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A spatiotemporal analysis of photovoltaic electricity storage potential in electric vehicles

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ABSTRACT

Decarbonizing mobility and integrating more renewable sources in electricity production are necessary levers to meet the climate targets. Coupling electric vehicle (EV) charging with photovoltaic (PV) electricity generation could help to provide clean electricity for charging EVs and provide flexibility storage to PV installations. The batteries of the vehicles can then be discharged into the grid to support the electricity supply during periods of high demand. This study uses a GIS-based methodology to analyse the mobility needs of the European population and estimates the charging needs of an electrified vehicle fleet. Charging scenarios are then applied to distribute the charging needs between home, work, and point of interest to quantify the charging demand both in space by hectare and in time by hour. The charging load curves are then compared to a typical PV production to estimate the amount of PV electricity that can be stored locally in the EVs. Considering two charging scenarios (comfort and flexible charging) the spatio-temporal methodology was applied to three cities with varying solar irradiance and mobility patterns: Aalborg (Denmark), Bern (Switzerland), and Palermo (Italy). Results show that 10% of the building footprint covered with PV can cover from 53% (in Alborg) to 61% (in Bern) of the charging need over a year. EVs and PV electricity together can reduce the CO_2 emission related to private cars of 17 to 28% by 2035 compared to the current fuel-based vehicle fleet.

Keywords

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

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1. Introduction

Private road transportation is responsible of 15% of the CO_2 emissions in Europe [1]. Switching from internal combustion engine vehicle (ICEV) to electric vehicles (EVs) has the potential to reduce the CO_2 emissions from driving, but this reduction is highly dependent on the carbon intensity of the energy mix used to recharge the EVs. Therefore, the decarbonisation of the power grid is of primary importance for the maximisation of the environmental benefit of EVs. Photovoltaic (PV) electricity generation provides a clean energy source for EV charging. Its potential can be fully unlocked through smart charging by shifting EV demand to PV production hours, maximizing PV-based charging while also reducing curtailment [2], [3]. Furthermore, electric vehicle batteries can be employed as a daily storage solution for PV electricity. This PV electricity stored in the EVs can then be reinjected into the power grid or houses thanks to vehicle-to-X (V2X) technologies. Consequently, V2X can increase the share of PV electricity in the electricity consumption and thus contribute to further decarbonize the electricity in the power grid. As the potential storage

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List of acronyms

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*
V2X	*vehicle-to-X (grid, home or local energy communities)*

in the EVs in Europe varies depending on local parameter such as mobility habits or solar irradiance, a geographical approach to quantify the potential of storage in the EVs is particularly interesting. Moreover, the large-scale usage of V2X requires investments in bidirectional chargers, active participation of EV owners to plug in both at electricity production and demand peaks, and a clear legislative frame. Therefore, it is important for municipalities and local policymakers to have methods to quantifies the potential electricity storage and flexibility, CO_2 emissions reduction and need for public chargers.

Most existing approaches analysing the interplay between electric vehicles (EVs) and photovoltaic (PV) energy do not account for geographical factors. The potential benefits of coupling electric EVs and PV production has been shown in the literature. Gudmunds et al., showed that the batteries in EVs have the potential to enable self-consumption levels to reach those of stationary batteries at the household level [4]. Mendek et al. have demonstrated the potential of using EVs as country-wide energy storage in Slovenia. [5] Syla et al. created a model based on travel survey data [6] and found out that V2X increases optimal installed PV and reduces battery storage needs in Switzerland. In practice, Fu et al. showed the applicability of solar charging at work by a year-round experiment in China [7]. EV and PV can also be coupled with static storage and heat systems inside of *Smart Local Energy Systems* [8]. However, most existing approaches analysing the interplay between EVs and PV do not account for geographical factors. The aforementioned studies have been based on time analysis only, and have not included geospatial analysis. Several studies used a geographical approach to quantify the charging needs of the EVs but without including the coupling with PV electricity. In their study, Staub et al. employed travel survey data to construct a geographical model of the demand for EV charging [9]. Jiang et al. constructed their model based on travel trajectories, incorporating a representation of charging behaviour [10]. Yousefi et al. employed the load on the road network as the basis for their model, complementing it with a gravity model [11]. Gschwendtner et al. used an agent based model to study the impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load [12], and found that charging behaviour substantially impact the flexibility potential and the demand peak.Those studies used a geographical approach to quantify the charging needs of the EVs but not the coupling with PV electricity. To the knowledge of the authors, only few studies explored the coupling potential between EV charging and PV production with a geographical approach. In their subsequent study, Staub et al. augmented their previous findings with data on solar potential on two days of the year. [13] However, this approach does not fully account for the inherent unpredictability of solar radiation, as recommended by Alrubaie et al. [14] Wanninayaka Mudiyanselage et al. developed a stochastic method using cross probability distribution to assess the spatiotemporal EV-PV coupling capacities, but only on the range of a low voltage network [15]. Yu et al. used statistics to study the spatial-temporal distribution of the charging demand of EVs at the neighbourhood level [16].

