IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 13 January 2023, accepted 29 January 2023, date of publication 3 February 2023, date of current version 8 February 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3242115

RESEARCH ARTICLE

Power and Energy Demand to Support E-Mobility on Highway: The Italian Case Study

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ABSTRACT In recent years, market trends are confirming the increasing use of electric vehicles for private mobility. The use of such vehicles is inevitably affecting highway contexts as well. Therefore, highway network operators need to plan for the installation of adequate infrastructure to enable and manage the growing demand for fast charging expected in the coming years. This paper aims to assess the impact that this charging demand may have on the service areas (SAs) of the highway network operated by Autostrade per l'Italia. Starting from available traffic data, this paper proposes a methodology to forecast, for each service area, the future charging needs of EVs on a daily, monthly, and yearly basis. The analysis considers both the energy and the power that needs to be made available to ensure charging during daily traffic peaks. The results show that the impact generated by EVs will be generally significant, especially in terms of power demands with peaks between two and three megawatts. The methodology developed is entirely general and therefore applicable for similar planning in other highway or suburban roadway contexts. The validity of the developed methodology and the made assumptions have been preliminary confirmed through an initial set of data collected from one of the charging stations installed in one representative service area.

INDEX TERMS Electric vehicles, electric mobility, BEV, charging stations, highways, transportation.

I. INTRODUCTION

Carbon dioxide (CO2) emissions from the transport sector account for about 23% of the global emissions level [1], [2], and within this, the most significant contribution comes from road transport, which accounts for just over 70% [3]. These figures underscore the urgent need to move towards more sustainable mobility solutions that, in terms of emissions, will enable the Paris Climate Agreement and other targets set by the European Commission for 2030 and 2050 to be met [4].

Battery electric vehicles (BEVs) are considered an environmentally friendly alternative to internal combustion engine vehicles, reducing dependence on fossil energy sources, as well as reducing global greenhouse gas emissions worldwide [5], [6], [7], [8]. The wide adoption of this type of electric vehicle is crucial to reducing air pollution in urban areas and is a key factor to achieve sustainable mobility. As a result, several countries have initiated policies to adopt Electric Vehicles (EVs) and aim to completely banish the internal combustion engine within the next decade [9], [10]. As of 2018, European highways had a total of 2550 fast charging stations (FCSs) and more than 5000 combined charging systems (i.e., the European standard plug and socket type used for connecting electric or plug-in hybrid cars to a DC rapid charger), which means an average of one charging station every 60 km.

In 2020, there were about 1000 more ultra-fast charging stations – with rated power from 150 to 350 kW - in service areas (SAs), which allowed conventional service stations to increase their appeal by becoming "multi-energy" [11], [12], [13]. At present, the share of EVs, composed of BEVs and plug-in hybrid electric vehicles (PHEVs), in Italy is around

The associate editor coordinating the review of this manuscript and approving it for publication was Razi Iqbal.

0.6%. The real growth of the Italian electric vehicle market started in 2018, with +60% compared to 2017, and continued in 2019 and 2020 with +87% and +143% respectively [14]. The expansion in the last years is largely attributable to incentives allocated by the national governments [15]. Doing some analysis of EV market development on a short-term time horizon (2025 and 2030) we can expect a 30-fold growth from the current 100000 EVs reaching about 3 million units by 2030 [16]. This growth will have to be accompanied by the strong development of the charging infrastructure. This transformation has already been underway for some years in urban areas, but the highway infrastructure is not yet ready for such a massive presence of EVs. Therefore, the problem of deployment and management of charging infrastructure has become an urgent issue of strong interest.

Several researchers have started to study it from different viewpoints and with different methodologies presented in recent works. The work [17], starts from the analysis of an existing infrastructure on a specific stretch of Canadian's Ontario Highway 401 and develops an algorithm to optimally schedule stops for charging in order to minimize the overall travel time. Other works, however, address the problem of locating charging stations. In [18], for example, the authors sought to understand what was the minimum number of fast-charging stations that should be installed in the whole European highway network to ensure a minimum range of 150 km for different EVs. In this work, the highway network is treated through graph theory, but several approximations were necessary to reduce computational effort. A similar approach was used in [19] and [20]. The analyses conducted in these papers do not use actual traffic data but assume a region-based distribution based on vehicle registration data. The method is then tested on a simulated model based on a regional network. With respect to the aforementioned works, the present one aims to assess the impacts that the charge of electric vehicles will have on the Italian highway network and, in particular, on the electric infrastructure of the service areas present on the portion of the network managed by Autostrade per l'Italia (ASPI) [21]. The assessment aims to estimate the expected electricity consumption and peak power that may be required to meet future recharge demand. The final goal is to provide the necessary information to schedule the operations of installation, correctly size the charging infrastructure of the service areas, and be able to meet future user demands. The work is based on real traffic data generally available to all highway infrastructure managers and can be adapted to different EV penetration scenarios or traffic volumes. The developed method can be generally applicable on other highway stretches but can be also easily extended to other road settings.

The paper is organized as follows: Section II presents a brief overview of the current infrastructure and technologies for electric vehicle charging on the highway, Section III describes the Italian highway context and the specific case study of the present work in detail, and Section IV is devoted to the developed methodology for the assessment of future needs in terms of power and energy for the electric vehicles charge in service areas. The results of the assessment are presented in Section V and their preliminary validation is discussed in Section VI. Conclusions and indications for future improvements are presented in Section VIII.

II. FAST-CHARGING INFRASTRUCTURE

At present, the most popular charging stations, especially in urban settings, take advantage of on-board vehicle converters. These are typically AC systems, which are referred to as AC Level 1 and Level 2, and are designed to handle powers ranging from a few kW to about 22 kW [22]. These power levels allow the battery to be fully recharged but taking several hours. Thus, they are clearly not suitable for highway charging where charging may not result in an appreciable lengthening of total travel time. That is why, in such contexts, installations almost exclusively involve DC charging systems, typically called fast-charge, which are capable of handling powers ranging from tens of kW to several hundred via converters external to the vehicle [22]. The powers of such stations are also gradually increasing to meet what may be the future need for charging heavy-duty vehicles as well. With this in mind, the CHAdeMO organization has recently introduced, CHAdeMO 3.0 fast-charge technology capable of providing up to 500 kW [23], [24].

