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From PV to EV: Mapping the Potential for Electric Vehicle Charging with Solar Energy in Europe

Noémie Jeannin[a*], Alejandro Pena-Bello[a], Jérémy Dumoulin[a], David Wannier[b], Christophe Ballif[a], Nicolas Wyrsch[a]

[a]Photovoltaics and thin film electronics laboratory (PV-LAB), Institute of Electrical and Micro Engineering (IEM), École Polytechnique Fédérale de Lausanne (EPFL), Rue de la Maladière 71b, CH-2002 Neuchâtel, Switzerland
[b]Institute of Informatics (II), HES-SO Valais/Wallis, CH-3960 Sierre, Switzerland

ABSTRACT

The electrification of the transport sector is a key element in decarbonizing our societies. However, energy systems will have to cope with additional electricity demand due to the charging needs of electric vehicles (EVs) together with the integration of fluctuating renewable energy sources. Shifting EV charging during the day can contribute to absorbing photovoltaic (PV) production peaks and limiting the additional demand during peak periods. The EV batteries can then be discharged to the grid or home during the evening or other demand peaks. We developed a new methodology to quantify the flexibility gained from the EV-PV coupling from local mobility habits and local (or decentralized) photovoltaic production. Our approach first focuses on the geospatial modelling of mobility habits across Europe to quantify energy demand for charging. The charging demand is then distributed between residential areas, workplaces and points of interest (shopping, leisure, etc.) to model the spatiotemporal distribution of energy needs. We show and discuss a practical case in Copenhagen illustrating the impact of charging behaviour for three different scenarios. The methodology is implemented as a calculation module in the open-source online geographic tool for energy transition planning, *Citiwatts*.

Keywords

Electric Vehicle Charging;
Flexibility;
Solar coupling;
EV-PV coupling;
Geographical analysis

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1. Introduction

The energy transition can pose several challenges for the electricity grid. The increase in electricity demand from electric vehicle (EV) charging and the production peaks from solar panels can both overload the grid. Coordinating EV charging and photovoltaic (PV) power generation can benefit the electric grid. EV charging during PV electricity production peaks reduces the impact of the production peaks on the grid and avoids demand peaks for EV charging in the evening [1,2]. The EV-PV coupling also reduces the CO_2 emissions from driving [2–4], which contributes to the transition toward a fully renewable energy system [4]. At the local scale, PV power can cover fast charging nearby [5,6], or be used over carports [7]. Solar energy production is attractive to EV owners, who have shown a high willingness to install solar panels [8], and having solar panels increases the likelihood of buying an EV [9].

Although the daily vehicle kilometre travelled (VKT) vary from day to day [10], the driven distance was shown to be less than 100 km more than 80% of the days in Italy [11]. In Europe and North America, the driven distance is less than 200 km 97% of the days [12]. A part of the battery is therefore available typically 80 to 90% of the time and can be used as a flexibility asset for PV electricity production if the car is plugged in during the PV production periods. The planning of EV-PV coupling

*Corresponding author – e-mail: noemie.jeannin@epfl.ch

Abbreviations

CS	charging station
EV	electric vehicle
ICEV	internal combustion engine vehicle
OSM	OpenStreetMap
POI	points of interest (restaurants, shops, services)
PV	photovoltaic
VKT	vehicle kilometre travelled

must account for local mobility habits to quantify the VKT.

EV owners are not likely to stop at a charging station solely to charge, unless they travel farther than their battery range allows. This sets them apart from combustion engine car owners who frequently stop at petrol stations for refuelling. EV owners will rather take the opportunity to charge while their EV is idling [13]. Charging at home is currently the most common option and is expected to remain the main charging location for the majority of EV owners in the future [14,15]. For those without access to a charging station at home, charging at work is a common option to have regular access to a charging point [14,15]. The remaining charging events take place at points of interest (POIs), such as shops, restaurants, or cafes, that the EV owner visits for other reasons. Planning for the future charging infrastructure requires a deep understanding of the mobility habits of EV owners and the evolution of demand in time and space [16].

Several studies attempted to quantify the potential of coupling EV charging and PV electricity production to reduce the costs of electricity and CO_2 emissions. EV-PV coupling was studied at a city scale in Kyoto by Kobashi et al. [17] and in Paris by Deroubaix et al. [18] with a techno-economic approach. Both studies used the System Advisor Model (SAM) to quantify the cost-effectiveness and the potential reduction of CO_2 emissions. However, the precise time evolution of the local demand for charging is not studied in detail.

Østergaard et al. [19] showed the potential of vehicle to grid in Denmark to reduce curtailment of off-shore wind turbines with a one hour resolution. Beltramo et al. [20] compared temporal data from a charging infrastructure with a modelled power system to study the effect of V2G on the costs and power curtailment. Mangipinto et al. [21] and Xu et al. [22] created a model to generate trips inside a synthetic population using statistics. The time series of charging demand generated by the models are then compared to the renewable energy overproduction to estimate the potential of V2G in both studies. The open-source model, RAMP from Mangipinto et al. was applied at a country level in Europe. Those three studies include variations in time of the charging demand but the mobility is only obtained through statistics, not with a geographical approach. Moreover, the results are not geographically displayed. The geographical approach for the modelling of the mobility needs proposed in this study generates the charging needs at the hectare scale and takes into account the charging behaviours in the quantification of the flexibility potential.

