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IMPACT OF GREEN MOBILITY ON THE ELECTRIC POWER SYSTEM: A NUMERICAL ANALYSIS IN A 2030 SCENARIO

Davide Falabretti[1]*, Francesco Gulotta[2], Lorenzo Papis[1]

[1] Politecnico di Milano, Department of Energy, Milano, Italy
[2] Ricerca sul Sistema Energetico, Department of Energy System Development, Milano, Italy
* davide.falabretti@polimi.it

In this paper, a methodology is proposed to evaluate the impact on the Italian electric power system deriving from the increasing adoption of Battery Electric Vehicles (BEVs). To this purpose, a case study that involves the Lombardy region in a 2030 scenario is analyzed. To accurately estimate travel habits within the region, datasets publicly available were used, complementing them with suitable energetic models of BEVs. Detailed data about the journeys traveled by commuters in the region, distinguished by reason to move and modes of transport, were provided in input to an online routing machine to extract significant information about the vehicle's instantaneous speed, length, and duration of each trip. This allowed for an accurate assessment of the energy and power requirements of private electric mobility in a 2030 scenario. The quantities in output to the analysis can be effectively used by transmission and distribution network operators to identify the issues that could arise on the grid due to increased demand related to electric vehicles. In addition, these analyses can support the proper design and planning of all the reinforcement actions needed on the electrical grid to improve its capability to supply the energy and power required during the charging processes.

Keywords: decarbonization process, electric power demand, electric mobility, load profiling, routing analysis

1 INTRODUCTION

The protection of the environment, reduction of polluting emissions, and sustainable use of the planet's resources have become critical global priorities. The future climate must not be jeopardized by unregulated environmental exploitation, which could lead to irreversible damage. In this context, the advancement of electric mobility plays a key role in reducing carbon emissions and achieving the European Union's energy sustainability objectives [1].

To this end, the European Union (EU) has set ambitious goals to decarbonize the transport sector. In response, member states have implemented policies to promote fossil-free vehicles, with a particular focus on promoting electrification [2]. Although the share of renewable energy in transport reached the 2020 EU target of 10% [3], the use of alternative fuels remains low. One of the primary obstacles to road transport electrification is the high cost of Electric Vehicles (EVs) [4, 5]. To improve the cost-competitiveness of EVs, financial incentives have been introduced or are still under discussion in many countries [6].

In order to remove such barriers, governments worldwide have been using various policy levers in the form of taxation and incentives [7, 8]. Financial incentives, if appropriately designed, could possibly balance out the cost differential between EVs and traditional gasoline cars, which in turn could become the most important driver for customers to buy an EV [9].

Concerning the spread of EV's adoption in the EU countries, in 2023, 1.5 million new battery-only electric passenger cars (Battery Electric Vehicles: BEVs) were registered in the EU, bringing the total number to 4.5 million (+48.5% increase compared with 2022) [10]. The share of BEVs among new registrations reached 14.6% in 2023. This marks a continuation of the rapid increase in the adoption of electric vehicles in the EU. When it comes to the stock of passenger cars, on 31 December 2023, BEVs accounted for 1.7% of all cars in the EU, with noticeable variations among EU countries. In Denmark, BEVs made up 7.1% of all passenger cars. Similarly, high shares were observed in Sweden (5.9%), Luxembourg (5.1%), and the Netherlands (5.0%). Conversely, 14 countries recorded shares below 1%, with the lowest shares recorded in Cyprus, Greece, and Poland, each at 0.2%.

Regarding the situation in place in Italy, at the end of December 2023, the electric car fleet in Italy included about 220'188 vehicles (261'731 at the end of September 2024) [11]. In 2023, the new BEV registrations were 66'276 over a total of 1'572'144 new cars (market share of 4.22%), with an increase of +35.11% with respect to the previous year (Table 1). The geographical distribution of BEVs shows that, in 2023, Trentino-Alto Adige was the Italian region with the highest number of new BEV registrations with 12'807 vehicles registered (+53.75% compared to 2022), ahead of Lombardy with 12'509 registrations (+52.20%). This trend was quite stable in the first nine months of 2024, with the same two regions being the ones where BEVs are most sold in Italy and with Lombardy having slightly surpassed Trentino-Alto Adige in terms of number of new BEV registrations (8569 vs 8509 from the beginning of the year).