It should be borne in mind that, the actual use of such power, is highly dependent on the ability of the battery pack to accept such power by effectively managing the thermal issues and the state of health maintenance [25]. In any case, fast charging allows 80% of the battery capacity to be reached in tens of minutes [26]. Charging the remaining 20%, if conducted efficiently, would take longer [27]. Furthermore, several manufacturers strongly suggest not exceeding this level to extend battery life [28], [29].

Currently, FCSs are primarily used as a backup option on the road if the battery runs out during long trips or when there are not sufficient public Level 2 charging stations nearby [30]. However, many are convinced that fast charging will become all the more predominant as the charging time will approach gasoline refueling times, and for this very reason, FCSs are seen to be strongly deployable in highway service areas [9].

The adoption and diffusion of FCSs are facing several challenges that relate to their integration into the electric network such as the requirement of relevant power levels and their compatibility with renewable energy sources and storage systems [31]. Studies on the usage patterns of FCSs in the context of daily travel are needed. This is both to validate the ability of the electric grid to tolerate and handle their sudden power demands and to assess the long-term effects on the health of vehicle batteries.

As of 2020, fast charging has taken up about 5%-10% of the market for total energy charged by EVs [32], and this number is expected to strongly increase in the near future, especially on highways [18]. Eventually, this type of charging is considered more suitable also for the charge of cabs, shared vehicles, or freight transport, i.e. for all those services or vehicles used with high uptime and for which slower charging is certainly not the optimal solution [33], [34], [35].

III. HIGHWAY INFRASTRUCTURE IN ITALY: CASE STUDY DESCRIPTION

The Italian highway network extends for about 6600 km as of 2021 [36] both in the peninsular territory and in the islands. It is divided into 36 main branches, 3 highway tunnels for transit to neighboring countries, and several branches and junctions between the different branches. 13 branches have a suburban character and serve as orbital roads in the vicinity of major cities. At present, the network reaches a density of 22.4 km of highway per thousand square kilometers of Italian land area.

The management of the network is entrusted to 26 different companies and, among these, the company Autostrade per l'Italia is the one that manages the most extensive portion equal to about 2855 km, which is among the largest in Europe. The highway network managed by Autostrade per l'Italia covers 14 of the 20 Italian regions. On this network, there are 204 service stations placed at an average distance of 29 km and about two million vehicles circulating every day [36].

Because each SA is set in a particular geographic context and faces very different levels of traffic, energy consumption, and power that will be necessary to install to guarantee electric vehicle charging service, change from SA to SA. For this reason, a methodology has been developed to estimate both quantities (power and energy) for each service area while also evaluating their evolution from the present until 2030. In this context, one of the key data available is represented by the daily light vehicle transits in the portion of the road facing each SA. This data is typically measured through traffic management systems by each highway operator [37], [38].

The SAs of the ASPI highway network that will be the subject of the present study are shown in Fig. 1 together with the remaining part of the whole Italian network.

FIGURE 1. Whole Italian highway network. The portion of the highway object of the study is indicated in light blue. White circles represent the service areas considered in the assessment.

IV. METHODOLOGY FOR THE ASSESSMENT OF THE IMPACT OF EV CHARGING

This section describes the followed methodology to calculate energy and power, respectively.

Section IV-A presents the methodology that, for each service area of the ASPI network, allows to calculate the expected energy consumption on a daily, monthly, and annual basis. The results obtained will make it possible to predict the expected consumption and, given the expected variations on a daily/monthly basis, the information derived from the calculation algorithm could make it possible to make predictive evaluations on the infrastructure: a typical use of these results could be the sizing of photovoltaic generation systems coupled with a storage system that makes it possible to cope with the energy needs linked to vehicle's recharging needs by maximizing, for example, the quota of self-consumption or minimizing the quota of energy taken from the grid [39].

Section IV-B presents the methodology to estimate the impact of EVs on the service areas in terms of power to be committed to allow the simultaneous recharging of inflowing EVs.

The whole assessment assumes that the charging stations are of the DC fast charging type with a power equal to 100 kW capable to recharge the batteries up to 80% within 20 minutes. This level is considered representative of the majority of available DC FCS and of the practical power limit accepted by several car manufacturers [25]. Considerations on this assumption are provided in the concluding sections.

A. ENERGY ASSESSMENT

The starting point of the whole methodology is the data of daily passages of light vehicles passing through the portion of the highway facing the service area (simply referred to as "in front of the service area" in the following). This value is multiplied by an empirical factor F, which represents, on average, the number of vehicles entering an SA with respect to all those passing on the facing highway section. The experience of ASPI allows us to say that the number of vehicles that stop inside the SA, is between 8 and 12% of the passing ones. Starting from the expected entrances in each service area, it is possible to predict how many of these vehicles will be electric by assuming a certain EVs' share E that can be related to a considered market scenario. The inputs of inflowing BEVs for the j-th service area $BEV_{in,j}$ are calculated according to equation (1):

$$BEV_{in,j} = TLG_j \cdot F \cdot E \tag{1}$$

where TLG_j is the daily light traffic in front of the j-th SA.

Once the number of EVs entering a service area during the day is known, it is necessary to know two other quantities in order to correctly estimate the amount of energy that each of these vehicles will absorb from the grid during charge: the residual charge of the vehicle battery, i.e., the state of charge (SOC), and the capacity of the battery (C_{batt}). A stochastic approach is used for both of these variables. The SOC of a vehicle at the arrival at the SA is estimated by using the following Weibull distribution, as similarly suggested in previous works [40], [41]:

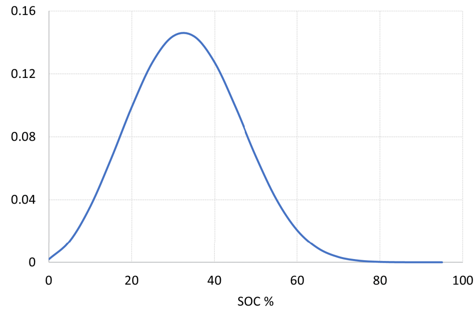
$$\text{pdf}(SOC) = \begin{cases} \frac{k}{\lambda^k} SOC^{(k-1)} e^{-\left(\frac{SOC}{\lambda}\right)^k} & \text{for } SOC \geq 0 \\ 0 & \text{for } SOC < 0 \end{cases} \tag{2}$$

This distribution is characterized by two always positive parameters: the shape parameter k and the scale parameter λ. As can be seen in Fig. 2, the adopted k and λ lead to assuming that almost all vehicles entering the service area with the aim to benefit from fast charging, have a residual charge level between 20% and 70% of the initial battery capacity. The final SOC is always considered to be 80% of the installed onboard capacity, considering that this level could be typically reached in about 20 minutes using the charging system we are considering [42]. At the same time, it is assumed that vehicles with SOC of 80% or higher do not need to make use of charging services.