This article presents a new methodology to quantify the needs for EV charging in an area based on mobility habits, with a geographical approach. The vehicle density and their VKT are obtained from the population density and the mobility habits following the methodology detailed in a previous study [23] and explained in Section 2. Several possible charging locations are then considered to distribute the needs in accordance with the three behaviours listed above: charging at home, charging at work, and charging at POIs, as presented in Section 3. Recently, remote work has become an internationally accepted and a widespread working modality [24], which directly impacts the charging behaviour at home as well as the distance driven, therefore, it is also considered in this study. The methodology has been developed for all Europe and will be implemented in the online platform Citiwatts [25]. In Section 4, the methodology is applied to a case study in the Copenhagen area to quantify the potential of using EV batteries as flexibility assets for photovoltaic production.

2. Methods for Quantifying the Energy Demand for EV Charging

This section details the methodology to quantify the energy demand for EV charging and its distribution over space and time. The methodology used in this section is based on a previous study [23]. The methodology encompasses 3 steps. The first step is to locally quantify the electrification of the vehicle fleet, i.e. to calculate the density of electric vehicles. Then, the distance driven by the vehicles is quantified to estimate the charging demand and different scenarios of charging behaviour are developed, where the demand is distributed between charging at home, work, and points of interest.

2.1. Electric vehicle density map from 2022 to 2050
The annual EV density map is obtained from the population density [26] and the motorization rate [27]. The fleet electrification is then based on a linear evolution of the EV share in the new registrations from 2020 to 2035. From 2035, the new cars are assumed to be electric following the ban on internal combustion engine vehicles (ICEV) pronounced by the European Union [28]. Based on the annual number of new registrations and the size of the fleet, the share of fleet renewal in Europe is around 5% [29,30].

2.2. Vehicle kilometre travelled
The second step is to estimate the kilometres travelled by cars in each area. Commuting to work is the main contributor to daily travelled distance. With over half of the population using cars as their main mode of transportation, it is expected that commuting accounts for a substantial share of the distance travelled [31].

The dataset *Cities and Commuting Zones* from Eurostat [32] contains the commuting areas for each city larger than 50k inhabitants in Europe. OpenRouteService [33], a tool for calculating travel distances, was used to calculate isodistances of driving distance by car to the city centre every 5 km inside the commuting areas. In other words, we calculated polygons of distance by car to the centre of each city every 5 km. An example of isodistances is given in Figure 1. The resulting polygons give an approximation of the driving distance to the city. The original dataset from Eurostat covers about 60% of the population. To increase the amount of population covered to 87%, we included a dataset from Natural Earth [34] covering cities with a population between 20k and 50k inhabitants and proceeded to consider the isodistances around them as in the precedent case.

3. Charging Demand and PV Potential

This section presents the assumptions and parameters considered to model the charging behaviour of EV users and the PV production potential.

3.1. Identifying potential charging locations for EVs
To model the geographical impact of charging behaviour, potential charging places were identified from OpenStreetMap (OSM) [35]. OSM uses tags to identify amenities (see OSM Wiki for a detailed list). Annex 1 presents the amenities corresponding to the main workplaces that were used in this study. These correspond to places where many people are expected to commute every day during office hours, for example, offices, industries, or governmental buildings.

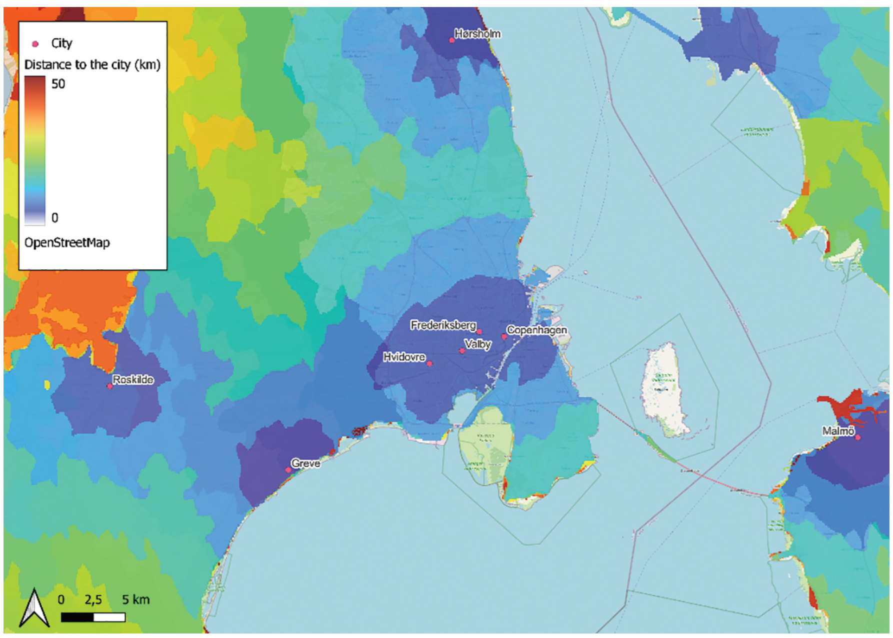

Figure 1: Map of the isodistances around Copenhagen.

POIs such as shops, bars, restaurants, and museums were also collected from OSM [35]. The POIs can be registered in OSM as points or closed polygons (ways). Ways were only considered through their centre points. As the aim is to implement this methodology in an online tool, the datasets must be optimized in size to speed up access to the data by the calculation module and limit the space needed for their storage.