Table 1. Market analyses comparison [11]

Vehicle type	December 2023	December 2022	Diff. month [%]	YTD 2023	YTD 2022	Diff. YTD [%]
BEV	6798	4530	50.07%	66’276	49’053	35.11%
All car types	111’545	105’435	5.80%	1’572’144	1’322’525	18.87%
Percentage on all car types	6.09%	4.30%	1.79%	4.22%	3.71%	0.51%

Charging infrastructure development is vital for the acceptance of BEVs. At the end of 2023, the EU charging infrastructure accounted for 632’423 public charging points, serving around 3 million BEVs [12]. However, 61% of all charging points were concentrated in just three countries (France, Germany, and Netherlands) and only 13.5% of all charging stations offered fast charging capabilities. To cope with the challenging target set by the European Commission of 3.5 million charging points by 2030 [13], a significant growth in their installation rates is required, with an estimated 410’000 new points needed to be installed annually. In addition, an increase in the number of high-capacity chargers is required to accommodate growing BEV adoption. Concerning the charging infrastructure in Italy, at the end of 2023, there were 47’228 charging stations available, which increased to 56’992 stations at the end of September 2024.

Regarding the BEV charging infrastructure expansion, studies in the literature show that a well-planned schedule of its deployment can significantly reduce range anxiety and can help BEV adoption [14]. However, even if a general consensus exists about the need to support a rapid deployment of BEV charging stations, there seems to be still significant disagreement about when, how, and which kind of charging infrastructure should be developed and most importantly, for what reasons [15]. This is a crucial aspect, since, based on the different needs and constraints of the territory, it is usually necessary to carefully choose charging stations with the right characteristics and they must be properly placed, in order to ensure the adequacy between charging needs and resource allocations, and thus maximize the utility of the infrastructure while avoiding a waste of resources that could be used for improving it [16, 17].

Given the relevance of the topic and the pressing need for a rapid evolution of the transport sector toward more sustainable schemes, a careful assessment is required of the potential impact of BEV penetration on the electric power system infrastructure [18]. This is essential for prompt and efficient planning of investments necessary in electrical grids to host new charging stations. Regarding this, most of the studies in the literature agree on the fact that, although BEVs will bring an increase in power demand, this in itself is not their most relevant impact [19]. A more important issue is represented by BEV’s charging patterns and drivers’ consumer behavior. The charging pattern will determine whether BEVs will add load to the peak hours or not, if they could help reduce energy curtailments, and if they will charge during low-price hours [20, 21]. In the absence of incentives, charging will take place most probably upon arrival at a destination, in the workplace or at home, depending mainly on the availability of charging stations [22, 23]. Moreover, electric transportation could have a promising role in the provision of regulation services to the power systems, which could increase the hosting capacity of the network for new charging stations without the need for investments in new network assets [24, 25].

To support numerical analyses aimed at evaluating the impact of electric mobility on the electric power systems, an accurate assessment of the power profiles’ evolution as an effect of the spread of BEVs is required. While some studies at the national and occasionally regional levels exist, there is still a significant gap in research that accurately assesses the impact of EV adoption on electric power demand profiles from the grid, particularly for Northern Italy. This paper aims to address this gap by proposing an analytical approach to estimate the BEV’s charging demand in the Italian Lombardy region by 2030. To this purpose, the data adopted as input for the study and how they were employed to characterize the e-mobility behavior across the considered region are explained in Section 2. Then, the importance of a careful routing analysis is presented as well as the tool used to perform it (Section 3). Section 4 will focus on the approaches adopted for evaluating the BEV’s consumption according to the characteristics of the traveled route. In Section 5, the results obtained regarding the energy and power requirements of electric vehicles in the Lombardy region in 2030 will be presented. Finally, some conclusions are drawn regarding the main outcomes of the study and possible future research directions.

2 COMMUTERS HABITS CHARACTERIZATION

As a first step, the present study aimed to carry out a suitable characterization of BEVs’ usage in the Lombardy region, in Italy, in a future 2030 scenario. As already introduced, the main goal of the research is to provide an accurate estimation of the electric power demand profile from BEVs in charge: a clear understanding of the energy and power requirements of electric transportation is fundamental to support quantitative analyses of the impact of these new technologies on the electric transmission and distribution power system.