The contribution of this paper is twofold: firstly, it employs a geospatial methodology for the estimation of charging requirements, and secondly, it conducts a time analysis over a one-year period to account for the inherent variability in solar production. Moreover, the methodology presented in this paper can be applied using only open data and over a whole metropolitan area. This article presents a methodology for quantifying the potential for integrating EVs and PV in a system that enables the charging of EVs from PV electricity and the utilisation of EV batteries for storing PV electricity. A methodology based on the geographical estimation of the daily vehicle-kilometres driven by EVs is completed by integrating PV analysis to obtain this potential.

This article is structured as follows. The methodology is presented in detail in Section 2. In Section 3, the methodology is tested against two scenarios of charging behaviour and applied to three case studies of cities in Europe to highlight the generalization ability of the methodology: Aalborg, Denmark; Bern, Switzerland; and Palermo, Italy. The results and discussion of the case studies are presented in Section 4. The conclusion is given in Section 5. The methodology described in this article is implemented in Citiwatts [17], an online open-source tool for energy transition planning. The results produced by the methodology are expected to help municipalities and energy planners to plan the deployment of distributed PV installation and incentive the use of V2X as flexibility asset for the PV production.

2. Methods

This section outlines the methodology employed to assess the potential for integrating electric vehicle charging with PV electricity generation. This methodology builds up on a previous work developed to estimates the electric vehicle share and the vehicle kilometre travelled (VKT) with a geographical approach [18]. The novelty of this work is to compare the mobility needs with an all-year-round PV production potential to quantify the potential storage and the CO_2 emissions reductions depending on the PV production variability. The initial step involves determining the local charging demand by quantifying vehicle fleet electrification rate and analysing the distances travelled by the vehicles. Secondly, a series of scenarios are developed, in which the charging demand is distributed between home, workplaces, and points of interest (POIs). In the third step, the potential for PV energy generation is estimated using a model that incorporates radiance data. Then, the PV potential is used to quantify the V2X potential. Ultimately, the CO_2 emissions are quantified based on the coupling potential.

2.1 Mobility Analysis

The motorisation rate is employed to derive the vehicle density map from the population layer. In this study, we used the population layer from the European Joint Research Centre [19], with a resolution of one hectare. It is assumed that the share of EV in the new matriculations will increase in a linear progression until it reaches 100% in 2035, in accordance with the ban on ICEV proclaimed by the European Union [20]. This linear progression in the electrification rate leads to a S-shaped curve in the number of EVs. By applying the aforementioned electrification rate to the vehicle density map, the electric vehicle density map is obtained.

The VKT of the electric cars in an area is based on commuting distances and values for leisure and shopping based on local statistics detailed in the case study. The commuting distance is estimated on a pixel-by-pixel basis using the distance to the nearest urban centre as a proxy. It is assumed that the distance travelled for commuting increases with the distance from the city centre. This distance is obtained with a precision of 5 km through the use of polygons of isodistances to the city centre of the aforementioned cities, shown on Figure 1. The isodistances are cut to match the definition of functional urban areas, including the city and its suburban areas, by Eurostat [21]. The charging needs are derived from the VKT by multiplying it by the average electricity consumption per kilometre of European cars [22].

2.2 Charging behaviour

Once the expected charging requirements have been quantified, the following step is to ascertain the anticipated charging behaviour, with a particular focus on the location where charging is expected to occur. POIs were identified from OpenStreetMap to construct a density map of amenities per hectare. The same process was employed to obtain a density map of workplaces per hectare.