The vector layers of collected POIs and workplaces are thus converted into raster layers with the same properties as the population layer. The resolution of the resulting raster layer is hence 1 hectare. The conversion consists in creating a density map of the POIs and workplaces. The values attributed to each pixel are the sum of the number of respectively POIs and workplaces located in the pixel (Figure 2). This conversion significantly reduces the dataset file size and has the benefit of being more easily readable for the areas with a high density of POIs. Yet, the information on the types of POIs inside of the pixels is lost.

In this version of the methodology, the demand is attributed to every POI and workplace regardless of its tag. This is a strong assumption, discussed later in this paper, given that, for example, a small hairdressing salon has the same weight as a supermarket. The current POI density layer does not consider the size of the building of the POI. However, in the case of a shopping mall, for example, each shop has its own tag and is therefore considered as a POI.

3.2. Charging scenarios

Four charging locations are identified to develop the charging scenarios. The scenario of charging at home entails that the EVs recharge at home the energy required for the VKT driven every day, in the evening (plugged-in from 18:00 to 20:00, unplugged from 6:00 to 8:00). Charging at home is the default option.

Charging at work distributes the charging demand for work over the pixels containing workplaces identified in the previous subsection. The number of workplaces in each pixel is used as a weight for the charging demand. The timeframe for charging at work is 9:00 to 18:00. The framework is the same for charging at POIs, the demand for the commuting area is distributed across the pixels containing POIs, weighted by the number of POIs in each pixel. It is assumed that every commuter is able to find a charging station at work or at the POI he visits.

As mentioned before, remote work also affects the VKT. Within this paper, we hypothesise that the commuters working remotely do so twice a week, thus, their

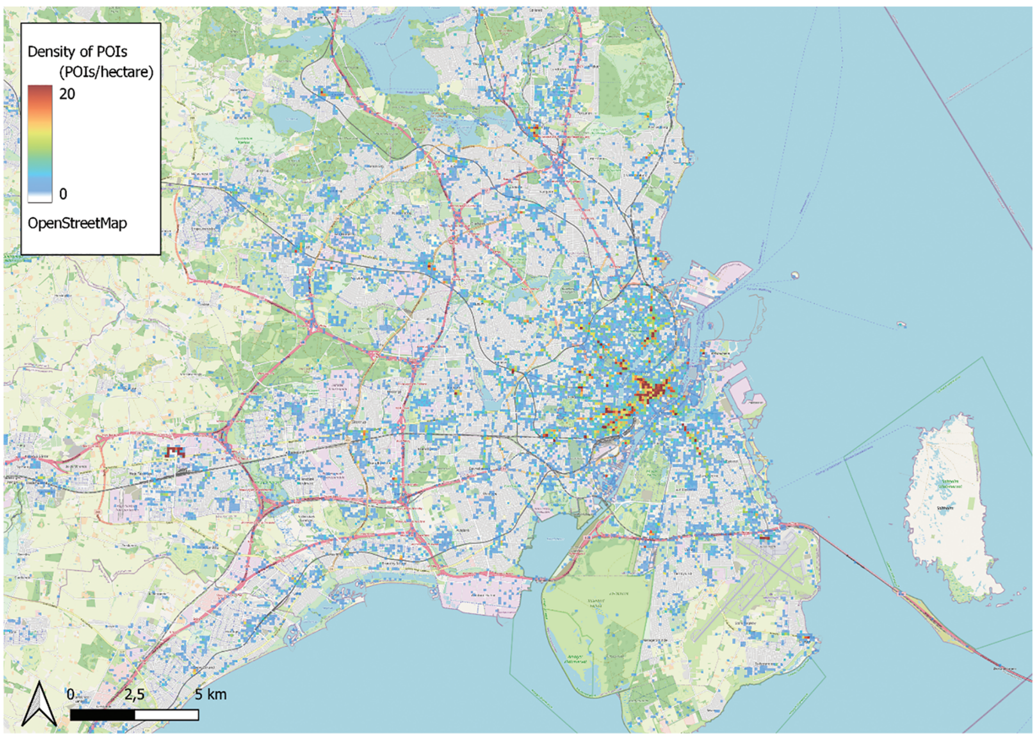

Figure 2: Density of POIs and workplaces per hectare in the centre of Copenhagen obtained from OpenStreetMap.

VKT for commuting is reduced by two-fifths over the work week on average (please note that in the online tool, this is a variable input to be defined by the user). When commuters work from home, they are assumed to recharge the amount of electricity necessary to drive for their three commuting days of the week, during the day. In this study, weekend days are not considered.

3.3. Photovoltaic potential

The potential photovoltaic production is deduced from the potential of solar radiation on building footprints. The area of interest is selected in the dataset from Garegnani & Scaramuzzino [36] collected within the HotMaps project framework (Horizon 2020). The dataset is a combination of the solar irradiance G from PVGIS [37] and the building footprint (abbreviated as Gross Floor Area GFA) from Copernicus [38] as explained by Scaramuzzino [39]. The total building footprint is calculated from the sum of the GFA_i of the pixels i included in the area of interest. The solar potential on building footprint P_{solar} is obtained from the eq. (1).