To this purpose, publicly available datasets were used, to allow for better replicability of the study. In detail, to characterize car transportation usage in the Lombardy region, data included in the Origin-Destination (OD) matrix published by Regione Lombardia were used [26]. Specifically, the OD matrix for the 2030 scenario is a public dataset created through socio-economic analyses, mobility growth projections, and taking into account expected updates of infrastructures, particularly for rail, metro, and cycling networks. These projections incorporate demographic trends, new attraction centers, and key transport network enhancements. Estimations for the 2030 scenario were carried out by considering the growth rates of traffic resulting from the main improvements to rail services and metro networks, for each O/D relationship affected by each development intervention, while considering the possible development of road infrastructure along the same routes. The road network graph was built using the network in output to the Regional Mobility and Transport Program (Programma Regionale della Mobilità e dei Trasporti, PRMT) [27] and considering updates and feedback from the Lombardy Region on the plans and projects already implemented and planned for the future.

The OD matrix includes data relevant to 8 travel modes (car as driver, car as passenger, road public transport, rail public transport, motorcycle, bicycle, foot and other) and 5 reasons for moving (work, study, occasional, other reasons, and return to home). The area involved in the dataset is divided into 1,450 mobility zones (Fig. 1): 1,264 areas are made up of individual municipalities (in green), 108 areas are formed by the aggregation of small municipalities (yellow), and 78 zones are formed by the disaggregation of large municipalities (violet).

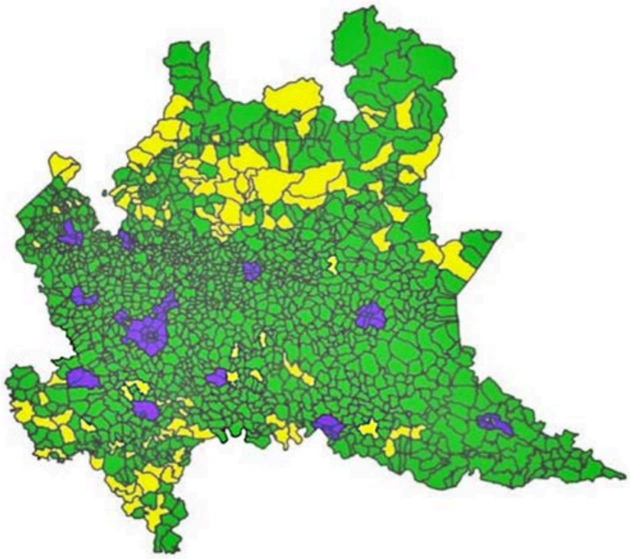

Fig. 1. Origin and Destination cells considered in the analysis

The full dataset is composed of 8’513’400 rows (one for each O/D combination and hour of the day) and 40 columns (one for each parameter considered in the mobility study performed by the Lombardy Region: 8 travel modes multiplied by 5 reasons for moving). In each cell, the number of trips accomplished by commuters between a given Origin and Destination pair in each hour of a representative weekday of the year is reported.

For the goal of the present study, the matrix was properly rearranged to facilitate its processing and better highlight the main features of travel habits in the region. Given that this work focuses on the impact on the power system specifically of BEVs’ power demand, among all data available in the OD matrix only the ones relevant to the mode “car as driver” were considered. Then, for every reason to move (work, study, occasional, other reasons, and return to home), the trends related to the hourly journeys’ distribution over the representative day taken as a reference were obtained, which are reported in Fig. 2 for the whole dataset considered. By this approach, it was possible to extract travel people’s habits and better identify the time windows of the day when trips are concentrated.