Secondly, the expected charging needs are modelled by scenarios of charging, which are distributed between three locations: the home, workplaces and POIs. Additionally, the scenarios include parameters that enable the refinement of the modelling of charging behaviour over time, namely, the use smart charging at home or not, and the share of people doing home office. The smart charging parameter allows the vehicle to be charged over the entire time period in which it is connected to the charging point. In the absence of this parameter, the vehicles will undergo charging for a period of four hours following their connection to the charging point in the domestic setting. A home office allows a proportion of workers who are based at home to charge their vehicle during two days of the week, thus avoiding the necessity for travel. This will result in a reduction of their total distance driven by 40% over the workweek. They will charge their vehicle during the two days at home for the remainder of the weekdays. The load curves of charging at home are derived from the data on vehicle idling at home presented by Sorensen et al. [23]. The load curve of charging at POIs is derived from a study of vehicle attendance at public charging infrastructure in Switzerland recorded on the platform 'jerechargemonauto.ch' [24] from October 2022 to October 2023.

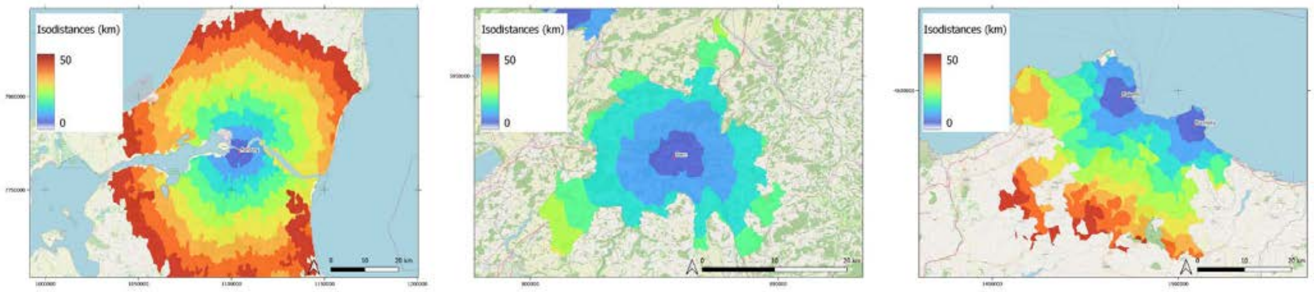

Figure 1: Map of the isodistances around Aalborg, Bern and Palermo.

2.3 Photovoltaic potential

The PV potential is calculated using data from a typical meteorological year (TMY) and a model of solar panel coverage and performance presented in Equation (1). The TMY solar radiation data are obtained at the location of interest from the online platform PVGIS. The data are provided at one-hour intervals over the course of a year, with the objective of representing a typical year in terms of meteorological events. The model employs the global irradiance on the horizontal plane (G(h), in W/m^2), which incorporates both direct and diffuse irradiance.

The potential for PV electricity generation, designated as P (in W), is a function of three parameters: the area, A (in m^2), of installed solar panels, their nominal efficiency, η, and performance ratio, PR, as presented in equation (1). The area is expressed as a proportion of the building footprint covered by solar panels. For the sake of simplicity, changes in efficiency due to temperature variations are ignored.

$$P = G(h)*A*PR*\eta \quad (1)$$

The application of this model to the TMY data provides an estimation of the potential power production at the specified location at each time step. Subsequently, this potential is employed as a realistic exemplar of production at the specified location.

2.4 EV-PV coupling and CO_2 savings

The EV-PV coupling comprises two distinct aspects: charging EVs from the PV production and storing the PV overproduction to reinject it into the grid later. It is assumed that the PV production is solely allocated to EV charging and storage. The potential of EV-PV coupling is determined by a comparison of the load curves associated with the EV charging process and the potential for PV production. Figure 2 illustrates both curves. When PV production is available, EVs will charge from PV (illustrated by the orange area in Figure 1). In the event that the production potential exceeds the charging demand, the EVs will store PV power (illustrated by the blue area in Figure 1). When the demand for EV charging exceeds the PV production, the residual demand is met through the utilisation of grid electricity (illustrated by the green area on Figure 1).

In order to evaluate the potential for storing electricity produced by PV systems in EV batteries, we consider only cars that are plugged in during the period of PV production: at workplace, at POIs or at home during the day. Each EV maintains a reserve of 20% of its battery capacity, in addition to the electricity required for its daily driven distance. This reserve aims at mitigating the risk of complete battery depletion, if an unforeseen short trip arise before the vehicle reaches its usual charging point. The 20% threshold was selected as it was deemed a reasonable balance between maintaining sufficient reserve power and maximizing the battery capacity available for V2G applications. In this study, each EV begins the day with a state of charge of 20% upon arriving at its designated charging location. Consequently, the storage capacity on a given day is not contingent upon that of the preceding day in our model. It is assumed that the EVs will charge as much as possible from the PV production.

