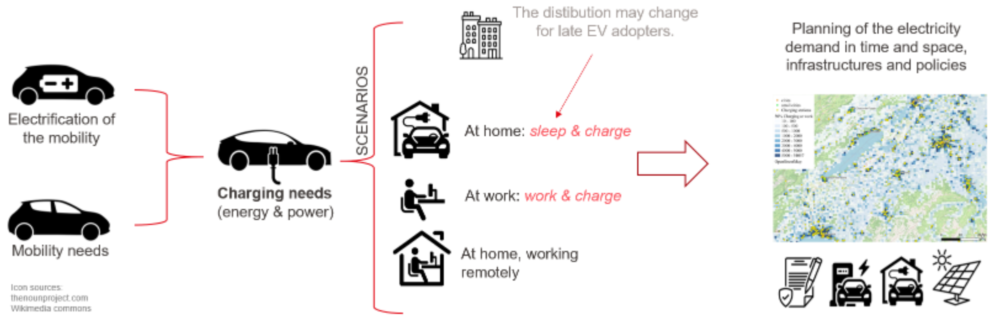
Graphical Abstract

Mapping the charging demand for electric vehicles in 2050 from mobility habits

Noémie Jeannin, Alejandro Pena-Bello, Christophe Ballif, Nicolas Wyrsch



Highlights

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- This paper presents a new methodology to quantify the charging needs of electric vehicles based on mobility habits.
- Charging needs are higher in cities, despite shorter commute distances and a lower motorisation rate.
- Charging behaviours such as charging at work and while working from home have a significant impact on the additional demand for electric vehicle charging in the evening, especially in suburban areas.

Mapping the charging demand for electric vehicles in 2050 from mobility habits

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Abstract

This paper proposes a method to spatially model and compare charging needs on the European scale considering local disparities in population density, distance to city centres, car ownership and mobility habits. Mobility habits are modelled across Europe in terms of distance and time frame, to elaborate scenarios of charging behaviour. The first step of the method is to calculate the density of electric vehicles with a resolution of $1\,km^2$, according to the progressive electrification of the fleet each year between 2020 and 2050. The second step is to quantify the mobility of commuters using their driving distance to work areas and mobility statistics. The model is then applied in a case study in Switzerland to plan the public charging infrastructure required to satisfy the charging needs of the local population. The results show a stronger need for charging in cities despite lower motorisation rates and driving distances. With 50% of commuters charging at work and 20% at home during the workday, the demand in the evening can be reduced by 50% in the suburban areas compared to the baseline scenario in which all commuters are charging at home in the evening. This model can be used to quantify the energy needs of commuters, plan the deployment of the charging infrastructure, or simulate the effect of policies.

Keywords: charging demand, electric vehicles, map, mobility, GIS

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1. Introduction

The number of electric vehicles is expected to increase significantly in the next few years. They already represented 21% of newly registered passenger cars in Europe in 2022 and 25% in Switzerland in 2022 [1]. Both the European Union and the Swiss Confederation are taking strict measures to accelerate this growth. The European Union established a complete ban on internal combustion engine vehicle (ICEV) sales from 2035 and the Swiss Confederation set a goal of 50% share of electric vehicle (EV) in the new registrations in 2025 [2, 3, 4].

To meet the needs of this growing fleet, the recharging infrastructure must develop rapidly. The International Energy Agency recommends installing at least one charging point per 10 EVs to ensure the quality of service of charging infrastructures, which will lead to more than 15 million units in 2030 [5, 6, 7]. Regional particularities must be carefully studied to adapt this number of chargers per EV, according to local charging needs. The number and type of charging stations vary between rural and urban areas. According to several studies [8, 7, 9], regions with extreme climates or long travel distances will have a higher energy consumption and therefore will require more charging stations. A more accurate estimate of the required number of charging station (CS) would also include the capacity of the batteries in the area, the cost of charging sessions, the average daily mileage and the parking conditions of the households to identify a lack of charging opportunities at home [10, 11].

The optimal location of the charging stations is based on criteria evaluating reachability, proximity to points of interest, other nearby charging stations, and population density. The main challenges highlighted with respect to charging station installation are the lack of space and the need for electric grid reinforcement [7, 12]. Geospatial modelling is particularly suitable to take into account these criteria. In the literature, the optimisation is primarily based on charging demand and then optimised among several possible locations [10, 13, 14]. Some studies also include specifications for the power grid [15, 16, 17], and minimisation of investment cost [17, 18]. The chosen methods are diverse: constrained minimisation [15], data-driven [16], Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), integer programming [18], or Mixed Integer Linear Programming (MILP) [13], and applied at different scales from city to highway network [16] or even country [17]. Multi-criteria decision analysis methods applied for energy planning problems appear to be suitable for EV charging as well [19].