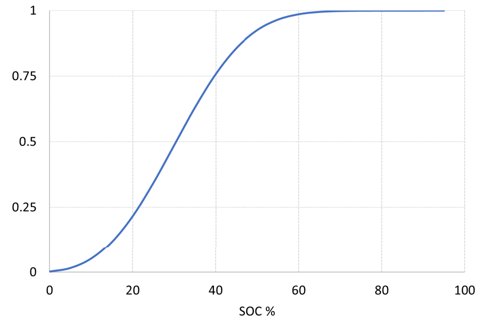
The probabilistic distribution of the EV battery capacity is derived from a snapshot of the real Italian electric car fleet with reference to the year 2019 [14]. In the present work, this distribution is assumed for the entire period considered in the study (i.e., up to 2030). This choice is supported by several studies that indicate as the current battery capacity is more than sufficient to provide for the majority of trips [43], [44]. Many other studies [45], as well as statements from CEOs of automobile manufacturers [46], suggest that battery capacity will be less important as public EV chargers become ubiquitous. These instead indicate how potential technological changes will not be in the capacity of batteries as much as in their volume and weight.

The different vehicles have been grouped into 6 classes according to the size of the battery installed on board: from a minimum value of 15 kWh to a maximum value of 105 kWh, with intervals of 15 kWh. A probability is associated with each class, based on the ratio between the number of registered EVs with that range of onboard battery capacity and the number of total EVs circulating in Italy in 2019. Table 1 summarizes what has just been described.

Hence, for each SA, the capacities of the batteries of the various EVs entering during the day are stochastically redistributed and each vehicle is associated with a certain level of residual charge. At this point, assuming a final SOC equal to



(a)



(b)

FIGURE 2. Probability distribution associated with the SOC of an electric vehicle at the arrival at the service area. Actual probability distribution (a) and cumulative distribution (b).

TABLE 1. Battery capacity distribution reconstructed from data available in [14].

Battery capacity interval (kWh)	Number of EVs in the Italian car fleet	Probability
$15 \leq C_{\text{batt}} < 30$	5176	26%
$30 \leq C_{\text{batt}} < 45$	9434	48%
$45 \leq C_{\text{batt}} < 60$	2395	12%
$60 \leq C_{\text{batt}} < 75$	108	1%
$75 \leq C_{\text{batt}} < 90$	264	1%
$90 \leq C_{\text{batt}} < 205$	1974	10%

80% of the whole battery capacity, it is possible to calculate the average daily electrical energy $E_{d,j}$ that will be absorbed by charges as:

$$E_{d,j} = \sum_{1}^{N} \left(SOC_i^{\text{final}} - SOC_i^{\text{init}}\right) \cdot C_{\text{batt},j} \tag{3}$$

where:

- N is the number of EVs entering the service area j
- SOC_i^{final} is the final state of charge of the i-th vehicle (always equal to 80%)
- SOC_i^{init} is the initial state of charge of the i-th vehicle
- $C_{\text{batt},j}$ is the battery capacity of the i-th vehicle.

B. POWER PEAK ASSESSMENT

To correctly assess the electrical power that will be required in a given service area, it is not sufficient to know the absolute number of EVs that stop during the course of a day (i.e.,

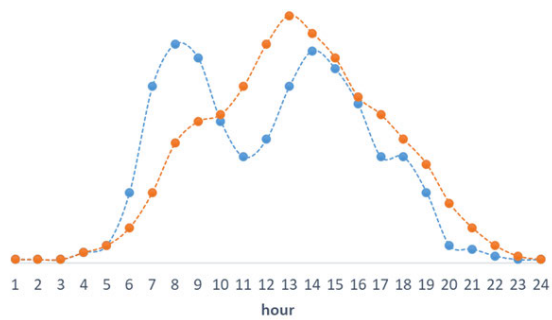


FIGURE 3. Qualitative reproduction of the service area entrances made available by Google. An urban highway section (in blue) and a recreational highway section (in orange) are shown.

as done for the calculation of energy consumption). In fact, in this case, it is fundamental to know the temporal distribution of recharging occurrences, i.e., the time at which vehicles arrive and enter the SA to recharge. The estimated maximum number of EVs that may need to be recharged at the same time provides a direct indication of the maximum power level that has to be made available. To make this assessment, it is, therefore, necessary to know how the flow of vehicles varies throughout the day in order to quantify the traffic peak. Since it is not always possible to obtain this level of detail as the data is either proprietary or associated with sensitive information (such as car number plates), the methodology proposed by the Highway Capacity Manual (HCM) has been used [47].

According to the HCM, traffic varies during the course of a day with a shape depending on the day of the week (weekdays or holidays), and whether the considered stretch of highway is typically associated with business or leisure travels. In particular, stretches of highway used mainly for recreational purposes (i.e., for example, stretches of highway leading to seaside or vacation resorts) show more pronounced hourly peaks in traffic than stretches of highway used mainly for work purposes, where traffic is more uniform during the day. Some of the results of these experimental campaigns and traffic data acquisitions along American highways can be found in [47]. It is important to emphasize that, although the HCM is a reference developed in the US, the guidelines provided in that manual are also widely used in the European and therefore Italian context.

The hourly pattern of daily traffic also has an impact on service area entries: service areas located on highway stretches close to large urban centers, used mainly for work purposes, show a more uniform inflow of users than service areas located on rural highway stretches used mainly for recreational purposes (see Fig. 4).

To evaluate the power required at the delivery point in order to meet user demand for charging, it is necessary to move from average daily traffic to hourly transits. The Average Annual Daily Traffic ($AADT$) is simply defined as the ratio between the number of transits TA_j recorded on a road section in a year and the number of days in a year as indicated in (4):

$$AADT_j = \frac{TA_j}{365} \tag{4}$$

The HCM provides an empirical factor called the K-factor (simply indicated also as K in the following), which makes it possible to switch between the $AADT$ and the expected hourly traffic volume during the daily peak hour [47]. The K-factor, which is basically nothing more than a percentage of the $AADT$, varies according to the type of highway section urban/working or rural/recreational. Using the K-factor to identify the peak hour traffic volume as a percentage of the $AADT$ can overcome the problem of the lack of data discussed at the beginning of this section. The hourly peak traffic volume that can be expected on an urban/working highway section is about 9% of all average daily traffic. In the case of a rural/recreational highway stretch, the hourly peak can represent 10% of all average daily traffic. Generally, on rural highway sections, there is greater variability, with some hourly peaks of up to 30% of daily traffic.