Then, the daily VKT requirements are deducted from the storage potential, thereby considering solely the electricity that can be reinjected into the grid. We assume a 50 kWh EV battery for all vehicles, which is the average capacity for EVs in Europe [25]. It is assumed that all vehicles are participating every day to the storage capacity.

The CO_2 emissions are calculated using the carbon intensity of PV electricity generation (39.8 gCO_2/kWh in Aalborg, 34.7 gCO_2/kWh in Bern and 27.6 gCO_2/

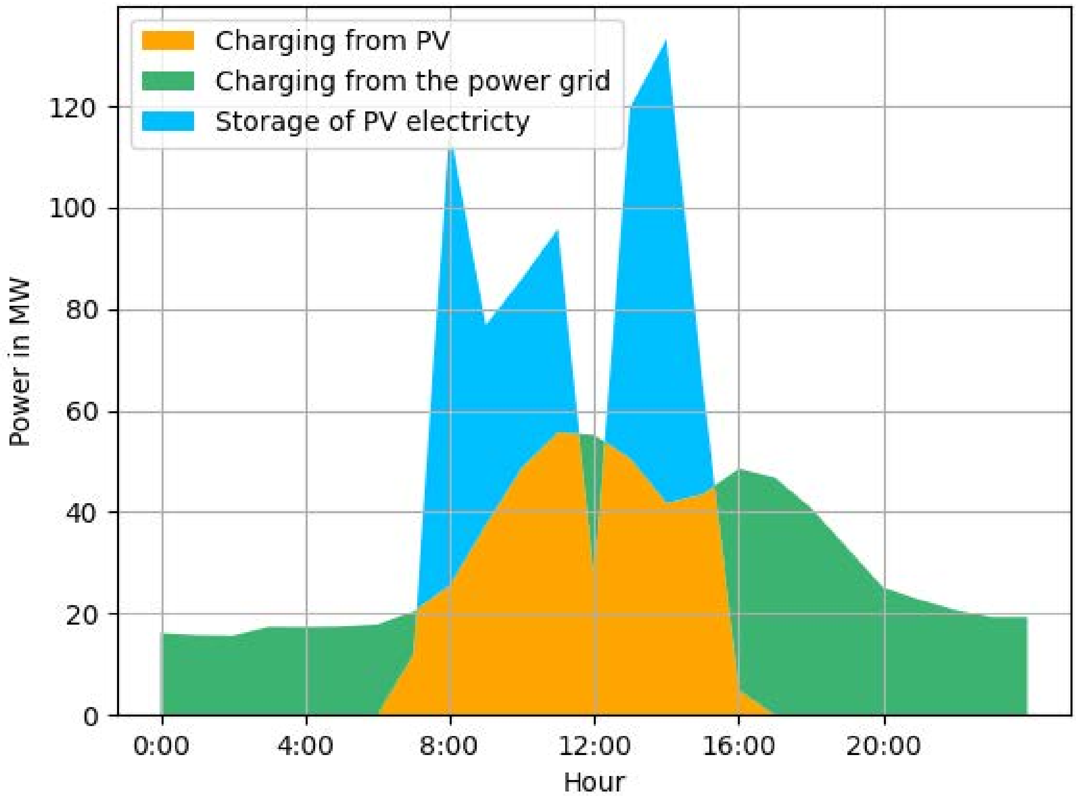

Figure 2: Example of load curves compared to an example of PV electricity production.

kWh in Palermo [26]) and the carbon intensity of the electricity produced in each country: 158 gCO_2/kWh in Aalborg, 78 gCO_2/kWh in Bern and 356 gCO_2/kWh in Palermo [27], as presented in Table 1. The carbon intensity of the 2035 decarbonized electricity mix is considered to be 37.5 gCO_2/kWh in the tree cities, following the Net Zero Scenario from the International Energy Agency [28]. In this analysis, only CO_2 emissions from driving are considered.