Although charging needs are one of the primary parameters for optimisation of the charging infrastructure, most projections of the charging need in 2050 are aggregated values at the regional or national level and do not rely on precise modelling of mobility at the local scale. This study aims to develop a new methodology to map the geographical distribution of the electricity demand for EV charging from the mobility habits of the car owner, especially with respect to commuting. Observations in Switzerland have shown that commutes to work are the main contributor to daily mobility during the week, moreover, 80% of the acting population are commuters [20, 21]. It is assumed that commuting is also the main contributor to the mobility of other Europeans during the work week. The mobility of commuters is estimated in terms of number of cars, distance driven, and charging locations to estimate their charging needs. The chosen approach is to first establish the electric vehicle density throughout Europe, then to calculate the vehicle travelled distance for work and for other purposes (e.g., leisure, shopping), and to calculate the charging needs. Several scenarios are then used to allocate the obtained charging needs at home or at the workplace over different time frames. This model is open source and will be implemented as a calculation module on the Citiwatt platform, based on Hotmaps [22]. This will contribute to improving decision tools for policy makers and municipalities.

2. Methods

This section explains the methods used to develop the model from the density of the car to their distance travelled on the European scale.

2.1. Electric vehicle density

Estimating the charging needs of a region requires quantifying its mobility and its car usage, in particular. The use of cars as the main mode of transport varies between European countries from 35 to 94% and depends heavily on the density of the population [23]. The European Union comprises 560 passenger cars per $1'000$ inhabitants on average [24]. The first step of this study is to calculate the density of electric vehicles with a resolution of $1\,km^2$, according to the progressive electrification of the fleet between now and 2050.

The base layer is the "GEOSTAT $1\,km^2$ population grid" available from the *Eurostat* website [25]. The vehicle density was deduced from this layer by applying a ratio of 560 passenger cars per 1'000 inhabitants [24].

From Swiss Microcensus data, we can observe that rural households own 20% more cars than the national average. In contrast, urban households own 20% fewer cars than the average [20]. This contrast between urban and rural motorisation rates is considered the same for the European Union. The study of the vehicle fleet evolution in Switzerland from 1990 to 2020, gives us an estimate of the fleet renewal share (i.e., the percentage of the vehicles in the fleet that are replaced by new ones) of 6% per year. This share of fleet renewal is considered to be the same for the European Union. Taking into account the goal of the European Union to reach 100% EV in the new sales by 2035, the share of EV in the new sales every year until 2035 is estimated, assuming a linear evolution. Combining these two pieces of information, the yearly share of EVs is estimated from 2022 to 2050 as a spatial density throughout Europe in car/km^2 (Fig. 1).

2.2. Vehicle kilometre travelled for commuting

The energy consumption of the vehicles is directly related to their vehicle kilometer traveled. This step of the study is based on a geodata set that contains commuting ranges around cities with more than 50 000 inhabitants in Europe [26]. As this data set does not contain city points, they are obtained from Natural Earth [27]. Polygons of equal distance by car to cities (isochrones), with a resolution of 5 km from 5 to 45km, are calculated using the OpenRouteService tool [28] and cropped inside these commuting areas. Figure 2 shows the commuting ranges within Europe. Commuting ranges from [26] covers above 60% of the population. To extend the amount of population covered in this study, a second data set of cities with between 20 000 and 50 000 inhabitants is added from the Natural Earth database [27]. The same process is applied to these smaller cities to obtain isochrones from 5 to 35 km. Both of these commuting ranges cover 87% of the European population.