As defined through (5), the peak hourly traffic volume in front of the j-th service area, or hourly peak volume (HVP_j), is defined as the product of the $AADT$ and the K-factor, where the latter is a function of the type of road section in which the service area j is located:

$$HVP_j = AADT_j \cdot K_j \tag{5}$$

To calculate the expected peak hourly traffic volume, it is necessary to choose one of the two values of the K-factor proposed (i.e., 9% or 10%). Given the large number of service areas to be considered, it was decided to implement a rapid and automated process that would allow the classification of the SAs according to the territorial context and the type of road section in which they are located. To do this, the GIS (Geographic Information System) software QGIS [48], has been used. The GIS software has allowed overlaying of two different spatial layers:

- A layer containing all the spatial information related to the 204 service areas of the ASPI network
- A layer that divides the entire Italian territory into 4 types of zones according to the population residing in the area, the level of urbanization, the population density, and the industrialization of the territory [49]:
    a. Inhabited centers
    b. Inhabited nucleus
    c. Productivity locality
    d. Scattered houses.

By overlapping the two layers it is possible, for each service area, to characterize the territory in which it is located and classify it as urban SA, if it falls into categories a, b, or c, or rural SA, if it falls into category d. The result of the classification is shown graphically in Fig. 4.

Once the K-factor value is assigned to the different service areas, it is then possible to estimate the hourly traffic volume HVP_j by applying (5). To know the share of purely EVs that could stop in the service area during that one-hour time frame

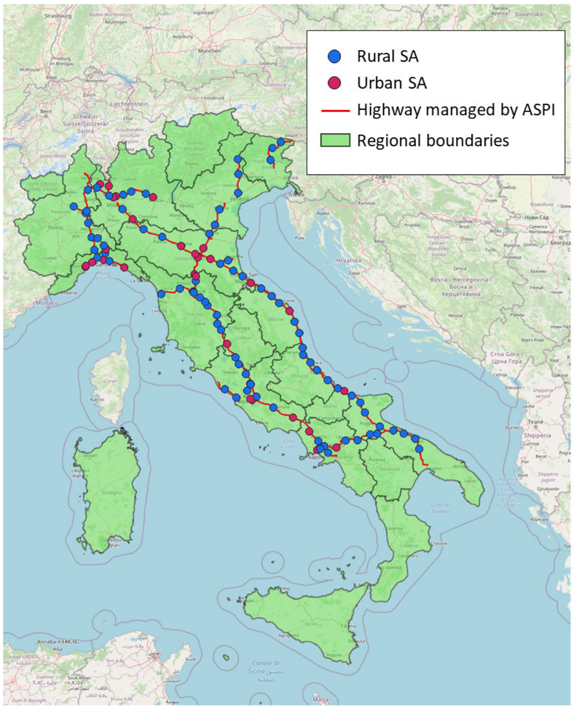


FIGURE 4. Classification of service areas according to the territorial context in which they are located (urban in red, rural in blue).

($BEV_{\text{in},j}$) it is possible to use the same two parameters E and F defined for (1) as for (6):

$$BEV_{in,j} = HVP_j \cdot F \cdot E \tag{6}$$

Once the number of EVs that could stop at the same time to recharge is estimated, it is necessary to define a contemporaneity factor Γ_c to assess the probability that these vehicles will charge at the same time. The contemporaneity factor is here defined as the ratio between the total time needed for charging and the considered time interval in which the vehicles arrive at the service area, i.e., one hour. On the basis of these assumptions, equation (7) is then found:

$$\Gamma_c = \frac{T_r}{\Delta t_{ob}} \tag{7}$$

where T_r is the time required for a complete recharge including all the complementary operations necessary to start and conclude the charge (i.e. cable connection, start charging, payment) and Δt_{ob} is the one-hour observation interval in which vehicles arrive at a generic service area. It is worth noting that the contemporaneity factor is independent of the service area considered and therefore generically applicable. The number of simultaneous charges expected in the j-th service area (RC_j), therefore, can be estimated from the number of hourly inputs of EVs ($BEV_{in,j}$) previously defined as indicated in (8):

$$RC_j = BEV_{in,j} \cdot \Gamma_c \tag{8}$$

Knowing the estimated number of EVs that could simultaneously require fast charging, the power that would be needed in the SA to meet this demand is calculated. The total power $P_{\text{SA},j}$ required in a given service area is calculated according as:

$$P_{\text{SA},j} = RC_j \cdot P_{\text{nom}} \tag{9}$$

where RC_j is the expected number of simultaneous charges during the peak hour in the j-th service area and P_{nom} is the power delivered to each vehicle plugged in a charging station (which we recall, was assumed to be 100 kW).

V. ANALYSIS AND DISCUSSION OF RESULTS

As mentioned above, ASPI's experience allows us to say that the number of vehicles that decide to enter a service area is between 8 and 12% of the total number of vehicles passing in front of the service area itself. For this reason, an average value of 10% has been chosen for parameter F. The share of expected BEVs (parameter E) has been set equal to 10.1%, according to the most accelerated development scenario found in [16] by choosing the year 2030 as the time horizon. The contemporaneity factor Γ_c has been set equal to 0.5 since it is assumed that the duration of the whole charging operation (T_r) is equal to 30 minutes (see eq. (7)). Table 2 summarizes the values of all the parameters presented in the Section IV and selected for our model calculations.

The flexibility of the developed methodology (which is its most important strength) allows to use it for any different highway infrastructure and scenario as these parameters can be modified according to the context in which this model is applied (i.e., service areas with higher or lower entrances, more or less accentuated traffic peaks, higher or lower powerful FCSs installed, different levels of penetration of EVs on different time horizon).