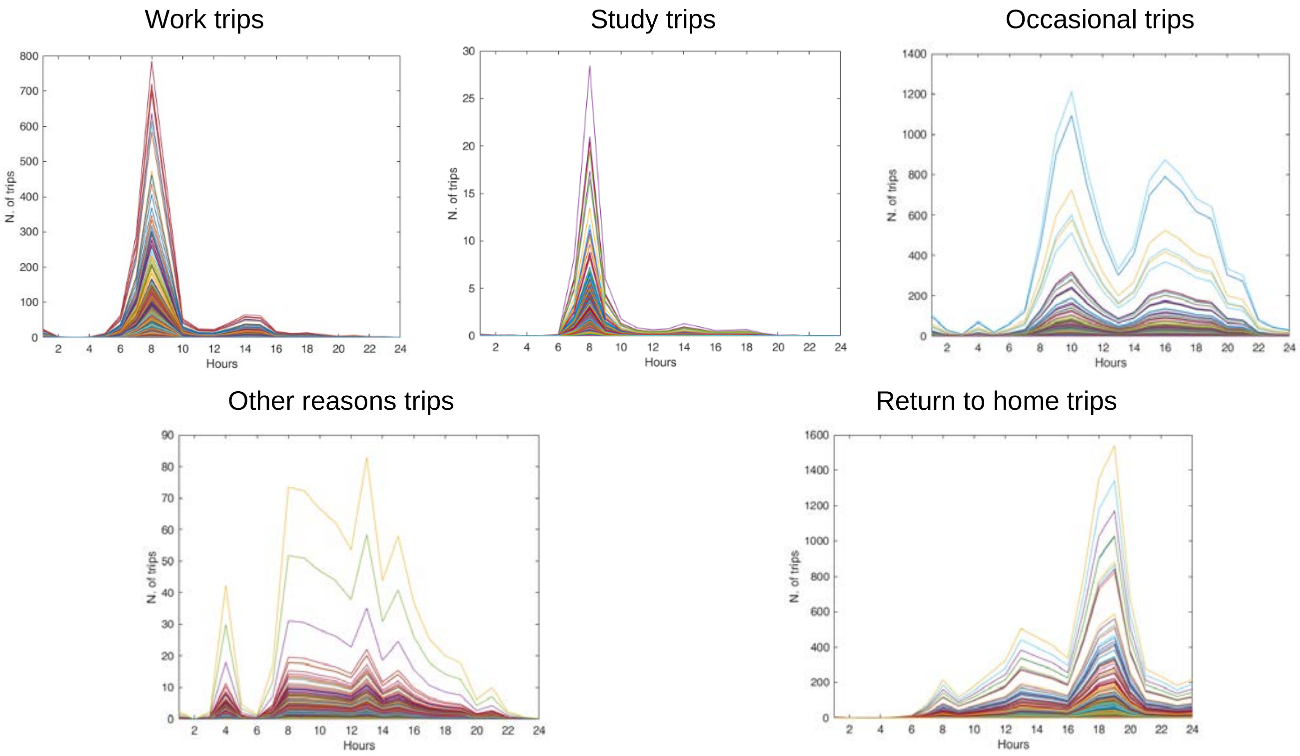

Fig. 2. Number of journeys per hour on the representative weekday analyzed

As one can observe from the trends in Fig. 2, each reason for travel shows a specific trend, which is strictly correlated with the motivation at the basis of the journey itself. In particular, the curve in Fig. 2 related to “work” activities shows a clear peak between 7:00 and 8:00 a.m., representing the most common time for people to commute to work. There is also a smaller peak between 1:00 and 3:00 p.m., corresponding to the start of the afternoon shift. A similar pattern is observed for “study” trips, following the same peak hours, coinciding with school attendance times. “Occasional” trips, on the other hand, are more concentrated in the mid-morning and mid-afternoon. Unlike “work” and “study” trips, these routes are more evenly distributed throughout the day, likely due to their random nature. Finally, the distribution of “other reasons” trips is marked by five distinct peaks around lunchtime, dinner, and the early morning and afternoon hours. Additionally, a peak at 4:00 a.m. is observed, which is probably related to the start of long-distance journeys. Please note that, according to the assumptions of the OD matrix, all trips back home are classified as “return to home” journeys, independently from the primary reason for the trip. As expected, “return to home” journeys are concentrated around midday and late afternoon, coinciding especially with returns from work or lunch breaks.

By summing the trends of all travel purposes, the overall regional journey profile was obtained, which identifies key time windows when most routes are traveled. This allowed evaluating the periods of the day when most EV charging requests will occur. To this end, it is important to note that the OD matrix provides an estimation in 2030 of the journeys performed in the region with any type of car and not just with BEVs. Therefore, suitable assumptions needed to be introduced to quantify the actual share of cars out of the total to be considered electrified. In addition, the publicly available data on car travel within the region only relate to the number of daily trips, while no details are provided regarding the characteristics of the journey as such (actual distance traveled, speed, etc.). Consequently, this information, which is essential for an accurate estimation of BEVs’ energy requirements also needed to be determined. The approach adopted in the study for this purpose, based on the routing theory, is explained in the next section.

3 ROUTING ANALYSIS

To estimate the impact of EV charging requests on the electric power system, a reprocessing of the data relevant to the car trips expected in the Lombardy Region in 2030 was necessary. The goal of the approach developed was to define the properties of each car journey in the region in terms of actual length, speed and duration. These pieces of information were used to elaborate reliable estimations of the power requested for BEVs charging in the 2030 scenario under analysis.