The value of the isochrone determines the distance between each pixel and the city d_k^{city}. An additional parameter is calculated for pixel less than 60 km near a border, taking into account the share of transborder commuters r_{border} [29]. The average vehicle kilometer traveled (VKT) in each pixel k, is obtained from :

$$VKT_k^{commut} = r_k^{city} \times 2d_k^{city} + r_k^{border} \times d^{border} + (1 - r_k^{city} - r_k^{border}) \times d^{default} \quad (1)$$

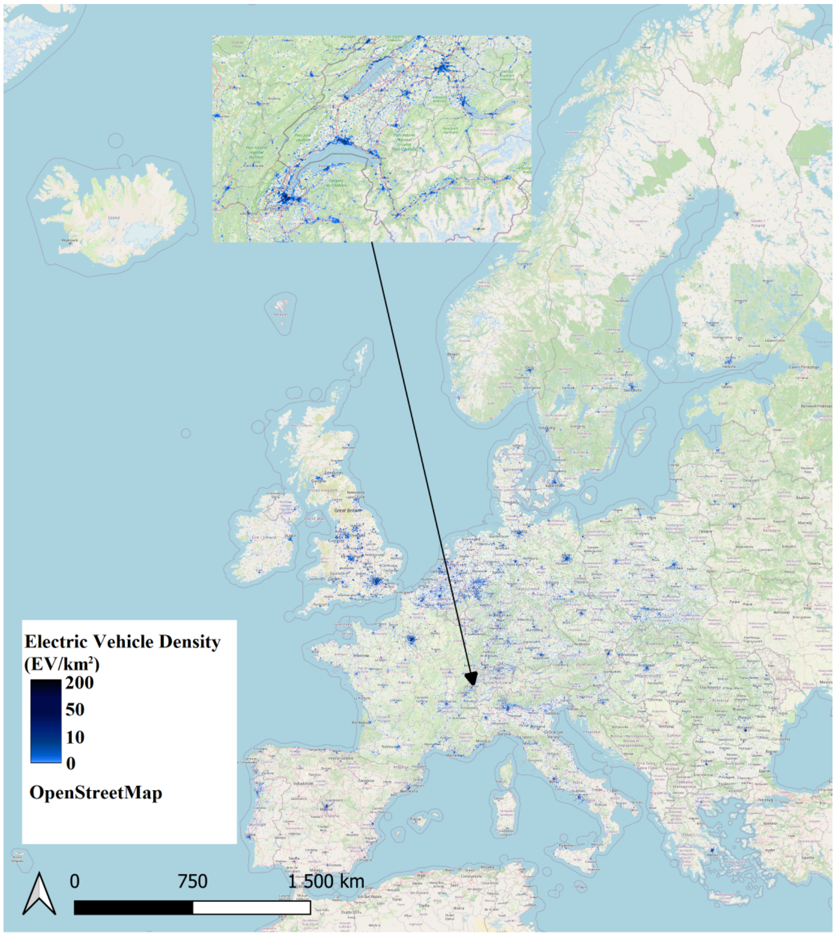

Figure 1: Electric vehicle density in Europe in 2050.

If the pixel is located in two commuting areas, one of a major city $city1$ and one of a small city $city2$, the term $r_k^{city} \times 2d_k^{city}$ becomes :

$$\alpha \times r_k^{city1} \times 2d_k^{city1} + (1 - \alpha) \times r_k^{city2} \times 2d_k^{city2} \tag{2}$$

with α the ratio of commuters who go to the major city while living in a small city commuting area. This calculation outputs a layer of average vehicle kilometer traveled (VKT) per squared kilometre, available in Fig. **??** in the Appendix.

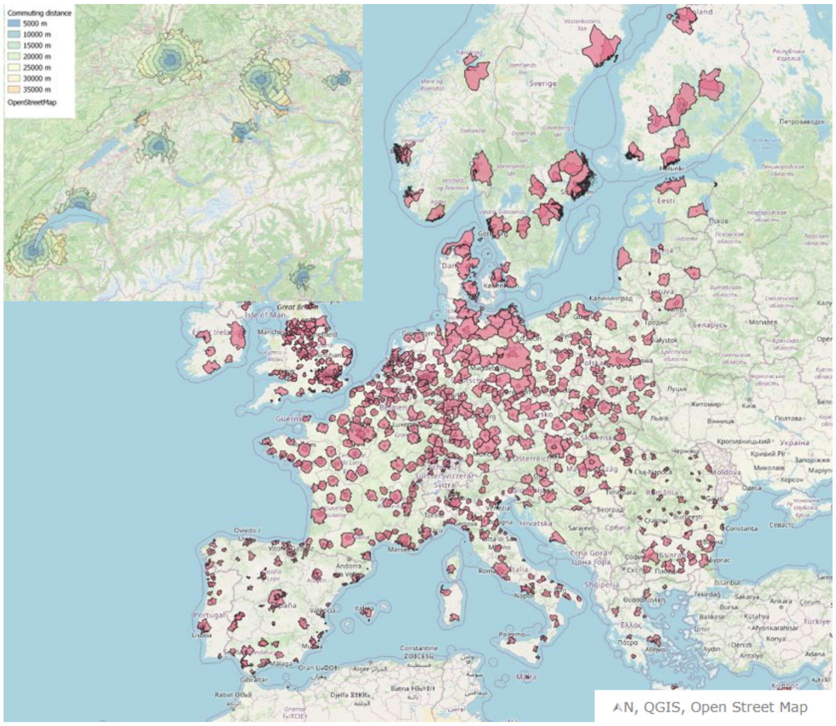

Figure 2: Commuting areas of cities in Europe. Source: Eurostat [26]