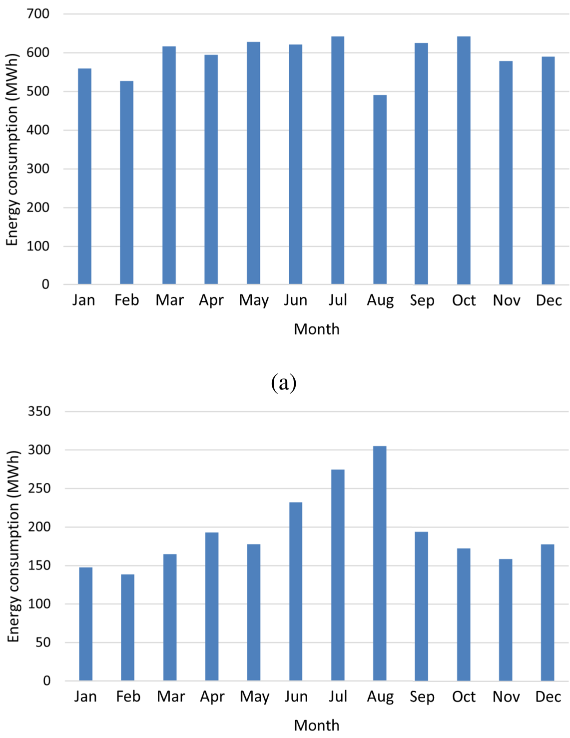
A. FORECASTED ENERGY CONSUMPTION IN THE SERVICE AREAS

Fig. 5 provides an example of the results obtained for a monthly consumption for EVs charging expected in 2030 in two different SAs. It is interesting to note that, in the urban SA (Fig. 5a) located near Milan on a stretch of highway characterized by travel for work-related purposes, a minimum in consumption is seen during August. On the other hand, in the rural SA (Fig. 5b), a peak in the consumption is noted in August. Since this SA is located along the Adriatic coast, the peak can easily be attributed to travels associated with summer holidays.

Fig. 6 summarizes the results of this first analysis: all service areas of the ASPI network are shown and each one is associated with the annual energy consumption expected in 2030 to meet the recharging needs of EVs. The color of the symbol identifying the service areas is defined according to the higher or lower level of expected energy consumption. This classification makes it possible not only to immediately identify the critical areas of the network in terms of energy consumption but also to have a quantification of the level of expected consumption. The most critical areas can be found

TABLE 2. **Battery capacity distribution reconstructed from data available in [14].**

Parameter	Description	Value
	Time horizon	2030
F	Share of vehicles entering an SA with respect to transit in front of it	10%
E	Share of expected BEVs, including light passenger vehicles and light-duty commercial vehicles, in the Italian car fleet	10.1%
SOC	State of charge distribution function	Weibull distribution ($\lambda = 45, k = 4$)
C_{batt}	Battery capacity distribution function	Values reported in Table 1
K	Parameter that converts total daily traffic into hourly peak traffic	9% (for urban stretches) 10% (for rural stretches)
T_{r}	Time required for the whole charging operations	30 min
Γ_{c}	Contemporary factor	0.5
P_{nom}	Nominal power of a charging slot	100 kW



(b)

FIGURE 5. **Monthly consumption expected in 2030 for recharging EVs in two sample service areas, urban (a) and rural (b).**

FIGURE 6. **Annual energy consumption for EV charging on the SAs belonging to ASPI network expected in 2030.**

along the stretch of the A4 highway linking Milan and Bergamo and partly also along the stretch of A1 highway from Milan to Bologna, with peaks of almost 5 GWh per year in the most frequented service areas. The total annual consumption associated with EV charging in all service areas of the ASPI network is therefore estimated at around 230 GWh.

B. FORECASTED POWER TO BE INSTALLED IN THE SERVICE AREAS

Fig. 7 summarizes the results obtained from the estimation of the power required in each service area to cope with the expected peaks of simultaneous charging. The 204 service areas, indicated in the figure by dots, are colored with different gradations of red according to the level of power that would be needed to be installed. A strong similarity with the results shown in Fig. 6 for energy consumption is immediately apparent. As expected, the critical points in terms of power demand are found where there is generally intense traffic (e.g., along the stretch of the A4 highway between Milan and Bergamo). As visible through the box plot of Fig. 8, in most of the service areas, the results indicate that power between 500 and 1000 kW is sufficient to meet the changing requirements by 2030. The peak in requested power is found in the two urban service areas along Milan ring road, where up to 3.5 MW may be needed. In general, the power that will be necessary decreases by moving from north to south and from urban to rural areas.

VI. PRELIMINARY VALIDATION

The campaign to deploy fast charging stations on the ASPI network was launched in the summer of 2021 and is currently

FIGURE 7. Power to be installed to meet the changing needs of EVs on the SAs belonging to ASPI network expected in 2030.

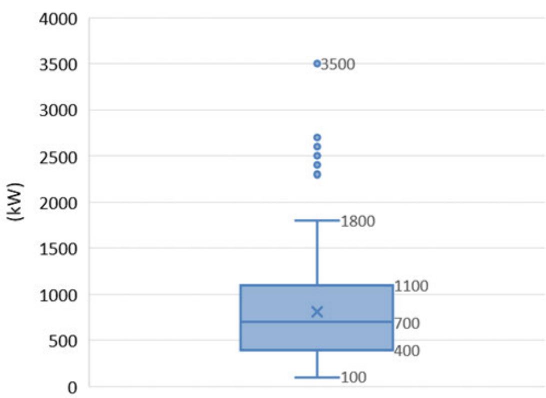


FIGURE 8. Distribution of the power to make available among the ASPI highway service areas summarized within a box plot. Almost all values are between 100 and 1800 kW, with an average of around 800 kW and a median of 700 kW.

underway. As can be expected, the data collected during these months is extremely sensitive for the charging service operator and at the same time cannot be made public for market and confidentiality reasons. It has, however, been granted by the ASPI group's charging service operator to access the data from six months of operation of the charging stations of a SA in the northeast area. This SA is classified as urban according to the criteria described in Section IV. For the reasons stated above, such data will be presented in anonymized form.

Despite these limitations, as much information as possible was extracted to validate, albeit in a preliminary way, some of the assumptions made in the development of the methodology presented. The available data are for the months from October

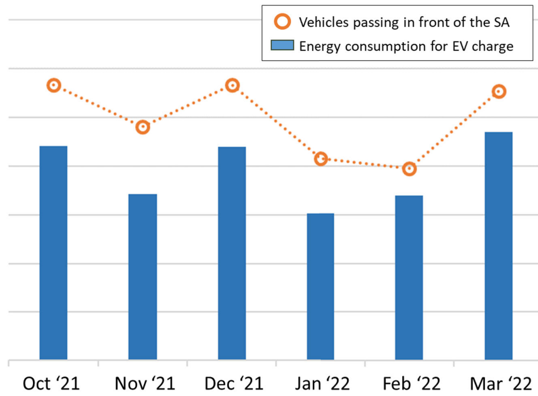


FIGURE 9. Anonymized data of monthly measured energy required by fast charging stations installed in an SA in the northeast area, classified as urban, and total number of vehicles passing in front of the SA. Period from October 2021 to March 2022.