Three parameters are then used to obtain a realistic value of the average photovoltaic electricity production from P_{solar}. First, a coverage ratio c expresses the percentage of roofs covered by solar PV panels. Second, the efficiency η of the solar panels reflects the energy conversion from the solar radiation to the electricity produced. Finally, a performance ratio PR expresses the difference between theoretical and realistic energy output. The daily average solar production E_{solar} is given by equation (2).

$$P_{solar} = G \times GFA \tag{1}$$

$$E_{solar} = P_{solar} \times c \times \eta \times PR \tag{2}$$

4. Case Study in Copenhagen

The methodology has been developed to be applicable across Europe. In this section, the methodology is applied to a case study in the city of Copenhagen, Denmark to quantify the potential of flexibility for PV offered by the EVs in a fully electrified fleet. The area considered includes København By and Københavns Omegn (DK011 and DK012, according to the Nomenclature of Territorial Units for Statistics (NUTS) [40]).

The population in the area is about 1.38 million people in 2023 [41]. Most of them are living in multi-dwelling houses (90% in 2023 [41]). Over 37% of households in Denmark do not possess a private car, resulting in a lower motorization rate (476 vehicles per 1000 inhabitants [27]) than the European average (560 vehicles per 1000 inhabitants [27]). The rate of renewal of the vehicle fleet in Denmark (8% [41]) surpasses the European average (5% [27]). Hybrid vehicles and EVs have already reached 8% of the fleet in 2023 [41]. The electrification rate is slightly higher in urban areas due to easier access to charging stations (CS) and more incentives [42]. However, the area considered in this study is almost entirely classified as an "urban centre" in the Global Human Settlement Layer [38]. Hence, no spatial variation of the coefficient of electrification is considered in this study.

Almost 53% of the daily mobility in urban areas in Denmark is travelled by car as driver [31]. The average distance travelled per person per day in Denmark is 38.5 km [43]. The average commuting distance in the region of Copenhagen is 23.7 km. Around 69% of the employees are commuting more than 5 km [41]. The distance travelled per car per day is 42 km, including leisure activities. The average EV consumption in Denmark is 0.183 kWh/km [44].

Denmark produced more than 80% of its electricity from renewable sources in 2022, mostly from wind (55%, 19 TWh) and bioenergy (23%) [45]. The share of photovoltaics in the electricity production is only 5.8% [45]. Chatzisideris et al. [46] studied the self-sufficiency performance of PV at residential buildings in Greece and Denmark. The study demonstrated that the lower direct solar radiation in Denmark (up to 450 W/m^2 in June [37]) had only a limited impact on the sufficiency and cost-effectiveness of PV, whereas the impact of electricity consumption profiles on the same parameters was non-negligible. Thus, the flexibility offered by the EV-PV coupling is especially interesting in Denmark, where electricity consumption profiles are less superposed with the solar radiation profile and the EV fleet is rapidly growing. Since we are considering only local generation, wind power is out of the scope of this study.

4.1. Charging scenarios

Table 1 presents the four charging scenarios investigated. The first scenario is a baseline where all commuters charge at home in the evening. This scenario presents the lowest compatibility with PV energy for EV recharging due to the inherent mismatch of generation and demand, however, it is the most current charging behaviour of the population in Europe.

In Scenario A, half of the commuters charge at work and half charge at home in the evening. This scenario illustrates a case where companies have been incentivised to provide charging stations for their employees.

In scenario B, half of the commuters charge at work, 20% of the commuters work from home and charge at home during the day, and 30% charge at home, in the evening. This scenario depicts a situation in which remote work is permitted and encouraged for employees. The implementation of home office policies is expected to reduce travel distance for employees and enable EV owners to recharge their vehicle by self-consuming PV electricity from their neighbourhood.

In Scenario C, 30% of commuters charge at work, 20% charge at home during the day, 20% charge at points of interest, and the rest charge at home in the evening. This scenario illustrates a situation in which the EV owner without a charging infrastructure at home do not only rely on work charging, but also charge at POIs.

Table 1: Charging scenarios considered for the case study in Copenhagen

	Baseline	A	B	C
At home (evening)	100%	50%	30%	30%
At work	0%	50%	50%	30%
Working from home	0%	0%	20%	20%
At POIs	0%	0%	0%	20%

4.2. Results on the charging needs

The overall charging demand is estimated to be about 2.8 GWh per day (see Figure 3). Certain charging behaviours are more appropriate to maximise the use of PV electricity for charging. During periods of PV production, electric vehicles can use PV electricity for first recharging for their daily mobility needs and then for storing any electricity overproduction.

Charging at work, at points of interest or during home office hours shifts demand from the evening to the daytime, during the PV production period, and from residential areas to centres. In Scenario A, 45% of the demand is shifted during the work hours and the total demand is the same as in the baseline scenario. In Scenario B, the total demand is reduced by 3.5% due to remote working. In Scenario C, up to 50% of the demand is shifted from the evening to the day, and from residential areas to areas with economic activities compared to the baseline scenario.

The geographical shift is particularly visible in peri-urban areas. As shown in Figure 4, the charging demand per hectare is mostly above 200 kWh/day in the baseline scenario and shrinks to about 100 kWh/day in the residential areas in the evening. The rest of the demand is reported to centres and industrial areas during the day.

