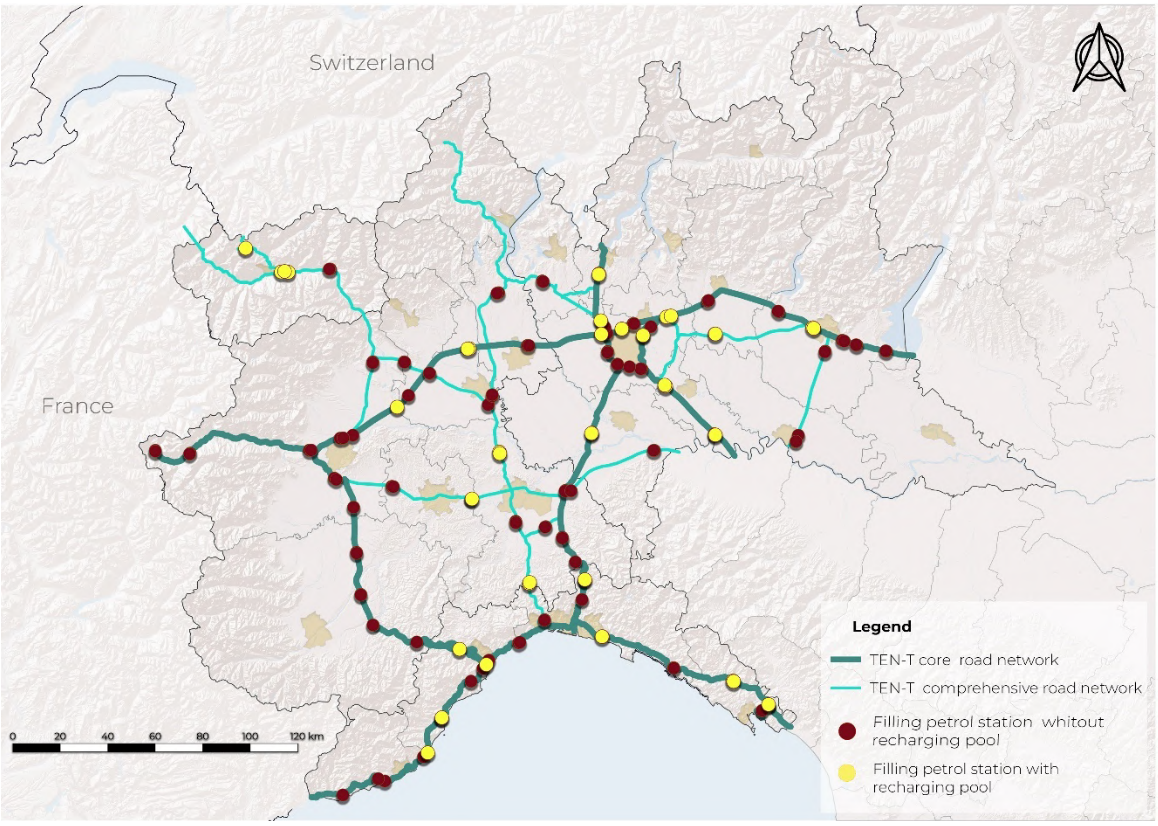

Fig.4 Filling petrol stations along the TEN-T core and comprehensive road network