2.3. Vehicle kilometre travelled for other purposes

Mobility due to leisure and shopping for commuters has yet to be added to the driven distance for commuting. The total vehicle kilometer traveled (VKT) is then multiplied by the EV density D^{EV} (number EV inside each pixel k) to obtain the total distance driven by all cars in each pixel.

$$VKT_k^{tot} = (VKT_k^{commut} + VKT^{shop} + VKT^{leisure} + VKT^{other}) \times D_k^{EV} \quad (3)$$

2.4. Charging at home

Several scenarios are developed to model the charging behaviour of EV users. As the literature highlights, the worst scenario for grid management would be massive charging at home during existing demand peaks. To assess the impact of EV charging on the grid if all EVs are charging at home, the VKT layer is multiplied by the average electricity consumption of an EV. The assumption is made that EV owners are charging every day and, thus, only recharging what was consumed during one day. The value of $c = 0.183\,kWh/km$ is chosen since the study by Fetene [30] was carried out on a data set from Denmark, which is assumed to be more representative of European car fleets.

$$E_k^{tot} = c \times VKT_k^{tot} \tag{4}$$

2.5. Charging at work

In a scenario where a share β_{work} of commuters charge at work, their VKT^{tot} is applied to the work area of their commuting range. In our study, the Corine Land Cover (CLC) areas are selected as work areas [31].

CLC_CODE	LABEL3
111	Continuous urban fabric
112	Discontinuous urban fabric
121	Industrial or commercial units

Table 1: Selected areas for work in the Corine dataset.

2.6. Home office

A parameter β_{home_office} is defined to account for commuters who charge at home during the day, while working from home. Their VKT^{tot} is applied to their pixel of residence. The charging needs during the home office can be satisfied separately from the charging needs in the evening after work and thus have an effect on the time frame of charging and load curves.

2.7. Current charging infrastructure

A layer of points corresponding to charging stations in Europe has been constructed by collecting data from two sources. Data of the charging stations in Switzerland are from Opendata.swiss [32], and those from the rest of Europe are from Open Charge Map [33].

3. Model analysis

This section gives general remarks on the results given by the method applied to all of Europe. The geographical distribution of the charging needs for commuters was obtained from the density of cars and the distance travelled by the cars to commute depending on the location of residence of the commuter. The layer of electricity required to charge the vehicles of commuters at home with a fully electrified fleet is shown in Fig. 3. We observe that charging needs are higher in city centres, despite the fewer kilometres travelled by car and the fewer cars by inhabitant.