4.3 Resulting load curves from the EV charging

The time series for workplace was obtained from Lawson et al. [47], who collected data from 105 stations at workplaces in the United States. As the tariff used for

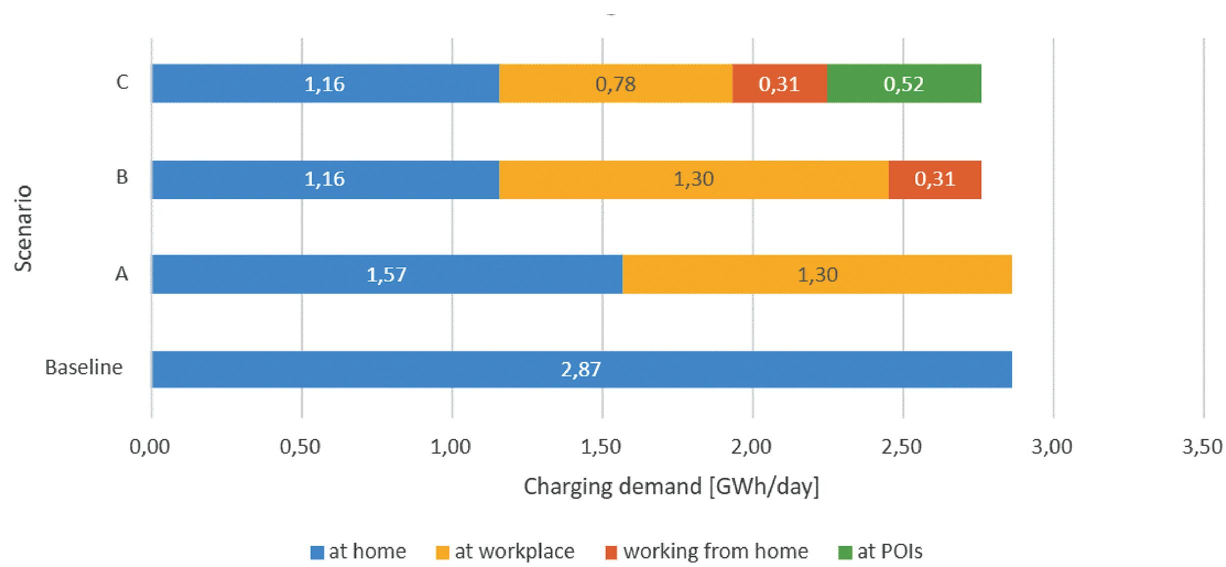

Figure 3: Resulting aggregated charging needs in the area for each scenario in GWh.

the study included a time penalty, the cars are assumed to be charging during all the plugged-in time.

The time series for POIs was constructed from the recording of CS occupation data in Switzerland, which are publicly available on the platform jerechargemonauto.ch [48]. For simplification purposes, the public CS were assumed to have a maximal power of 11 kW, so the maximal charging time is 4 hours. After this duration, the cars are not considered to be charging anymore.

The time series for private CS occupation was obtained from Sorensen et al. [49]. The data were used in two different charging behaviours. Firstly, the cars are supposed to start charging as soon as they are plugged in. In this case, the charging time does not exceed 4 hours. Secondly, a behaviour including smart charging assumes that the cars are charging during all the time they spend plugged in. In this case, the power is adapted to the available time for charging.

The obtained time series were normalized to a unit area under the curve. The profiles are then multiplied by the amount of energy corresponding to each behaviour for each scenario. Figure 5 shows the results for the Baseline (in red) and Scenario C (in blue). The demand peak in Scenario C has been reduced by 27% compared to the Baseline and shifted in time from 19:00 to 12:00. For this reason, Scenario C is more compatible with the PV production timeframes.

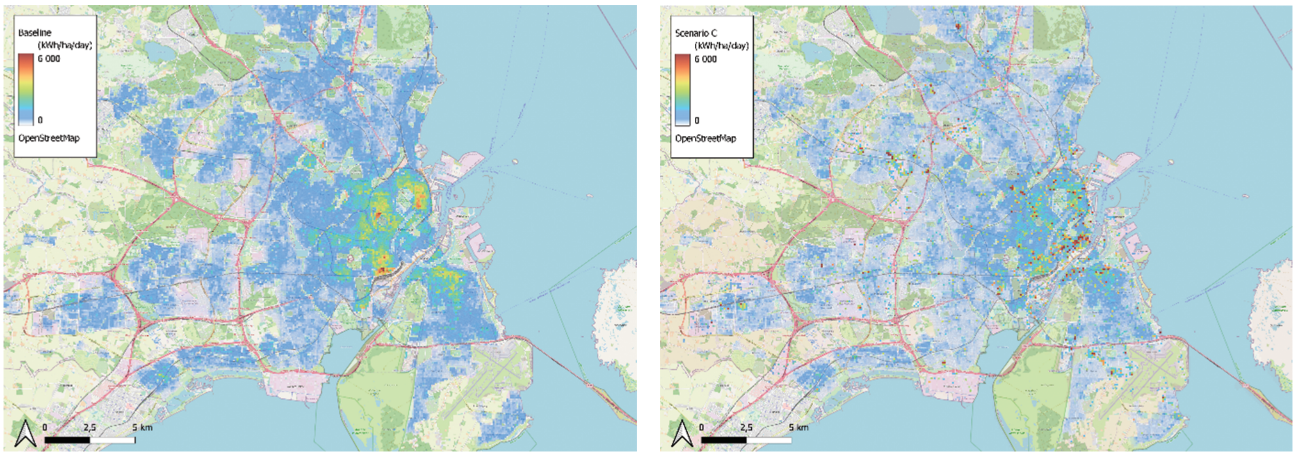

Figure 4: Daily charging needs for the baseline scenario and Scenario C in kWh per hectare per day in the region of interest. Please note that in both scenarios the total demand is the same.