To this purpose, the procedure described in Fig. 3 was applied. Specifically, the data contained in the OD matrix were provided in input to a routing machine to obtain a complete dataset of regional routes for the considered day. To perform the routing process, the open-source tool OSRM (Open-Source Routing Machine) was used [28]. OSRM platform was chosen for its ability to handle efficiently the high volume of trip data requested for the study and the fact of being a free open-source routing platform. To automatize the procedure, a software routine coded by Python programming language was developed: this was used to provide the OSRM routing machine with the coordinates of each origin and destination within the region as input (extracted from OpenStreetMap by the relevant API interface [29]), thus getting as output the route traveled by the commuters.

Each route computed by the OSRM routing machine from each Origin and Destination in Lombardy (i.e. cities, or districts of large cities) is defined as a sequence of segments, each relevant to a section of the total route traveled by the car, characterized by its length, duration, and maximum speed. Despite the computational burden required, this procedure allowed realistically identifying the route most commuters will follow when traveling from one city to another in Lombardy.

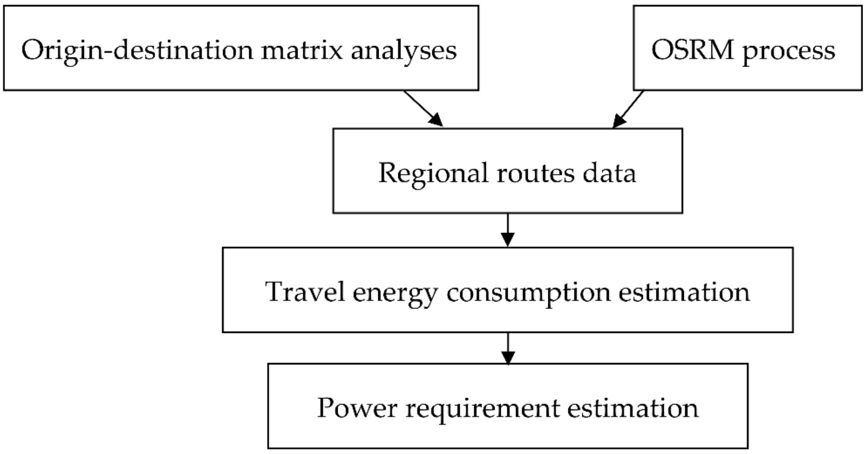

Fig. 3. Flowchart of the procedure adopted in the study

With respect to the various approaches already available in the literature, one of the peculiarities of the methodology proposed in this work is that it also takes into consideration the influence on the BEV's kilometric energy consumption of the actual speed of the vehicle along the entire route.

In the following, the procedure adopted to estimate BEVs' energy consumption from the output data of the routing process is explained. Once obtained, this information will be exploited to quantify the power demand from the grid associated with private electric road transport in a 2030 scenario.

4 ELECTRIC VEHICLES ENERGY CONSUMPTION ESTIMATION

The energy requirements of battery electric vehicles were calculated considering both the travel speed and distance, both determined with the methodology described in the previous section.

Since the OD matrix did not provide information about the type of vehicle used for each trip, suitable assumptions were introduced to define a realistic population of BEVs. For this, the most popular electric cars in Italy over the past three years, based on total sales and market share, were employed as a reference [30, 31, 32].

For the sake of simplicity, the BEV models were subdivided into three representative classes based on the declared Worldwide Harmonized Light Vehicle Test Procedure (WLTP) consumption [33]. The results of the classification are shown in Table 2.

Table 2. BEV classes adopted in the analyses

	Class 1	Class 2	Class 3
Share [%]	54.34	35.43	10.23
Average WLTP consumption [Wh/km]	155.67	165.85	182.88
Average battery capacity [kWh]	43.71	54.85	61.88

Then, an energy consumption trend (Wh/km) as a function of the vehicle's speed (km/h) was assigned to each BEV's class, as shown in Fig. 4. Specifically, by reprocessing data from the literature [34], three distinct trends were obtained. Each trend was designed so that the average energy consumption per kilometer of the considered BEV class, at the speed at which the vehicles are supposed to travel the routes computed by the OSRM routing machine, is equal to the average WLTP consumption values in Table 2.

These characteristics were applied to the instantaneous traveling speed in output to the routing analysis, to estimate the BEV's energy requirement for each route traveled in the region. Since detailed information on the number of BEVs in each category traveling specific routes was unavailable, the total consumption calculated over a route was evaluated considering a BEV distribution according to the current market share in Table 2 and the number of daily trips estimated in the OD matrix.