2021 to March 2022. According to the data reported in [50], there were 122138 BEVs registered in Italy at the end of 2021. The model developed by the authors in [16], and adopted in the present work (labeled as *accelerated scenario*) provided a number of BEVs in the same period equal to 122252, i. e. a deviation of less than 1%. This result, at the moment, allows verifying the validity of the input data on the share of electric vehicles over the whole Italian vehicle fleet used in (1) and (6).

A second important validation addressed the correlation between traffic volumes in the portion of the road facing the service area and the number of vehicles that used the charging services. As visible from the comparison made in Fig. 9, there is a quite clear correlation between traffic volume and the energy required for charging.

Regarding the forecasts about the energy required to supply the recharges, it was possible to observe, for each individual month a deviation in a range from a minimum of 2% to a maximum of 20%. In each case, the consumption predicted through the methodology adopted in this work was always higher than the actual demands. This result, as well, confirms the validity of this tool for planning energy needs for meeting user charging demands.

Finally, data on the distribution of vehicle battery capacity for 2021 extracted again from [14], emphasize that there was no evident increase in battery capacity. 91% of BEVs still has a battery capacity between 15 and 60 kWh, while higher values remain within a few percentage points.

VII. SENSITIVITY ANALYSIS

The results derived from the model presented, depend on two key preliminary assumptions: the power of the charging station considered and the percentage of electric vehicles entering the service area.

A modification in the power level of the charging station implies a change in the duration of charging itself and thus in the number of simultaneous recharges that can be handled

TABLE 3. Relative variations of the number of contemporary charges and required peak power versus variations of the charging station nominal power (P_{nom} from 100 kW to 200 kW) and share of vehicles entering the SA (F from 10% to 12%). Results evaluated for the two sample urban and rural SAs. Absolute values are reported in brackets.

URBAN SA		
	Max. contemporary recharges variation	Peak of requested power variation
$\Delta P_{\mathrm{nom}} = +100\%$ ($T_{\mathrm{r}} = 20$ min, $\Gamma_{\mathrm{c}} = 0.33$)	-26% (from 35 to 26)	$+49\%$ (from 3500 kW to 5200 kW)
$\Delta F = +2\%$ (same $P_{\mathrm{nom}}, T_{\mathrm{t}}, \Gamma_{\mathrm{c}}$ as in Table 2)	$+69\%$ (from 35 to 59)	$+69\%$ (from 3500 kW to 5900 kW)
RURAL SA		
	Max. contemporary recharges variation	Peak of requested power variation
$\Delta P_{\mathrm{nom}} = +100\%$ ($T_{\mathrm{r}} = 20$ min, $\Gamma_{\mathrm{c}} = 0.33$)	-20% (from 10 to 8)	$+60\%$ (from 1000 kW to 1600 kW)
$\Delta F = +2\%$ (same $P_{\mathrm{nom}}, T_{\mathrm{t}}, \Gamma_{\mathrm{c}}$ as in Table 2)	$+70\%$ (from 10 to 17)	$+70\%$ (from 1000 kW to 1700 kW)

(parameters T_r and Γ_c in (7)) as well as on the overall peak power required by a SA.

To have a measure of how sensitive the results obtained are to this parameter, the assessment was repeated assuming a power of 200 kW for the charging stations. Based on this variation, a shorter charging duration of 20 minutes was assumed (keeping the complementary operations period unchanged). This variation implies a contemporary factor Γ_c value of 0.33 compared with the value of 0.5 considered in the study. This type of assumption about a direct proportionality between charging power and charging duration is certainly a simplification. However, this correlation is considered acceptable in relation to the range of SOC assumed for the vehicles requiring charging services. In fact, as analyzed in detail in [41], in a range between 20 and 80 percent of SOC, charging is predominantly done with a linear variation of instantaneous power. Under these conditions, the approximation made is considered acceptable, especially in the absence of more specific information. A possible way to refine this approach is discussed in the conclusions.

The results of this evaluation for the two representative SAs considered so far are shown in Table 3. It can be seen that a doubling of charging station power implies a 20-26% reduction in contemporary recharges and a 49-60% increase in the total power required by the service area.

For completeness, the same evaluation was repeated while keeping the power of the charging station unchanged ($P_{nom} = 100$ kW), but considering a higher percentage of vehicles entering the service area. This variation may be related to a change in the market scenario compared to the one considered (i.e., the parameter E) or to a simple variation from the custom about the number of vehicles entering the SA compared to the traffic in front of the SA (i.e., the parameter F). As can be seen from equation (1), the change in the parameter F or E is indifferent to the final result. Thus, for the comparison, it was chosen to increase the parameter F from the 10% used in the study to 12% (the maximum value among those typically observed, see Section IV). The results of this evaluation have also been reported in Table 3. What can be seen is that, as expected, in both cases there is an increase in power demand, but the results are much more strongly dependent on the variation in the number of vehicles eligible for charging. For a 2% increase in total vehicles entering the service area, there is about a 70% increase in the overall peak power required, for both the urban and rural contexts.

VIII. CONCLUSION

The work presented has consisted in assessing the impacts that the spread of electric vehicles will have, in the short term, on the Italian service areas along the highway network. It has sought to provide a concrete response to the urgent need to equip the service areas with fast charging stations for EVs.

It is clear from the results that, particularly in the busiest areas of the network close to the biggest cities in the north, the needs in terms of energy and power that must be made available are onerous. The results also indicate as the future need for charging hubs capable of recharging from 20 to 30 vehicles at the same time, with a capacity of $2 - 3$ MW. This clearly means significant investments, physical space, and particular attention to safety aspects.

The proposed methodology can be extremely useful in planning the electrification of the highway network over the next years, guiding the construction of charging stations where they are most urgently needed and estimating the amount of electrical energy that will be required. This information is fundamental for the planning of energy management indicating the best policies to buy and manage electric energy. The strength of this methodology has been demonstrated to be double: the simplicity of the algorithm and its extreme flexibility. In fact, the algorithm requires data that is generally available to highway infrastructure managers, and it can be adapted to face different penetration scenarios of EVs or to different traffic data. Moreover, this methodology can be applied also to other contexts than the extra-urban one such as, for example, to a traditional refueling station located in a suburban area.

Preliminary data appear to confirm the validity of the adopted approach and assumptions.