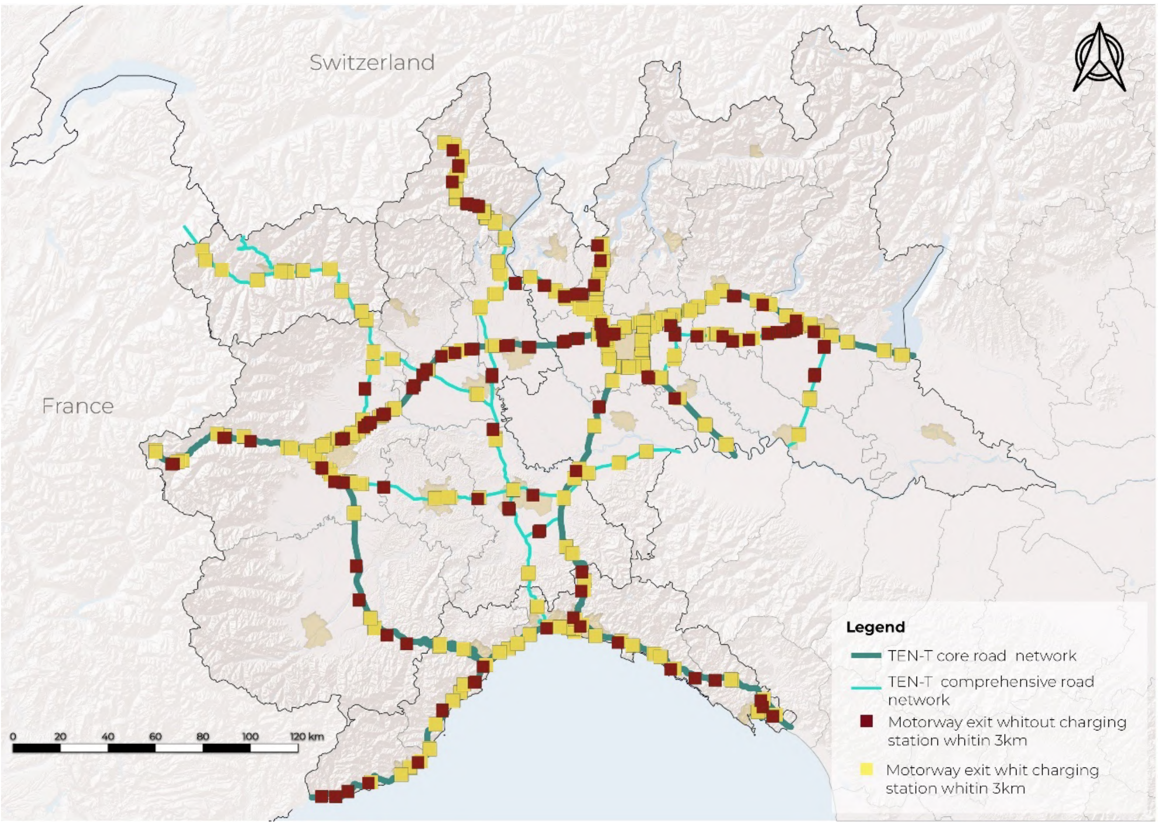

Fig.5 Motorway exits along the TEN-T core and comprehensive road network

Along the TEN-T core road network (Fig.ss 4 and 5) there are 95 filling petrol stations (27 of which offer at least one charging pool) and 344 exits (253 of which offer at least one recharging pool within 3 km of the exit). Along the rest of the comprehensive network, there are another 42 filling petrol stations (10 of which have at least one charging pool) and 176 exits (121 of which have at least one charging pool within 3 km).

In total, along the core TEN-T network drivers can currently reach 712 charging pools, for a total of 2,502 charging points and a power output of 171,995 kW. Of these 712 pools, 20 located at filling petrol stations already meet the standards set by the Regulation for both the end of 2025 (i.e., having a power output of at least 400 kW, including at least one charging point with an individual power output of at least 150 kW) and the end of 2027 (i.e. having a power output of at least 600 kW, including at least two charging points with an individual power output of at least 150 kW). Within 3 km of the exits, another 676 pools already meet the Regulation standards for 2025, and another 49 for 2027. The result is that, by the end of 2023, 71% of the core TEN-T network is already covered by these charging pools, meaning that in this portion of the network drivers can reach a charging pool anywhere (meeting the required standards by 2025) by travelling less than 60 km (Fig.6).