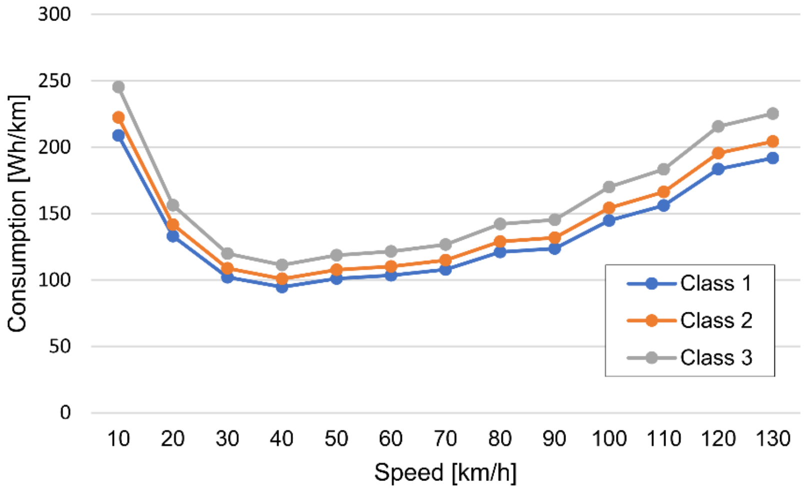

Fig. 4. EV energy consumption as a function of speed for the considered BEV classes

5 NUMERICAL RESULTS

To determine the total amount of energy required at a regional level to support BEV expansion, the share of BEVs over the total number of cars on the road in 2030 needed to be estimated. Numerous studies in literature elaborate projections for the spread of e-mobility, taking into consideration for the evaluation both technological factors and the effects of political choices; in some cases, these studies provide estimates very different from each other. It is well acknowledged, however, that producing accurate forecasts for the future is a very challenging task, particularly given the significant impact of socio-political uncertainties, which have recently demonstrated their potential to greatly influence everyday life. Therefore, in this study, the authors opted to adopt a BEV penetration rate for 2030 coherent with the national Italian targets for decarbonization established in the 2023 edition of the National Energy and Climate Plan (PNIEC 2023) [35], estimated at 16.5%.

The energy consumption required for BEV charging in the Lombardy region is reported in Table 3 and Fig. 5 at a provincial level. For trips between two different provinces, the energy consumption has been assigned to the province of the vehicle's departure. The total regional daily consumption calculated is equal to 2.413 GWh. It corresponds approximately to 1.11% of the total daily energy requirement expected for the Lombardy region in 2030 (grossly estimated at 218 GWh) [36].

Table 3. Estimated BEV daily energy demand in Lombardy provinces in 2030

Province	Daily energy demand [MWh]
Bergamo	295.70
Brescia	359.75
Como	117.64
Cremona	82.37
Lecco	74.52
Lodi	60.25
Mantova	92.12
Milano	772.41
Monza e della Brianza	154.34
Pavia	140.26
Sondrio	56.16
Varese	207.60

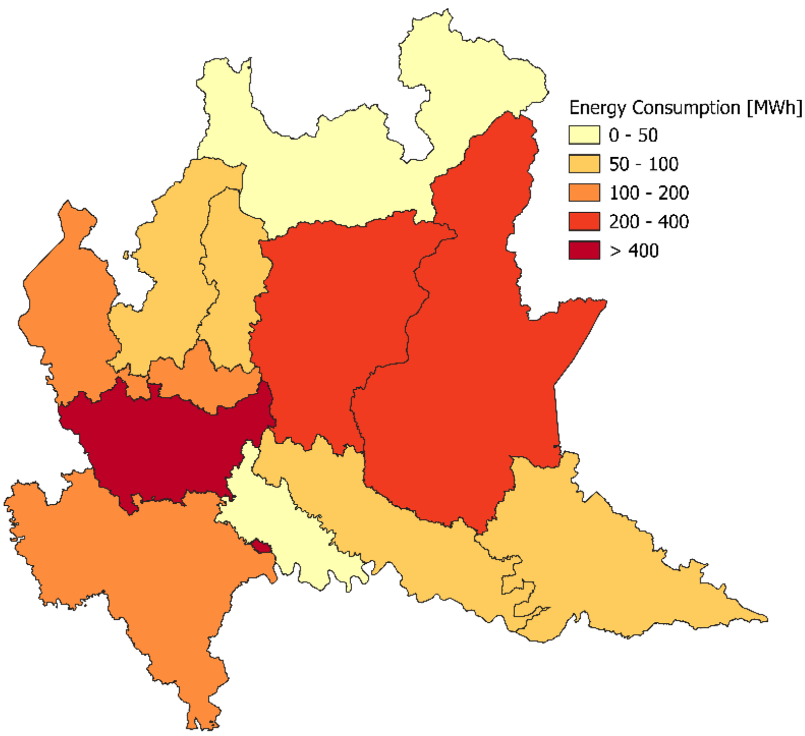

Fig. 5. Estimated BEV daily energy demand in 2030 (colormap)