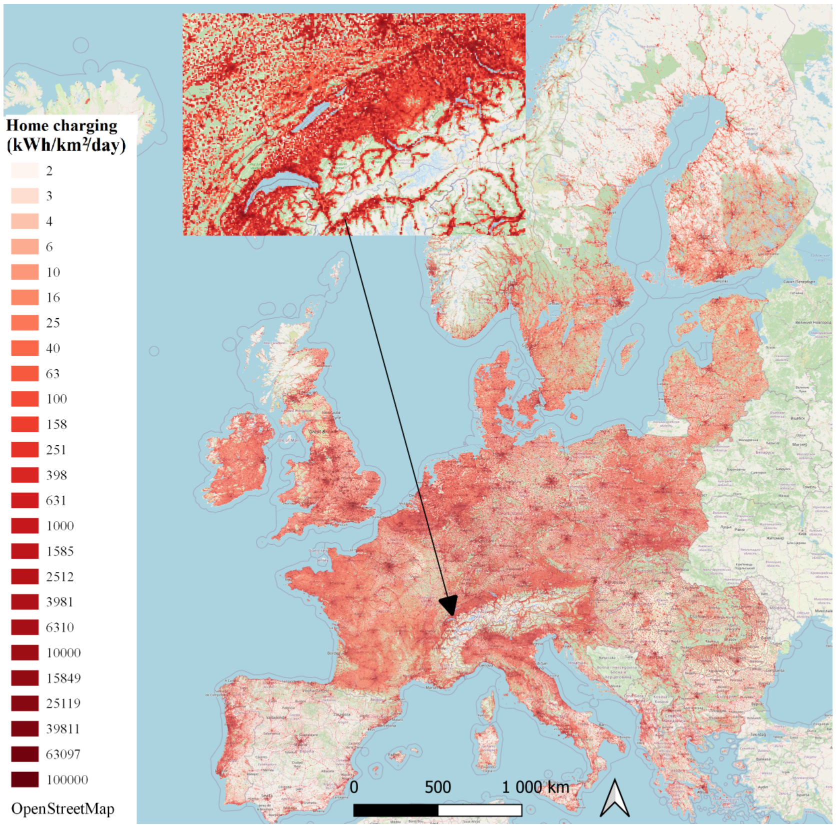

Figure 3: Daily electricity consumption of the EV charge at home, with a fully electrified fleet (in $kWh/km^2/day$).

The layer of charging needs with part of commuters charging at work with a fully electrified fleet is shown in Fig. 4. On a daily average, this tends to exacerbate the demand in the cities while reducing the demand in rural areas slightly. However, the additional demand in the cities does not occur at the same time as the initial demand obtained with the home charging scenario. At home, EV owners tend to charge in the evening, when the overall electricity demand is high. In contrast, work charging occurs during the day, when the overall electricity demand is lower. This consequently has the benefit of smoothing the demand curves.

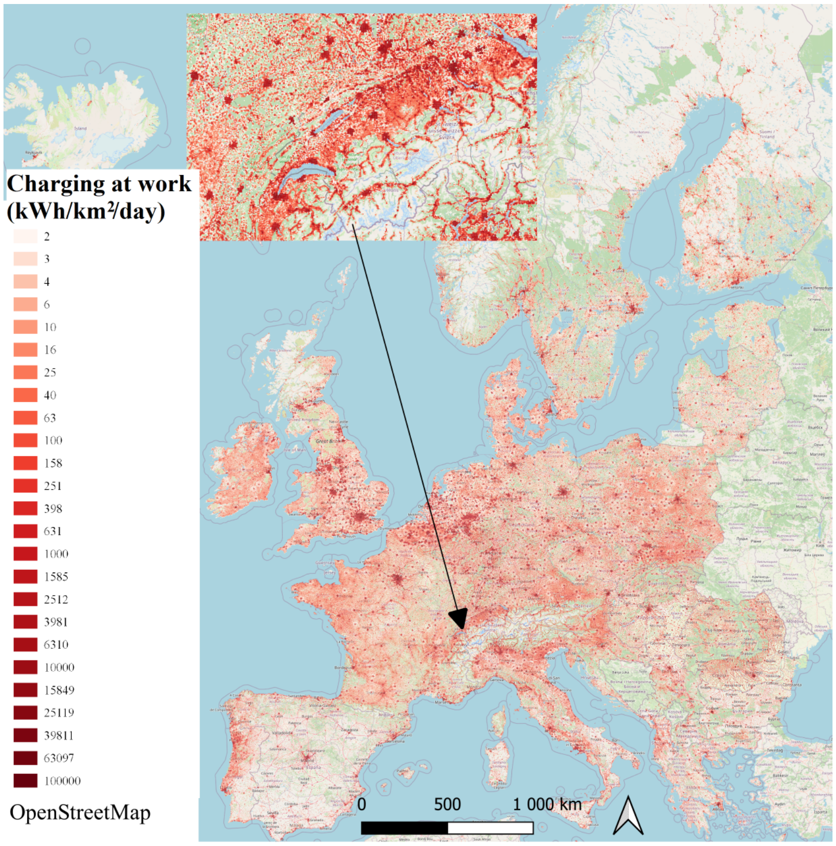

Figure 4: Daily electricity consumption of the EV charge at home and work, with a fully electrified fleet (in $kWh/km^2/day$).

4. Case study in Switzerland

4.1. Parameters

This case study focusses on the western region of Switzerland where the model is applied to quantify the charging needs of the local population in 2050. In 2020, commuters represented 80% of the active population in Switzerland [21] and thus represented a significant share of mobility during the work week.

The charging needs are directly related to the vehicle kilometer traveled (VKT) of EVs. The average daily VKT in Switzerland is 36.8 km (2015, [20]).