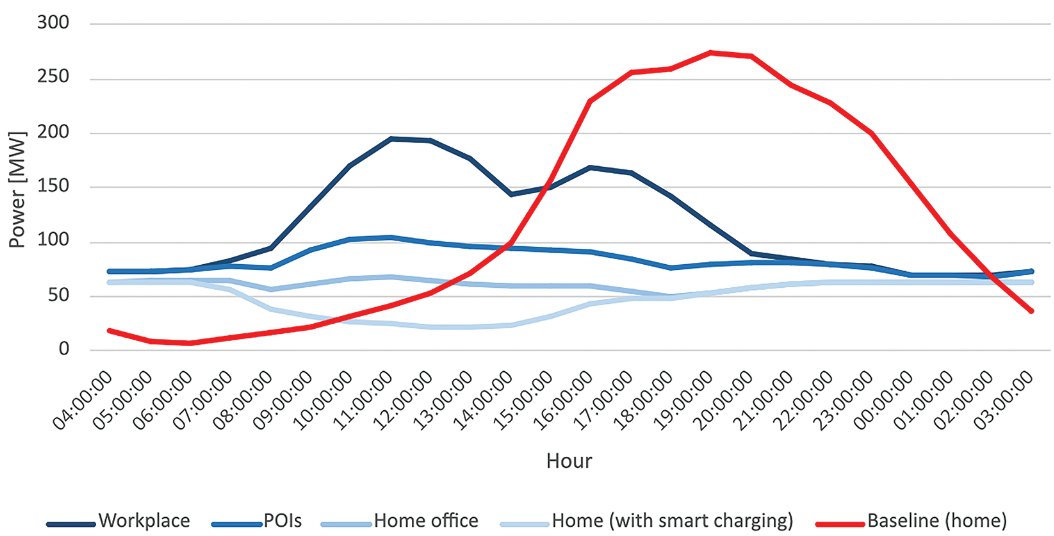

Figure 5: Load curves of EV charging obtained for the Baseline and Scenario C.

4.4. Photovoltaic production

In this case study, we assume that 30% of the building footprint is covered with PV panels, which have an efficiency of 20% and a performance ratio of 80%. In June, the average production over the years 2005-2020 was 175 kWh/m^2/month, while in December, the average production over the same period is 10 kWh/m^2/month [37]. The building footprint in the region of interest is 115 km² [38]. The average PV electricity production for a day in June is 32 GWh and covers much more than 100% of the charging needs. In December, the average daily production is 1.8 GWh and thus covers only 63% of the total charging needs.

However, not all the charging events occur during the production period of solar panels. In Copenhagen, the PV production period in June is from 7:00 to 19:00 and in December is from 8:00 to 15:00 [37]. In this timeframe, only the vehicles charging at work, during home office or at POIs are plugged in. In the baseline scenario, all the vehicles are charging in the evening, and the PV electricity cannot be used directly to recharge the batteries. In Scenario A, the charging demand during the day is 1.57 GWh and in Scenarios B and C, it is 1.64 GWh. Even in December, the average daily production is enough to cover the charging needs during the day. Scenarios A, B and C are consequently more suitable for the use of PV electricity to recharge the batteries.

4.5. Local flexibility from EV batteries

Without local flexibility assets, such as EVs, the PV overproduction on the sunny days of June is not used locally and is directly reinjected into the grid. This section will focus on using EV batteries as a local flexibility asset for PV electricity production.

Flexibility is limited by the total battery capacity of the fleet in the area remaining after subtracting the capacity used for mobility. As the average Danish motorisation rate is 476 vehicles per 1000 inhabitants [27], the total number of cars in the considered area is around 587’000 cars. With an average battery capacity of 45 kWh in each car [50], the total battery capacity of the EV fleet in the area is 26.4 GWh. As presented in the previous subsection, the daily mobility requires 2.8 GWh/day (11% of the total battery capacity of the fleet). Hence, a theoretical maximum of 23.6 GWh/day is available for flexibility. This value must be compared with the state of charge and availability of the EVs during the PV production period. In Scenario C, 70% of the EVs are charging during the day. In this scenario, the maximum capacity available during the day would be 16.5 GWh/day.

4.6. Results of the case study

The average daily PV production for every month of the year is shown in Figure 6. Except in December, the daily production of the PV scenario is enough to cover the daily charging needs on average. On cloudy days, the PV electricity production may not be sufficient to cover the charging needs of the whole fleet. From March to October, the average daily production exceeds twice the demand for charging. In this case, we can imagine that the EVs recharge on sunny days for several days.