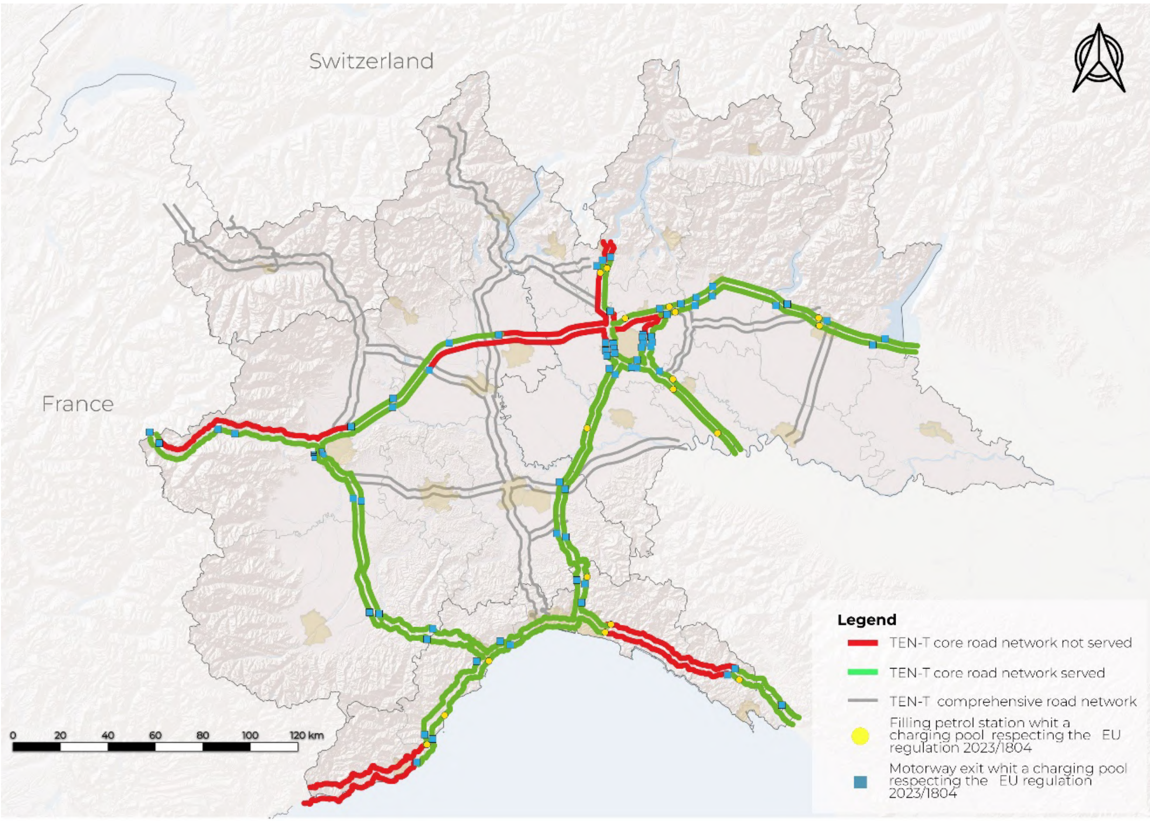

Fig.6 Served and unserved sections of the TEN-T core road network at the end of 2023

	n° charging pools	n° charging points	kW
TEN-T core road network			
On 31/12/2023	712	2,502	17,1995
target 2025	+0	+14	+2,100
target 2027	+0	+8	+1,200
TEN-T non-core road network			
On 31/12/2023	155	446	26,304
target 2027	+0	+0	+0
target 2030	+0	+17	+2,550
target 2035	+0	+22	+5,500

Tab. 2 Charging points (and relative power output) to be added in order to cover the TEN-T road network in northwestern Italian provinces according to the targets set by the EU Regulation 2023/1804 for the next years

To cover the remaining 29% of the core network (mainly located in Liguria and on the corridor between Milan, Turin and Bardonecchia) according to the target set for the end of 2025, the Greedy algorithm showed that it would be sufficient to upgrade 8 charging pools located at the 8 motorway exit indicated in Fig.6 by adding 14 charging points (for a total added power of 2,100 kW); another 8 charging points proving 1,200 kW are needed for the 2027 target (Tab.2). In other words, to increase by 29% the length of the road network served (585 km), it is not necessary to provide new pools; it is sufficient to increase the number of charging points by 0.88% and their power output by 1.92% (Fig.7).