Future activities will aim at refining the results obtained in the present work assuming the possibility that the power of the charging stations is different in the various service areas on the basis of the different inflows of vehicles expected. Moreover, the actual distribution of the vehicle fleet in the various Italian regions, assumed to be uniform throughout the country in this work, will be validated starting from more detailed data that will be available in the near future which will be more representative of the peculiar differences between the different parts of the national territory. Finally, a more accurate evaluation of the correlation between actual charging duration and charging station power can be addressed by building an average model obtained from data measured during the charging of an appropriate statistical sample of vehicles with different battery characteristics and capacities.

REFERENCES

[1] International Energy Agency. *Global Energy-Related CO_2 Emissions by Sector*. Accessed: Oct. 2022. [Online]. Available: https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector

[2] *Global CO_2 Emissions in Transport by Mode in the Sustainable Development Scenario, 2000–2070*. Accessed: Oct. 2022. [Online]. Available: https://www.iea.org/data-and-statistics/charts/global-co2-emissions-in-transport-by-mode-in-the-sustainable-development-scenario-2000-2070

[3] European Commission. *A European Strategy for Low Emission Mobility*. Accessed: Oct. 2022. [Online]. Available: https://www.eea.europa.eu/policy-documents/a-european-strategy-for-low

[4] *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) NO 401/2009 and (EU) 2018/1999 ('European Climate Law')*. Accessed: Oct. 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R1119

[5] R. Stammer Jr., and F. Stodolsky, "Assessment of the energy impacts of improving highway-infrastructure materials," Argonne Nat. Lab. (ANL), Argonne, IL, USA, Tech. Rep. ANL/ESD/TM-115, 1995.

[6] S. Chu, J. Goldemberg, S. A. Olende, M. El-Ashry, G. Davis, T. Johansson, D. Keith, L. Jinghai, N. Nakicenovic, and R. Pachauri, "Lighting the way: Toward a sustainable energy future," in *Inter Academy Council*. Amsterdam, The Netherlands, 2007. [Online]. Available: https://www.interacademies.org/sites/default/files/publication/lighting_the_way.pdf

[7] R. Bapna, L. S. Thakur, and S. K. Nair, "Infrastructure development for conversion to environmentally friendly fuel," *Eur. J. Oper. Res.*, vol. 142, no. 3, pp. 480–496, Nov. 2002.

[8] M. Kuby and S. Lim, "The flow-refueling location problem for alternative-fuel vehicles," *Socio-Econ. Planning Sci.*, vol. 39, no. 2, pp. 125–145, Jun. 2005.

[9] R. Wolbertus, S. Jansen, and M. Kroesen, "Stakeholders' perspectives on future electric vehicle charging infrastructure developments," *Futures*, vol. 123, Oct. 2020, Art. no. 102610.

[10] J. Buss, "Automakers need a global timetable for phasing out internal-combustion engines," Forbes Magazine, Tech. Rep., 2018. [Online]. Available: https://www.forbes.com/sites/oliverwyman/2018/03/27/automakers-need-a-global-timetable-for-phasing-out-internal-combustion-engines/?sh=7dab6fe923c3

[11] European Court of Auditor. *Infrastructure for Charging Electric Vehicles: More Charging Stations but Uneven Deployment Makes Travel Across the EU Complicated*. Accessed: Oct. 2022. [Online]. Available: https://op.europa.eu/webpub/eca/special-reports/electrical-recharging-5-2021/en/

[12] L. Mathieu, "Roll-out of public EV charging infrastructure in the EU. Is the chicken and egg dilemma resolved?" *Transp. Environ.*, Sep. 2018. [Online]. Available: https://www.transportenvironment.org/discover/roll-out-public-ev-charging-infrastructure-eu/

[13] *Realizing High Power Charging Networks for Europe*. Accessed: Oct. 2022. [Online]. Available: https://www.polisnetwork.eu/wp-content/uploads/2019/10/8-MEGA-E-high-power-charging-network-Frank-Verhulst-Allego.pdf

[14] *Automobile Club Italia. Dati e Statistiche*. Accessed: Oct. 2022. [Online]. Available: http://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche.html

[15] *Ministero Dello Sviluppo Economico*. Accessed: Oct. 2022. [Online]. Available: https://ecobonus.mise.gov.it/

[16] D. Franceschini, V. Cirimele, and M. Longo, "Analysis of possible scenarios on the future development of electric mobility: Focus on the Italian context," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, Oct. 2021, pp. 1–6.

[17] A. Stabile, M. Longo, W. Yaïci, and F. Foiadelli, "An algorithm for optimization of recharging stops: A case study of electric vehicle charging stations on Canadian's Ontario highway 401," *Energies*, vol. 13, no. 8, p. 2055, Apr. 2020.

[18] P. Jochem, E. Szimba, and M. Reuter-Oppermann, "How many fast-charging stations do we need along European highways?" *Transp. Res. D, Transp. Environ.*, vol. 73, pp. 120–129, Aug. 2019.

[19] G. Napoli, A. Polimeni, S. Micari, L. Andaloro, and V. Antonucci, "Optimal allocation of electric vehicle charging stations in a highway network: Part 1. Methodology and test application," *J. Energy Storage*, vol. 27, Feb. 2020, Art. no. 101102.

[20] G. Napoli, A. Polimeni, S. Micari, G. Dispenza, and V. Antonucci, "Optimal allocation of electric vehicle charging stations in a highway network: Part 2. The Italian case study," *J. Energy Storage*, vol. 26, Dec. 2019, Art. no. 101015.

[21] *Autostrade Per l'Italia Website*. Accessed: Oct. 2022. [Online]. Available: https://www.autostrade.it/it/la-nostra-rete

[22] M. Khalid, F. Ahmad, B. K. Panigrahi, and L. Al-Fagih, "A comprehensive review on advanced charging topologies and methodologies for electric vehicle battery," *J. Energy Storage*, vol. 53, Sep. 2022, Art. no. 105084.

[23] CHAdeMO Website. *High Power (ChaoJi)*. Accessed: Oct. 2022. [Online]. Available: https://www.chademo.com/technology/high-power

[24] D. Anil and P. Sivraj, "Electric vehicle charging communication test-bed following CHAdeMO," in *Proc. 11th Int. Conf. Comput., Commun. Netw. Technol. (ICCCNT)*, Jul. 2020, pp. 1–7.

[25] C. Suarez and W. Martinez, "Fast and ultra-fast charging for battery electric vehicles—A review," in *Proc. IEEE Energy Convers. Congr. Exposit. (ECCE)*, Oct. 2019, pp. 569–575.