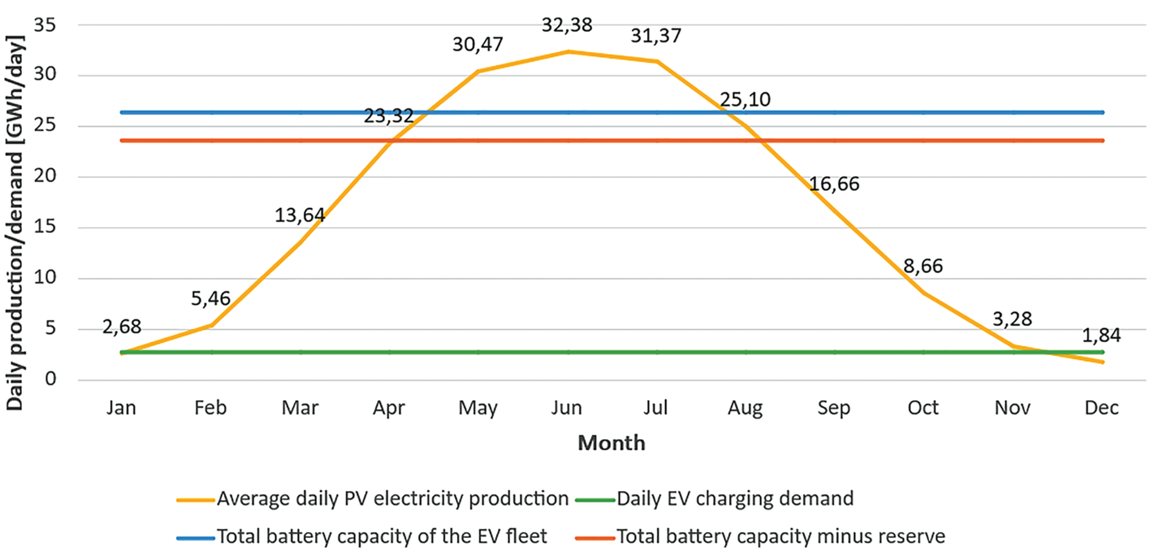

Figure 6: Comparison between charging needs and average daily PV electricity production.

Moreover, not all the charging events occur during PV production periods. As explained in Section 4.2, in the three studied scenarios, the maximal demand for charging during the day is 1.4 GWh. The charging demand during the day can be covered by the average daily PV electricity production for every month of the year. The remaining capacity of 23.6 GWh/day of the EV batteries can be used as daily storage for the overproduction of sunny days. As shown in Figure 6, the theoretical battery capacity can store at least 90% of the PV electricity production from August to April, if all the cars are plugged in during the day. In practice, it is more likely that a share of the capacity of each battery will be kept as reserve and not be used for flexibility. For example, if a commuter charges their electric vehicle at work, they are likely to reserve enough charge to get home in case the PV production would not be sufficient on that day. A reserve equal to the daily charging demand was thus subtracted from the total battery capacity in Figure 6. With the reserve, the total battery capacity of the fleet could store the PV production from September to March.

The results can lead to different policies to incentivise the use of PV electricity for EV charging at a regional scale. In 2023, there were 816 public charging stations close to POIs in the region of Copenhagen [51]. Installing PV panels close to charging stations with high occupation during the day will give the possibility to EV users to recharge their batteries with local renewable energy for driving or for their home (i.e. V2H). For companies, installing PV on their roof can supply the additional energy needs from the EV charging needs of their employees. For commuters who can work remotely for several days in the week, installing PV on their roof can enable them to recharge their EV for their daily mobility on the next week. The inhabitants who are not using their cars to commute can use their EVs as a direct flexibility asset for the PV production of their neighbourhood. As Copenhagen has a quite low irradiance compared to the rest of Europe, this case study reveals a potential for EV-PV coupling in other cities with higher irradiance.

5. Conclusions

This paper presents a new methodology to quantify the potential for coupling electric vehicle charging and photovoltaic electricity generation. The methodology is based on the daily travelled distance of cars obtained from the study of the mobility habits of commuters. The charging demand resulting from the total charging distance in the area is distributed between different charging behaviours: charging at home, at workplace and at POIs. Then, potential charging locations are identified from OpenStreetMap, to affect spatially the charging demand to the places corresponding to the different charging behaviours. The methodology was applied in a case study in Copenhagen to quantify the potential battery capacity of an electric vehicle fleet available as a flexibility asset for photovoltaic electricity generation. The temporal and geographical impact of charging behaviours was compared to a baseline through three scenarios.

The results highlight that except in December, 30% of the building footprint covered with PV could on average supply the charging demand for the daily mobility. As the methodology only considers monthly average, it tends to overestimate the PV production, in particular for cloudy or rainy days. Moreover, the amount of PV electricity directly used for recharge is highly dependent on the charging behaviour. In the baseline scenario (i.e. charging mostly at home), the recharge occurs at home in the evening and only very little PV electricity can be used. Charging during work, or at a point of interest allows 45% to 50% more PV electricity (scenarios A, B, C) to be used. In Scenario C, remote work 2 days per week for 20% of the commuters can save 3.5% of electricity and allow them to recharge in residential areas during the day. This behaviour could be beneficial to local energy communities with PV systems for example.

We also found out that only 11% of the total battery capacity of the fleet was used for daily mobility. Thus, 89% of the battery capacity remains available for PV electricity storage and flexibility. With a reserve equal to the daily electricity consumption for mobility, the remaining 78% of the capacity has the potential to store the entire PV production from September to March and at least 70% of the daily production from April to August. The 30% remaining will be injected into the grid to be used locally for other purposes, such as heating systems.

This model is mainly based on commuter mobility. The modelling of mobility for purposes other than work, such as for leisure and shopping, could be refined in terms of distance and timeframe. Charging at POIs (Scenario B and C) was assumed to be during daytime, this is consistent with the analysis of public charging infrastructure usage data from je-recharge-mon-auto.ch [52] but needs to be refined to illustrate the charging behaviour of EV owners in a fully electrified fleet. The timeframe of charging at POI is expected to vary according to the type of POI. For example, a theatre would not have the same affluence period as a museum. To implement the affluence hours of POIs into the model, a distinction must be made on the type of POI in the POI density layer.

Another non-negligible property of POIs is their size. In the current POI density layer, all the POIs have the same weight. However, a small convenience store will not have the same number of customers than a supermarket. An improvement could be made on the POIs density layer by adding weight to the POIs depending on the volume of their building and their type. This would also enable to model at which POI charging infrastructure is more likely to be installed.