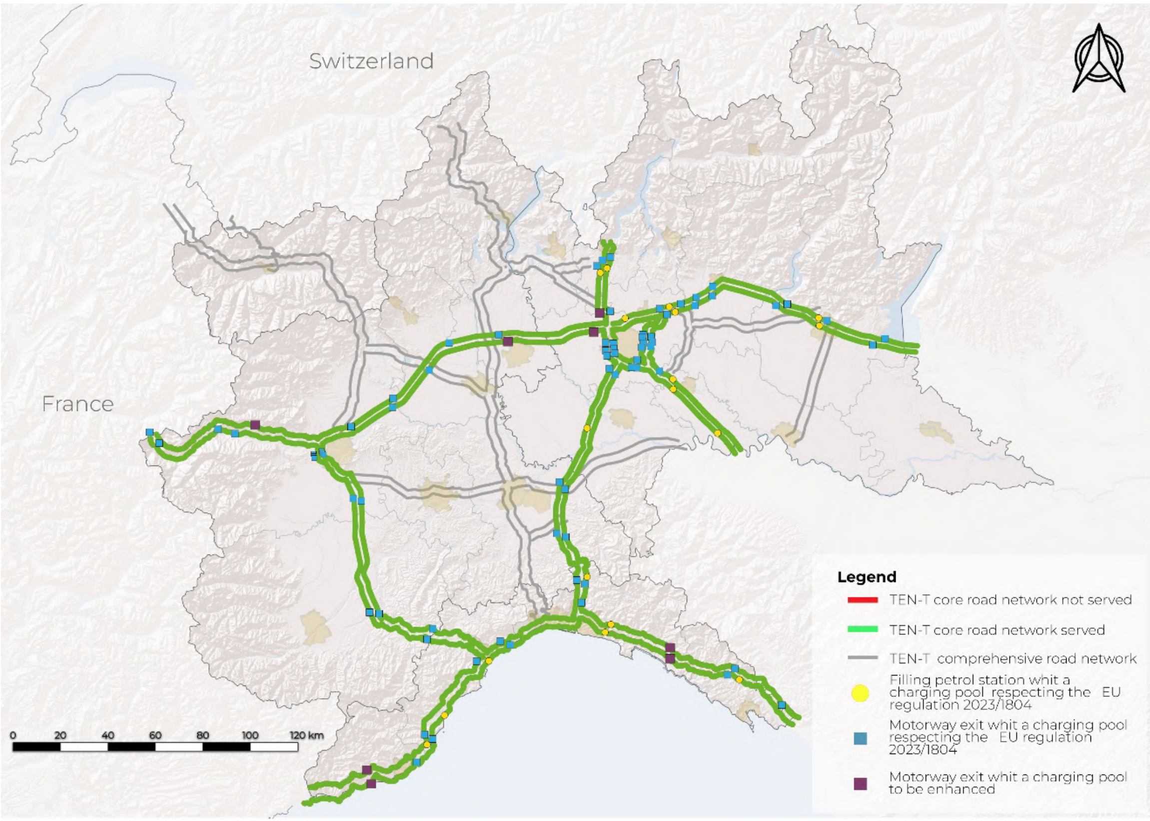

Fig.7 Charging pools to be upgraded at motorway exits to serve the entire TEN-T core road network at the end of 2027

As for the comprehensive network, 155 charging pools can be found along its non-core section, with a total of 446 charging points and a power output of 26,304 kW. Of these 155 pools, 9 located at filling petrol stations already meet the standards set by the Regulation for both the end of 2027 (i.e., having a power output of at least 300 kW, including at least one charging point with an individual power output of at least 150 kW) and the end of 2035 (i.e. having a power output of at least 600 kW, including at least two recharging points with an individual power output of at least 150 kW). Within a 3-km radius of the exits, another 224 pools already meet the Regulation standards for 2025, and another 17 for 2035.

The result is that, at the end of 2023, 33% of the TEN-T non-core network is covered by charging pools that meet the standards required by 2027 (mainly between Turin and Aosta, Milan and Brescia, Milan and Domossola, Ovada and Genoa). Considering the entire comprehensive network (both core and non-core), 54% of its length is already covered by these pools: in other work, the 2027 target (i.e., at least 50% of the whole comprehensive network must be served) is already met (Fig.8). To cover the entire network by 2030, existing pools need to be upgraded at 4 filling petrol stations and 8 motorway exits, by adding respectively 17 charging points (for a total added power of 2,550 kW); by the end of 2035, another 22 charging points are needed, so as to provide an additional 5,500 kW (Tab.2). Also in this case, it is not necessary to provide new pools; it is sufficient to increase the number of charging points by 8.7% and their power output by 30.6% (Fig.9).