3. Case studies across Europe

This section outlines the methodology employed in three case studies across Europe, which encompass a range of potential for PV production. The cities selected for analysis are Aalborg in Denmark, Bern in Switzerland and Palermo in Italy. The study was conducted on the urban functional areas corresponding to those cities defined by Eurostat [21]. The three metropolitan areas have a comparable population size, with an estimated 600,000 inhabitants. However, the geographical and social contexts of the three areas are distinct. As illustrated in Figure 2, the solar radiance exhibits considerable variation, ranging from 1111 kWh/m² per year in Aalborg to 1309 kWh/m² per year in Bern, with Palermo recording the highest value at 1889 kWh/m² per year. [29]

3.1 Parameters

The parameters utilized in the case study are presented in Table 1. The statistics of mobility from the three cities is quite different. The mean daily VKT is 24 km in Bern [30] and almost double that figure, at 42 km in Aalborg [31] and 54 km in Palermo [32]. The motorisation rate is higher in Palermo, 701 cars/1000 inhab. than in Aalborg, 432 car/1000 inhab. and Bern, 548 cars/1000 inhab. [33]. The car renewal rate is calculated as the number of new registrations divided by the size of the fleet. Palermo has a larger fleet, but it is renewed much more slowly (2%

Table 1: Parameters of the model for the three cities.

	Aalborg	Bern	Palermo
Motorization rate (car/1000 inhab.)	432	548	701
Renewal rate	5 %	4 %	2 %
EV share (2022)	10 %	2 %	0.4 %
EVs in new registrations	66 %	21 %	4 %
Average daily VKT	42 km	24 km	54 km
Average solar radiation kWh/(m²*yr)	1111	1309	1889
CO_2 intensity of the electricity mix ($kgCO_2/kWh$)	158	78	356
CO_2 intensity of the PV electricity ($kgCO_2/kWh$)	39.8	34.7	27.6

p.a.) than Aalborg and Berne (5 and 4% p.a., respectively). The share of EVs in the car fleet in 2022 is higher in Aalborg (10%) than in Palermo and Bern (respectively 0.4 and 2%) [34]. The electrification in Aalborg is also quicker, as 66% of the new cars registered are EVs compared to 21% in Bern and 4% in Palermo [34].

3.2 Scenarios

For each case study, we consider two scenarios adapted from the Swiss EV roadmap [35], presented in Table 3. The scenarios are defined for the year 2035. The first scenario, designated “comfort”, assumes that 52% of vehicles will be charging at home without the use of smart charging technology. Additionally, 5% of vehicles will be charging at home during the day, 14% at work, and 27% at POIs. This scenario is composed of a high demand for charging at home (57% in total), and charging at a visited location (41%) for individuals lacking a charging option at their place of residence. In the scenario designated as “Flexible”, the majority of individuals are charging during the day (68%). Specifically, 29% are charging at work, 31% are charging at POIs, and 8% are charging while working from home. In contrast, only 32% are at home in the evening, with the utilization of smart charging. In the solar potential calculation, we consider a scenario with 10% of the building footprint covered with solar panels, assuming an efficiency of 20% The performance ratio of the solar panels in Europe has been shown to be around 74% in the last decade [36] and is expected to grow to 80% until 2035.

4. Results of the case studies and discussion

This section presents the results of the three case studies in Aalborg, Denmark; Bern, Switzerland and Palermo, Italy for the two scenarios.

4.1 Results on the charging needs

The aggregated results on the charging needs over the functional urban areas are given on Figure 3. The modelled VKT results are 55 km/car/day for Aalborg, 28 km/car/day for Bern and 52 km/car/day for Palermo which are 13, 4 and 2 km above the average presented in Table 1, which represents an overestimation between 15 and 30%. This difference is particularly relevant at the boundaries of the functional urban area. As the commuters driving to Aalborg can come from 45 km, this increases the average VKT. The total number of EVs in 2035 is about 110,000 cars in Palermo, 73,000 cars in Aalborg and 40,000 cars in Bern.

The total charging needs on a weekday are 754 MWh/day for Aalborg, 207 MWh/day for Bern and 1027 MWh for Palermo. Despite a comparable population size, the disparities in motorisation rates, electrification and daily VKT result in significant variations in the charging requirements. The motorisation rate in Bern is moderate

Table 2: Charging scenarios considered for the case studies.

	Comfort	Flexible
Home	52%	32%
Work	14%	29%
Working from home	5%	8%
POIs	27%	31%
Smart charging	no	yes

Table 3: Parameters common to the three cities.

Parameter	Value
Average Battery capacity	50 kWh
State of charge for reserve	20 %
PV coverage	10 % of the building footprint
PV efficiency	20 %
PV performance Ratio	80%

(548 car/1000 inhab.), as is the electrification of vehicles (21 % in 2035). The average distance travelled per day is relatively short (28 km/day), resulting in reduced charging needs (208 MWh/day). In contrast, Aalborg has a low motorisation rate (432 cars/1000 inhab.) but a high rate of vehicle electrification (29% in 2035) and a higher average distance travelled per day (55 km/day), leading to a higher demand for charging (754 MWh/day). Palermo has a low rate of vehicle electrification (15% in 2035) but a high motorisation rate (701 car/1000 inhab.) and average distance travelled per day (52 km/day), resulting in a higher demand for charging (1027 kWh/day).