Even if some correlation exists, as expected, between BEV energy consumption and population density, it is also interesting to observe how the amount of energy required to supply BEVs is affected by other demographic and geographical factors. This is highlighted by Table 4 and Fig. 6, which report the amount of daily energy required by private BEVs per number of inhabitants in each Lombardy province.

Table 4. Unit BEV daily energy demand in Lombardy provinces in 2030

Province	Unit daily energy demand [MWh/inhab]
Bergamo	0.266
Brescia	0.285
Como	0.197
Cremona	0.233
Lecco	0.223
Lodi	0.262
Mantova	0.226
Milano	0.238
Monza e della Brianza	0.176
Pavia	0.260
Sondrio	0.314
Varese	0.236

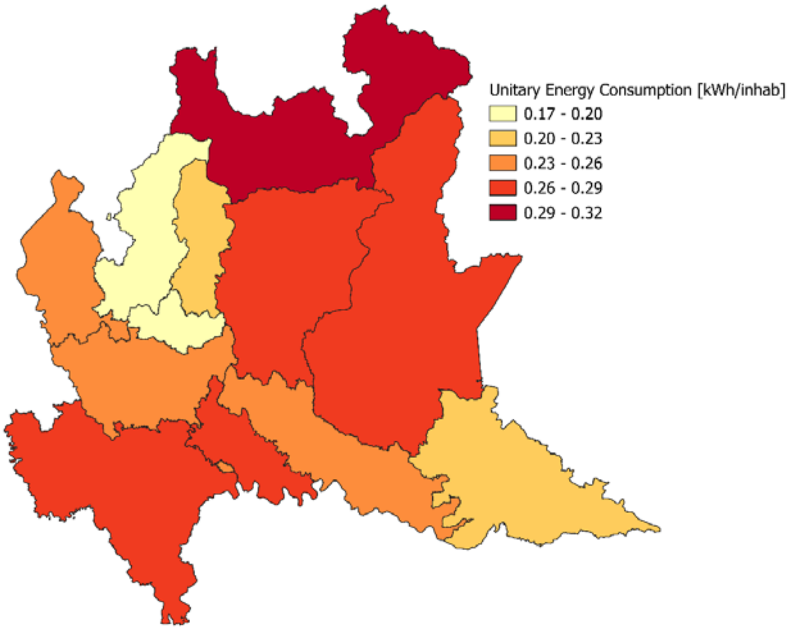

Fig. 6. Unit BEV daily energy demand in 2030 (colormap)

It is notable that provinces with low total BEV energy consumption can also exhibit high energy demands per capita. This is exemplified by Sondrio province, which, according to estimates, will require the least amount of energy for BEV charging in 2030, equal to 56.16 MWh, compared to other provinces in the region. This low energy requirement can be attributed to its small population of 178'948 inhabitants as of early 2024, representing just 1.79% of the region's total population of approximately 10 million. However, in terms of energy consumption per person, Sondrio leads with an average of 0.314 kWh per day. This discrepancy is likely due to its low population density, which implies longer commuting distances between cities. This can be considered a crucial factor for power system's planners, as the analysis performed in this work indicates that the e-mobility behavior in terms of expected energy increase in the future differs significantly from other energy uses (e.g., heat pumps).

Finally, the study has deepened the role of peak power requested from the grid by BEVs when charging. Indeed, even if the overall increase in energy consumption from the electrical network due to electric transportation can be considered modest, it is a well-known fact that issues could occur in particular hours of the day, for example when most commuters arrive at work or return home.