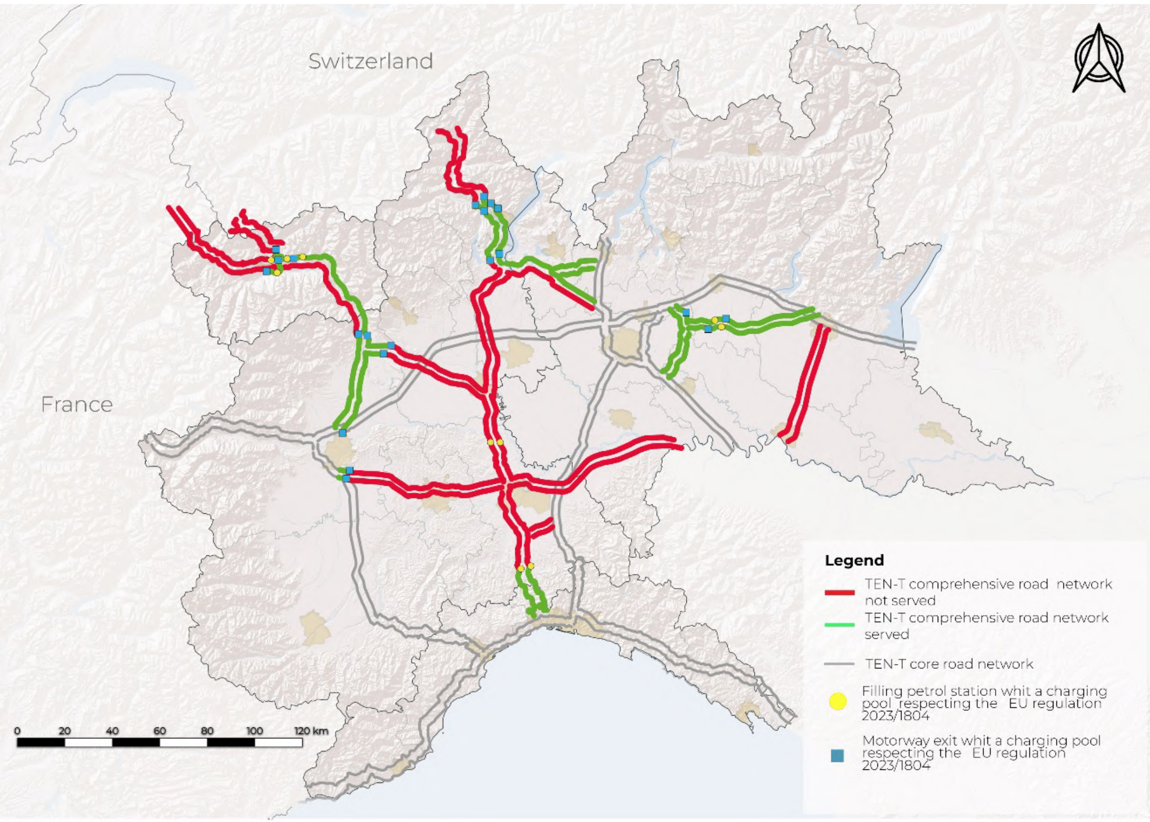

Fig.8 Served and unserved sections of the TEN-T non-core comprehensive road network at the end of 2023