In Europe, this distance can vary depending on the type of car, from 34 km for city cars to 75 km for executive cars (Turin, [34]). At least 97% of the VKTs are below 200 km [35, 34]. Despite the large fluctuations in successive daily VKTs, it is possible to find weekly patterns [36]. Transnational commuters are assumed to drive on average $60\,km$ every day ($d^{border} =$ in Eq. 1) [37]. The ratio of commuters who go to the bigger city while living in a smaller city commuting area is assumed to be 0.7 (α in eq. 2).

The statistics given by the Swiss Microcensus on Mobility in 2021 estimated mobility to be around $5\,km$ per day per car for shopping (VKT^{shop}) and $8\,km$ per day per car for leisure ($VKT^{leisure}$) [21].

The baseline scenario for 2050 considers that all commuters charge their vehicles at home in the evening. It is proposed to compare two scenarios from the baseline scenario. First, we assume that 50% of commuters are charging at work during the day (β_{work}). Second, in addition to the 50 % commuters charging at work, we consider an additional 20% of commuters working from home two days per week (β_{home_office}). This reduces the average VKT for commuting of 40% for commuters working from home, and we assume that they charge during the day.

4.2. Results on the VKT

The map of energy demand for this baseline scenario is shown in Fig. 5. Urban areas need a higher charging energy, close to $5000\,kWh/km^2$ per day, whereas other areas are below $2000\,kWh/km^2$ per day.

Compared to the baseline scenario, the two other scenarios show a reduced charging demand in the evening and a higher demand during the day. In other words, the charging energy demand is shifted in time from the evening to the office hours. By charging at work, commuters also shift the demand in space, from residential areas to work areas (industrial areas or city centres). Figures 6 and 7 focus on the share of energy shifted in time, from evening to day, and highlight the spatial variations of this shift. In the first scenario, with 50% of commuters charging at work, the charging needs in the evening are reduced by 35% in suburban areas, as presented in Fig. 6 compared to the baseline scenario. Even if the density of cars is lower in suburban areas, the share of commuters is still relatively high and the distance driven to the city is long ($15 - 20\,km$). In Scenario 2, where we consider the additional 20% of commuters working from home, the shifted energy pattern remains the same (see Fig. 7) but can reach 50% of shifted energy.

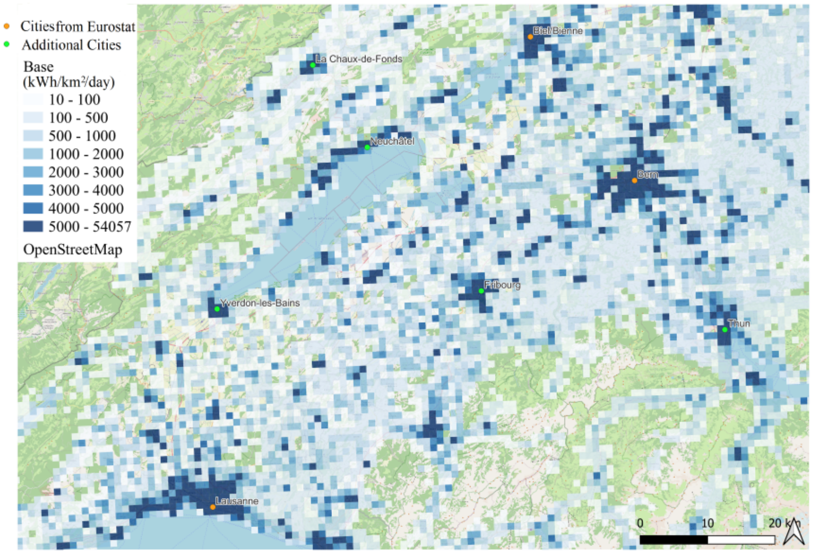

Figure 5: Map of the daily energy needs in a fully electrified fleet. All the commuters are assumed to charge in the evening (base charging scenario)