To compute the daily power profile associated with the charging processes of BEVs, each charging type has been matched with a different maximum absorption power, depending on the charging mode (e.g., AC/DC) and the peak power available at the point of installation of the charging point. To this end, the following assumptions have been made:

- Residential charging: 3.7 kW
- Work charging: 7.4 kW
- Public charging type 1: 50 kW
- Public charging type 2: 7.4 kW

The results of the routing analysis explained in the previous sections have been used to determine the initial time of the charging process and the initial SoC of the vehicle at arrival. Many aspects can contribute to determining the preferred place where charging is done: availability of free charging points, duration of the stay, and tariffs applied. In this work, for the sake of simplicity, we assumed that each vehicle starts the charging process when it arrives at the charging point. Moreover, the process continues until a full SoC is achieved.

According to these assumptions, the daily power absorption profile in Fig. 7 was obtained. As one can observe, the trend is characterized by two peaks: the one in the morning is due to the BEV charges at work, and it is characterized by a power greater than 350 MW, while the peak in the late afternoon is linked to the residential charging requests and shows a power value equal to 250 MW. This is important information for power system operators, since it allows identifying the periods of the day more prone to exhibit congestion on the transmission and distribution grids' components (e.g., transformers and lines). In addition, it allows for better management of the generation assets, because, according to the power demand expected at a given time, the transmission system operator must procure the regulating reserve services required to manage in safe conditions the power system.

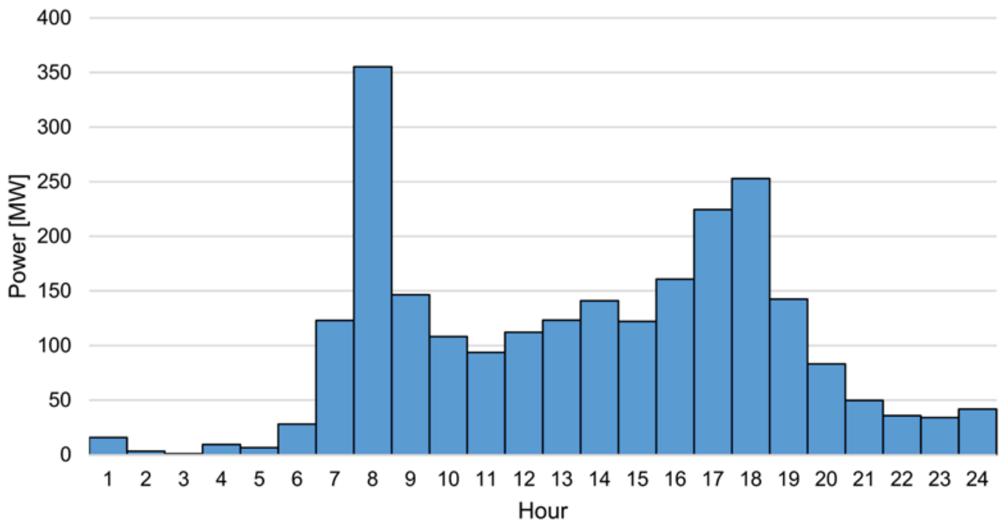

Fig. 7. Regional daily power absorption profile

6 CONCLUSIONS

The electric transmission and distribution system will be required in the future to efficiently support the decarbonization process, by enabling the use of electricity in many different sectors, from road transport to industrial and residential heating. To this purpose, an accurate estimate of the future trends related to the spread of electric transportation is key: a prompt and effective development of electric power networks can be carried out only through precise and reliable estimations of the energy and power requirements of electric vehicles. This is not a trivial task to be performed, since this evaluation requires knowing when the charging process will occur, which will be the actual amount of energy and power needed by vehicles, and where this will happen.

In this context, this research aimed to estimate the future impact of electric mobility on the electric power system of the Lombardy region, the most industrialized and populated region in Italy. The main novelties of this research lay essentially in two aspects. The first is relevant to the accurate predictions about the travel needs of commuters that have been considered in the analysis. On the other hand, by the extensive use of a free and open-source routing machine, a precise estimation has been made of the BEVs' energy demand and corresponding power absorption profile during the charging. This was possible by taking into consideration the actual speed, length and duration of each route.

A potential future direction for the study involves evaluating the expected impact of charging power requests on the electrical transmission and distribution infrastructure, which should also take into account the evolution of other types of electrical loads, such as heat pumps. This kind of analysis is crucial for helping grid operators optimize their investment plans for grid expansion. However, conducting these evaluations requires detailed data on power network structures, which are still hard to find in public repositories.

Data availability is also very important for enhancing the methods used in this study and other research with similar goals to model EV users' habits and charging power requests. To support this process, public authorities at both national and local levels (e.g., municipalities) should make available data on mobility patterns and public transport plans within their jurisdictions.

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