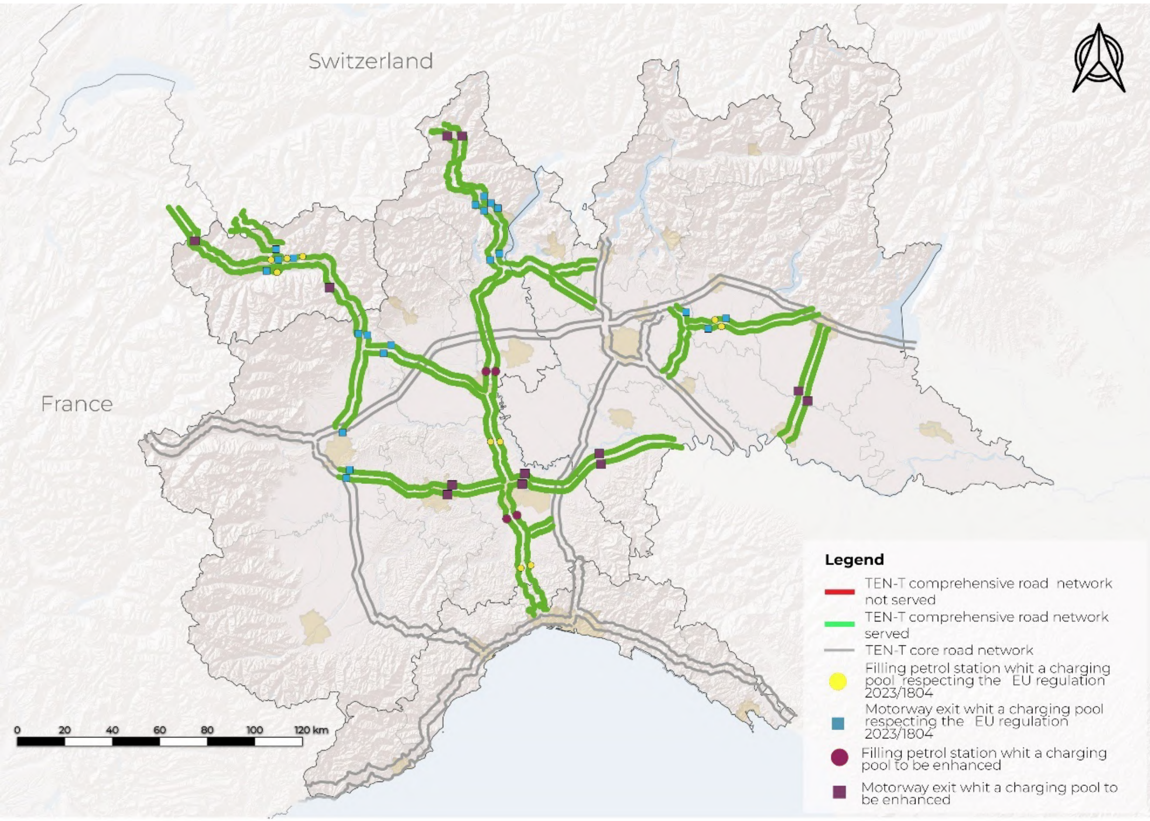

Fig.9 Charging pools to be upgraded to serve the entire TEN-T comprehensive road network at the end of 2035

5. Discussion

The results of the analysis presented in this article highlights a complex and nuanced picture regarding the alignment of northwestern Italy's charging infrastructure with the targets set out by EU Regulation 2023/1804. While the region shows promising signs of development, it also reveals important spatial and systemic gaps that need be addressed to ensure full compliance with EU mandates and enable effective deployment of EV adoption. As illustrated in the Introduction, the relationship between EV adoption and the deployment of charging infrastructure can be mutually reinforcing but is subject to the risk of a lock-in scenario due to underinvestment on both sides. The results seems to confirm this dynamic: while some provinces significantly exceed their fleet-based targets, others fall short of them, indicating a spatial mismatch that may hinder the diffusion of EVs despite broader regional progress. These findings appear to confirm the limitations of Directive 2014/94/EU, which did not propose a common methodology for setting national targets and hence did not prevent unequal development of charging infrastructure. Moreover, the results suggest that, where this infrastructure is abundant, it is likely the result of targeted investments, local incentives, or pilot initiatives rather than a consistent national approach.

These results must be interpreted through the lens of incentives in the Italian market, which have historically focused more on vehicle purchases than infrastructure. Generous subsidies have fostered some uptake in battery EVs, but without commensurate support for charging facilities, especially outside of major metropolitan areas. The Italian incentive structure has thus contributed to regional disparities and slow adaptation in rural and mountainous areas, where private investment is discouraged by lower expected returns and logistical challenges (Delle Site & Tribioli, 2022; Giansoldati et al., 2020).