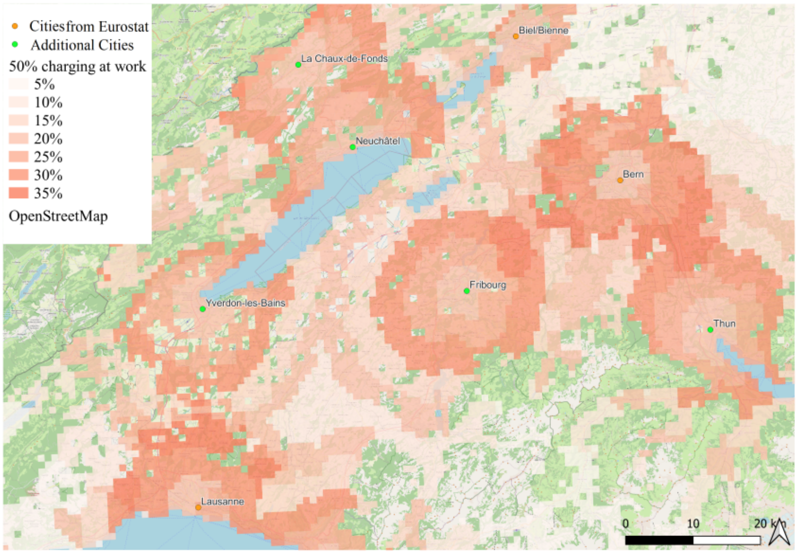

Figure 6: Percentage of the energy needed for charging in the baseline scenario, shifted during the day with 50% of commuters charging at work

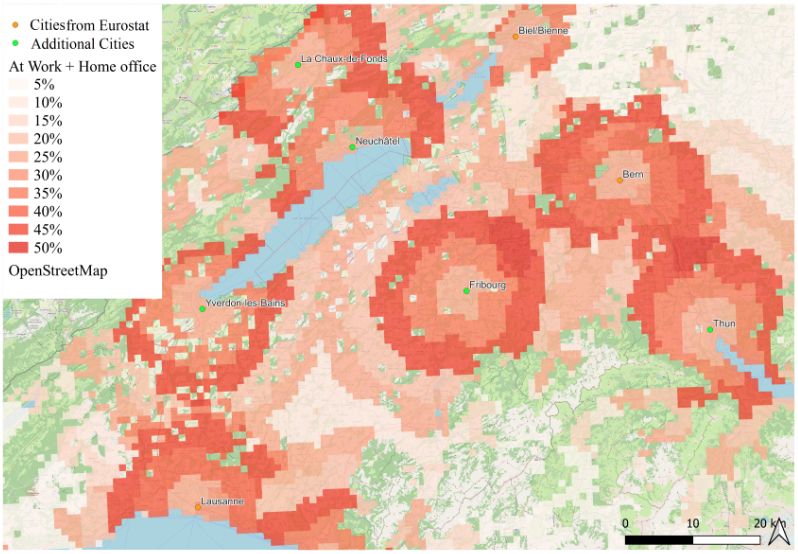

Figure 7: Percentage of the energy needed for charging in the baseline scenario, shifted during the day with 50% of commuters charging at work and 20% of commuters working from home

4.3. Charging stations

In a fully electrified vehicle fleet, probably reached in 2050, it is unlikely that every EV owner would have access to a private charging station. Today in Switzerland, only 24.3% of the dwellings are houses owned by their occupants [38], in this case the choice to have a private charging infrastructure depends only on the owner. For the 14.8% dwellings that are condominium or cooperative, the decision to install a charging station may be more complicated. Finally, in 57.7% of the dwellings, occupants are renting and therefore have limited influence on the choice of having a private charging station. Moreover, only half of the buildings are individual houses, and the other half may not have a private parking space [39]. Public policies will consequently have to promote the installation of private charging stations in rental dwellings and workplaces while deploying public charging infrastructure.

According to the observations of Lee [40], the home and the workplace are the main charging locations if EV owners have access to a charging infrastructure there. EV owners charging mainly at public charging stations are more likely to be a renter of a condominium without a charging station at work. Assuming that roughly two-thirds of rental dwellings and half of co-owned houses will have a private charging infrastructure, 46% of the households will have to rely on other charging options. In this scenario, if half of the workplaces have a charging infrastructure for their employees, about 23% of the EV owners will have to rely mainly on the public charging infrastructure.

A first look at the public charging infrastructure compared to the charging needs (Fig. 8) shows a good correlation between the high-energy-need areas and the existing charging stations. However, charging infrastructures are lacking in some areas of high energy needs and the number of charging stations may not be sufficient to meet all the needs. Some pixels with 7 charging stations are likely to be able to supply 23% of the needs (i.e. $1'150\,kWh/km^2/day$ in cities), but most of the pixels contain 1 or 2 charging stations which is not sufficient in cities.