[26] M. Khalid, F. Ahmad, and B. K. Panigrahi, "Design, simulation and analysis of a fast charging station for electric vehicles," *Energy Storage*, vol. 3, no. 6, Dec. 2021.

[27] W. Khan, A. Ahmad, F. Ahmad, and M. S. Alam, "A comprehensive review of fast charging infrastructure for electric vehicles," *Smart Sci.*, vol. 6, pp. 256–270, Jul. 2018.

[28] (Jun. 2020). *How to Keep Your Battery in Good Shape During Periods of Inactivity*. Accessed: Oct. 2022. [Online]. Available: https://incharge.vattenfall.de/en/knowledge-hub/articles/how-to-keep-your-battery-in-good-shape-during-periods-of-inactivity,

[29] A. Hoke, A. Brissette, D. Maksimović, D. Kelly, A. Pratt, and D. Boundy, "Maximizing lithium ion vehicle battery life through optimized partial charging," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. (ISGT)*, Feb. 2013, pp. 1–5.

[30] R. Wolbertus and R. Van den Hoed, "Electric vehicle fast charging needs in cities and along corridors," *World Electric Vehicle J.*, vol. 10, no. 2, p. 45, Jun. 2019.

[31] F. Ahmad, M. Khalid, and B. K. Panigrahi, "An enhanced approach to optimally place the solar powered electric vehicle charging station in distribution network," *J. Energy Storage*, vol. 42, Oct. 2021, Art. no. 103090.

[32] R. Wolbertus and R. van den Hoed, "Fast charging systems for passenger electric vehicles," *World Electric Vehicle J.*, vol. 11, no. 4, p. 73, Nov. 2020.

[33] S. Rajagopalan, A. Maitra, J. Halliwell, M. Davis, and M. Duvall, "Fast charging: An in-depth look at market penetration, charging characteristics, and advanced technologies," in *Proc. World Electric Vehicle Symp. Exhib. (EVS)*, 2013, pp. 1–11.

[34] J. Asamer, M. Reinthaler, M. Ruthmair, M. Straub, and J. Puchinger, "Optimizing charging station locations for urban taxi providers," *Transp. Res. A, Policy Pract.*, vol. 85, pp. 233–246, Mar. 2016.

[35] H. Liimatainen, O. van Vliet, and D. Aplyn, "The potential of electric trucks—An international commodity-level analysis," *Appl. energy*, vol. 236, pp. 804–814, Feb. 2019.

[36] Associazione Italiana Socieà Concessionarie Autostrade e Trafori–Aiscat. (Jun. 2021). *Dati Provvisori Delle Autostrade Italiane*. Accessed: Oct. 2022. [Online]. Available: https://www.aiscat.it/wp-content/uploads/2021/09/AISCAT-Mensile-06-Giugno-2021.pdf

[37] A. M. De Souza, C. A. Brennand, R. S. Yokoyama, E. A. Donato, E. R. Madeira, and L. A. Villas, "Traffic management systems: A classification, review, challenges, and future perspectives," *Int. J. Distrib. Sensor Netw.*, vol. 13, no. 4, pp. 1–14, 2017.

[38] C. Antoniou, R. Balakrishna, and H. N. Koutsopoulos, "A synthesis of emerging data collection technologies and their impact on traffic management applications," *Eur. Transp. Res. Rev.*, vol. 3, no. 3, pp. 139–148, Nov. 2011.

[39] F. Lo Franco, R. Mandrioli, M. Ricco, V. Monteiro, L. F. C. Monteiro, J. L. Afonso, and G. Grandi, "Electric vehicles charging management system for optimal exploitation of photovoltaic energy sources considering vehicle-to-vehicle mode," *Frontiers Energy Res.*, vol. 9, Nov. 2021, Art. no. 716389.

[40] P. H. Divshali and C. Evens, "Behaviour analysis of electrical vehicle flexibility based on large-scale charging data," in *Proc. IEEE Milan PowerTech*, Jun. 2019, pp. 1–6.

[41] F. Lo Franco, V. Cirimele, M. Ricco, V. Monteiro, J. L. Afonso, and G. Grandi, ''Smart charging for electric car-sharing fleets based on charging duration forecasting and planning,'' *Sustainability*, vol. 14, no. 19, p. 12077, Sep. 2022.
[42] Y. Zhang, R. Xiong, H. He, and W. Shen, ''Lithium-ion battery pack state of charge and state of energy estimation algorithms using a hardware-in-the-loop validation,'' *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4421–4431, Jun. 2017.
[43] X. Shi, J. Pan, H. Wang, and H. Cai, ''Battery electric vehicles: What is the minimum range required?'' *Energy*, vol. 166, pp. 352–358, Jan. 2018.
[44] C. Caruso, ''Why range anxiety for electric cars is overblown,'' *MIT Technol. Rev.*, 2016.
[45] N. Carey and P. Lienert. (Jul. 2022). *For EV Battery Makers, It's Go Small or go Home*. Accessed: Oct. 2022. [Online]. Available: https://www.reuters.com/technology/ev-battery-makers-its-go-small-or-go-home-2022-07-11/
[46] G. H. Ruffo. (Feb. 2021). *Audi's CEO Thinks EVs Will Have Less Range Due To Costly Battery Packs*. Accessed: Oct. 2022. [Online]. Available: https://insideevs.com/news/488469/audis-ceo-evs-less-range-costly-battery/
[47] H. C. Manual, ''HCM2010,'' Transp. Res. Board, Nat. Res. Council, Washington, DC, USA, Tech. Rep., 2010, vol. 4. [Online]. Available: https://www.trb.org/Main/Blurbs/164718.aspx
[48] *QGIS Website*. Accessed: Oct. 2022. [Online]. Available: https://www.qgis.org/it/site/about/index.html
[49] *Open Data of the Istituto Nazionale di Statistica*. Accessed: Oct. 2022. [Online]. Available: https://www.istat.it/it/archivio/104317
[50] *Pubblicazioni Motus-E*. Accessed: Oct. 2022. [Online]. Available: https://www.motus-e.org/pubblicazioni-motus-e

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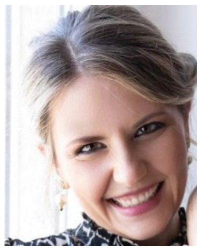

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Open Access funding provided by 'Alma Mater Studiorum - Università di Bologna' within the CRUI CARE Agreement