Another limitation of the results is that the stochastic aspects of PV production and mobility are not taken into consideration. On cloudy days, the PV production can be very low even during a month with a quite high daily average production. Therefore, the methodology tends to overestimate the potential for flexibility. Further studies must be carried out on quantifying the overestimation.

Copenhagen is a city with low irradiance compared with the European average. As the PV production in our case study can cover the charging needs for daily commuting in Copenhagen, PV electricity charging has a promising potential for cities with higher irradiance. The methodology can be used in other regions of Europe to plan the joint deployment of charging infrastructure and PV panels or design policies to incentivise charging outside the home to reduce grid reinforcement or maximize the use of renewable energy. Partner cities or regions will be used as case studies to adjust the methodology for better representation across diverse locations in Europe.

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Annex 1: Parameters for the OSM Queries

Included countries are:
country_codes = ['AT', 'BE', 'BG', 'HR', 'CY', 'CZ', 'DK', 'EE', 'FI', 'FR', 'DE', 'GR', 'HU', 'IE', 'IT', 'LV', 'LT', 'LU', 'MT', 'NL', 'PL', 'PT', 'RO', 'SK', 'SI', 'ES', 'SE', 'AL', 'AD', 'AM', 'BY', 'BA', 'FO', 'GE', 'GI', 'IS', 'IM', 'XK', 'LI', 'MK', 'MD', 'MC', 'ME', 'NO', 'SM', 'RS', 'CH', 'TR', 'UA', 'GB', 'VA']

The requests of Points of Interest have been performed with the Overpass API [2] (free of charge).

The codes included in each density are listed below:

'work'=['"building"="industrial"','"building"="office"','"company"','"landuse"="industrial"','"industrial"', '"office"', '"amenity"="research_institute"', '"amenity"="conference_centre"', '"amenity"="bank"', '"amenity"="hospital"','"amenity"="townhall"','"amenity"="police"','"amenity"="fire_station"', '"amenity"="post_office"', '"amenity"="post_depot"', '"office"="company"','"office"="government"',];

'highway' = ['"highway"="motorway"', '"highway" ="rest_area"'];

'parkings' = ['"parking"="surface"', '"parking"="multi-storey"', '"parking"="street_side"', '"parking"="underground"', '"park_ride"'];

'school' = ['"amenity"="college"', '"building"="college"', '"building"="university"', '"amenity"="university"', '"amenity"="school"', '"amenity"="school"', '"amenity"="kindergarten"', '"amenity"="library"'];

'health'= ['"amenity"="clinic"', '"amenity"="dentist"', '"amenity"="school"', '"amenity"="doctors"', '"amenity"="hospital"', '"amenity"="pharmacy"', '"amenity"="veterinary"'];

'cafe'= ['"amenity"="cafe"','"amenity"="ice_cream"', '"amenity"="internet_cafe"'];

'supermarket' = ['"shop"="supermarket"', '"shop"="mall"','"shop"= "department_store"', '"shop"= "convenience"'];

'restaurant'= ['"amenity"="restaurant"']; 'fastfood' = ['"amenity"="fast_food"']; 'sport'= ['"sport"'];

'hotel' = ['"tourism"="hotel"', '"building"="hotel"', '"tourism"="guest_house"','"tourism"="apart-

ment"','"tourism"="hostel"','"tourism"="motel"','"tourism"="camp_site"'];

'pubs' = ['"amenity"="bar"','"amenity"="pub"', '"amenity"="biergarten"'];

'theatre'= ['"amenity"="theatre"', '"amenity"="cinema"', '"amenity"="music_venue"', '"leisure"="stadium"'];

'night' = ['"amenity"="nightclub"', '"amenity"="casino"','"amenity"="gambling"','"amenity"="stripclub"'];

'socio' = ['"amenity"="arts_centre"', '"amenity"="community_centre"', '"amenity"="social_centre"', '"amenity"="music_school"', '"amenity"="language_school"'];

'shop' = ['"shop"'];

'tourism' = ['"amenity"="exhibition_centre"', '"tourism"="attraction"','"tourism"="viewpoint"','"tourism"="aquarium "','"leisure"="beach_resort "','"tourism"="gallery"','"tourism"="museum"','"tourism"="theme_park"','"tourism"="zoo"','"tourism"="artwork"'];

Annex 2: List of Communes Included in the Selected Area

Copenhagen City and Copenhagen Region (DK011 and DK012) contains the following municipalities: Copenhagen, Frederiksberg, Dragør, Tårnby, Albertslund, Ballerup, Brøndby, Gentofte, Gladsaxe, Glostrup, Herlev, Hvidovre, Høje-Taastrup, Ishøj, Lyngby-Taarbæk, Rødovre and Vallensbæk.

Annex 3: Table of Results of the Case Study

Table 2: Resulting aggregated charging needs in the area for each scenario

Charging needs (per day)	Base	A	B	C
at home (outside of work hours)	2.87 GWh	1.57 GWh	1.16 GWh	1.16 GWh
at workplace	0	1.30 GWh	1.30 GWh	0.78 GWh
at home (during home office)	0	0	0.31 GWh	0.31 GWh
at points of interest	0	0	0	0.52 GWh
Total charging need	2.87 GWh	2.87 GWh	2.77 GWh	2.77 GWh
Average km per car in the selected area	29 km	29 km	28 km	28 km

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