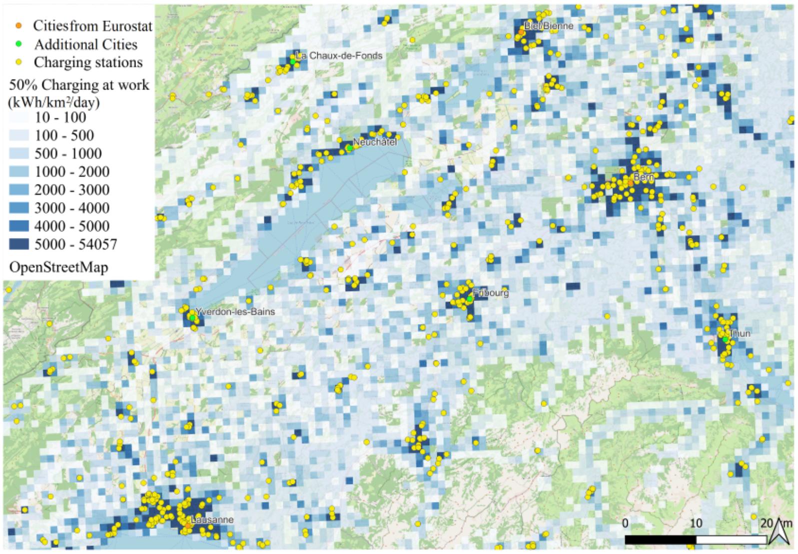

Figure 8: Comparison of charging needs with existing charging infrastructure

5. Discussion

Our results highlighted the need for a massive deployment of the public charging infrastructure. The new charging stations must be installed especially in cities, where the overall charging demand is higher and many work areas and other points of interest are located. However, charging behaviour, such as charging at work or charging while working from home, seems to have a huge effect on the planning of the charging infrastructure. Charging during the day not only reduces the need for electricity, but also shifts the occupation of the chargers from the evening to the day. Thus, fewer charging points are needed to cover the needs. The same effect is obtained by charging at work: fewer charging stations are needed in the evening in residential areas, while the charging stations located in the work areas can still be used in the evening by surrounding residents. Furthermore, charging at work, at points of interest or during home office has a huge potential to improve the use of photovoltaic electricity, as part of the demand is shifted during photovoltaic electricity production period. Policymakers can use this result to draw incentives and policies that would optimise the number of charging station, lower the load on the electric grid and maximise the use of renewable electricity sources.

As this method is based on the mobility habits of commuters, it is especially appropriate for commuting areas during the workweek. Improvements can be made to better take into account mobility for other purposes than commuting to work and outside of typical work hours. For example, leisure and shopping mobility can be refined to take into account rural and urban disparities. Other case studies will help to properly scale and test the model against various local contexts. Partner cities and regions joining the project in its upcoming development will become important locations to compare assumptions and results with real cases and to improve the model.

The sum of the values of the electricity consumption of all pixels in Switzerland gives a daily consumption of $35\,GWh/day$ for commuter vehicles with a fully electrified fleet at the federal level. The value estimated by the EV roadmap is closer to $27\,GWh/day$ [4]. This gap can be explained by the rough estimate of mobility for leisure and shopping, which can be included in commutes.

6. Conclusion

This work aims to develop a method to obtain the geographical distribution of the electricity demand for EV charging from the mobility habits of the car owner, especially with respect to commuting. We presented an approach to map the geographical distribution of the charging need for electric vehicles in Europe with a spatial resolution of $1\,km^2$. The first step of our approach is to quantify the density of electric vehicles every year until 2050. The second step is to establish the travel distance of the cars based on mobility habits for commuting, leisure, and shopping purposes. The results highlight spatial variations between urban and rural areas: a higher demand for charging in the centres of cities and working areas, strongly affected by the rate of vehicles charged at work and at home during work. Working from home and charging at work can shift the initial demand for charging in the evening to the day. A case study in Switzerland in 2050, showed a shift in demand up to 50% in suburban areas with 50% of commuters charging at work and 20% working from home twice a week. This shift offers more potential for using photovoltaic electricity for charging the batteries. The comparison of charging needs with the existing charging infrastructure highlighted areas where the public infrastructure is not sufficient to cover the charging needs of commuters without a charging station at home or at work. As the aggregated demand is similar to the projections of the Swiss EV Roadmap [4], the model seems to give a consistent output on charging needs.

7. Acknowledgments

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Acronyms

CS charging station. 2, 12–14

EV electric vehicle. 2–6, 8, 9, 12–15

ICEV internal combustion engine vehicle. 2

PV photovoltaic. 14, 15

VKT vehicle kilometer traveled. 4–6, 9, 10

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