Moreover, compliance in numerical terms risks obscuring critical system constraints that determine functional service. Regulation 2023/1804 sets clear spacing and power thresholds, yet implementation experience across Europe demonstrates that legal compliance does not guarantee operational readiness when grid connection, substation capacity and per-direction provisioning are not co-planned with charging siting. International assessments stress that corridor continuity often depends on distribution-network reinforcement or local flexibility measures rather than simply adding chargers (IEA, 2023). Two technical implications follow. First, siting and capacity planning must move beyond coverage models to incorporate power-flow and deliverable-power constraints. Location models such as maximum-coverage and p-median heuristics remain useful for identifying candidate sites (Lamontagne et al., 2023; Micari et al., 2017), but their outputs overestimate usable throughput unless they are integrated with distribution-grid simulations and energy-storage sizing. Empirical and modelling work shows that multi-dispenser DC sites operating under a shared connection can experience substantial reductions in per-plug deliverable power during concurrent use, meaning nominal kW figures are not equivalent to guaranteed service levels (Lappalainen et al., 2023; Sun, 2021). Second, operational reliability and user experience matter for network performance. Field audits have repeatedly found that a non-negligible share of public DC fast chargers is non-functional at any given time, and such availability problems disproportionately undermine long-distance travel confidence even where spatial coverage meets the required metrics. Stochastic and queuing analyses indicate that utilization thresholds beyond modest levels produce rapidly increasing waiting times; therefore, monitoring uptime, mean time to repair, and peak-period queuing should be part of compliance metrics (Rempel et al., 2024). Policy and governance implications flow directly from these technical realities. As already said, network or corridor rollout strategies that rely exclusively on national or operator-led investment risk leaving peripheral and mountainous segments underserved because of weak commercial returns and limited substation capacity. To address this, regional planning instruments - notably Sustainable Urban Mobility Plans (SUMPs) and Regional Energy and Climate Plans (RECPs) - should be mandated to include corridor-adjacent prioritization and grid reinforcements, and to coordinate deployment with distribution system operators and local renewable/storage projects. Complementary measures such as targeted infrastructure grants, contracts for difference on reliability, and support for on-site storage or local generation can reduce the need for upstream reinforcement while improving deliverable power (Lappalainen et al., 2023; Sun, 2021). Finally, demand-side instruments and performance-based monitoring will help reconcile EU targets with user needs. Time-of-use pricing, reservation/queue management and predictive maintenance reduce peak congestion and raise effective throughput; behavioural studies show that perceived reliability and wait times strongly influence charging choices on long trips, often more than spatial density alone (Hoen et al., 2023). In sum, moving from a counting-chargers mindset to a performance-oriented, grid-aware strategy will be essential to translate the promising coverage figures reported here into robust, equitable network service.

6. Conclusion

Northwestern Italy is well-positioned to meet European targets on EV infrastructure. Thanks to a strategically located base of existing infrastructure, 71% of the core TEN-T network and over 50% of the comprehensive network already meet the 2027 requirements. Importantly, simulations using the Greedy approximation algorithm demonstrate that full compliance with both 2027 and 2035 goals could be achieved with limited additional investment. Instead of building new pools, it would be sufficient to upgrade existing ones. This insight underscores the cost-effectiveness of a well-planned spatial redistribution strategy and echoes the findings of previous studies (e.g., Lam et al., 2014; Guo et al., 2024), in which optimization models showed that spatial proximity and power adequacy are more critical than simple quantity. The analysis also highlights several limitations. First, fleet- and distance-based evaluations are accurate from a regulatory compliance standpoint, but they do not capture user behavior, real-time network loads, or the quality and reliability of individual charging pools. Second, the use of publicly accessible datasets, however complete, may not take into account informal or private charging infrastructure that could significantly affect both supply and demand. Lastly, while the Greedy algorithm offers computational efficiency, it also favors quick solutions over potentially more equitable or resilient long-term network designs; sensitivity analysis could be appropriate to verify the robustness of the results. Future research should delve into behavioral dimensions: what motivates private actors to install charging infrastructure, how users perceive charging availability, and how seasonality or tourism (especially relevant in Alpine regions) influence demand. Another promising issue is the integration of renewable energy and smart grid compatibility into charging strategies along motorway network, which would further enhance sustainability outcomes. From a policy perspective, a few key recommendations emerge. First, incentive structures need to shift from a predominantly demand-driven approach to a more balanced model that includes infrastructure subsidies, especially in underserved areas. Second, regional authorities should be granted funding and planning autonomy to tailor interventions to local conditions, as these appear more predictive of success than national averages; in this sense, the role of Sustainable urban mobility plans can be crucial in coordinating the spatial allocation of charging pools to land use transformation (Delponte, 2021). Third, regulatory enforcement should be coupled with continuous monitoring and adaptive planning, using geospatial data and predictive analytics to anticipate future bottlenecks (Valentini et al., 2023). In conclusion, achieving equitable, sustainable, and user-friendly outcomes requires aligning incentives with spatial planning, embracing data-driven policy tools, and investing in both technological and social infrastructure. Only through such integrated strategies can the "chicken-and-egg" dilemma be solved, unlocking the full transformational potential of electric mobility.

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Image Sources

All the figures have been elaborated by the authors

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