4.2 Geospatial visualization of the results

The Figure 4 shows the maps of the daily charging needs for the three cities and two scenarios. In the three cities, the charging scenario has a strong influence on the geographical profile of the charging needs. The scenario "Comfort" creates higher charging demand in

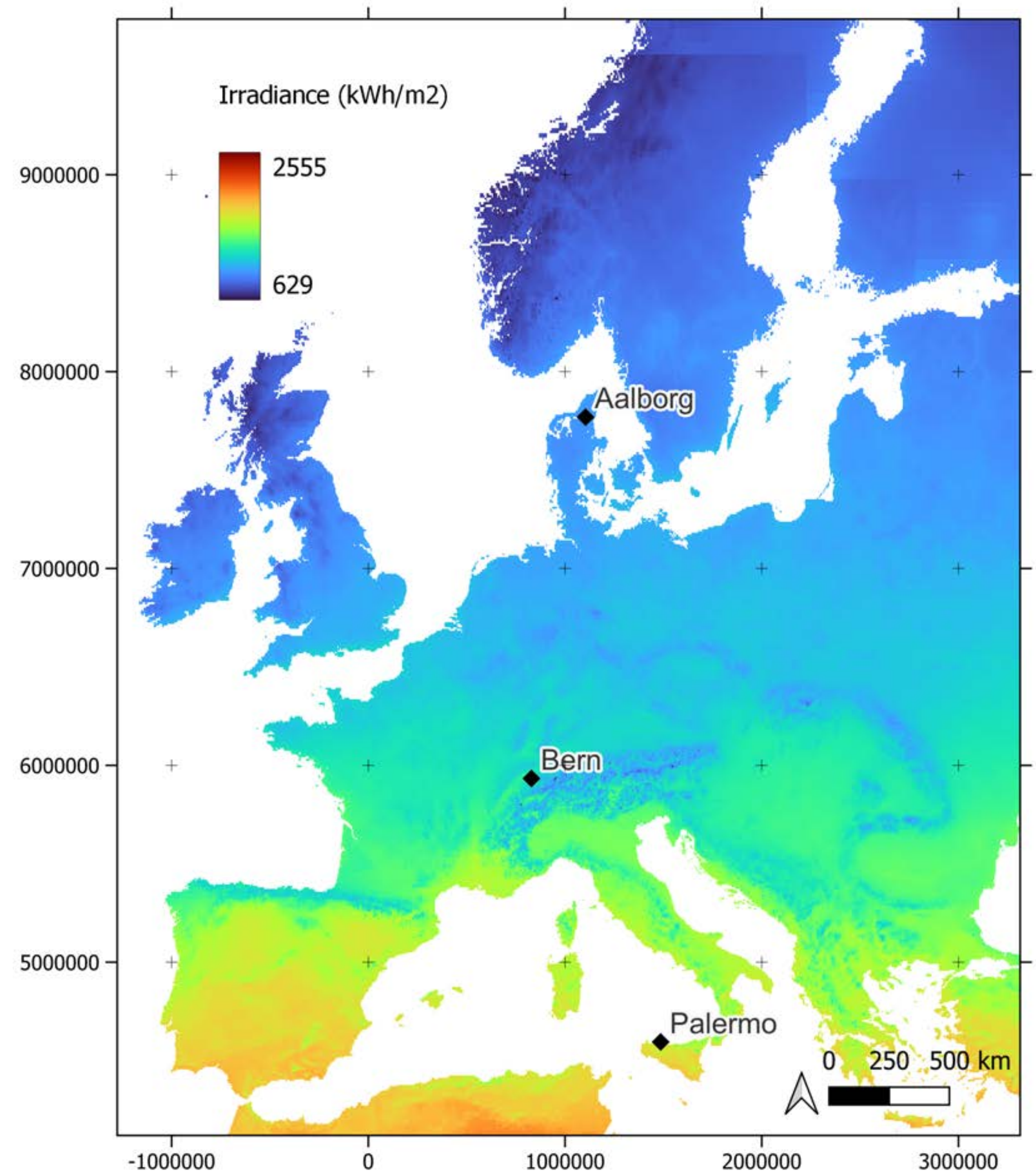

Figure 3: Map of the yearly average of annual global irradiance on a horizontal surface from PVGIS.

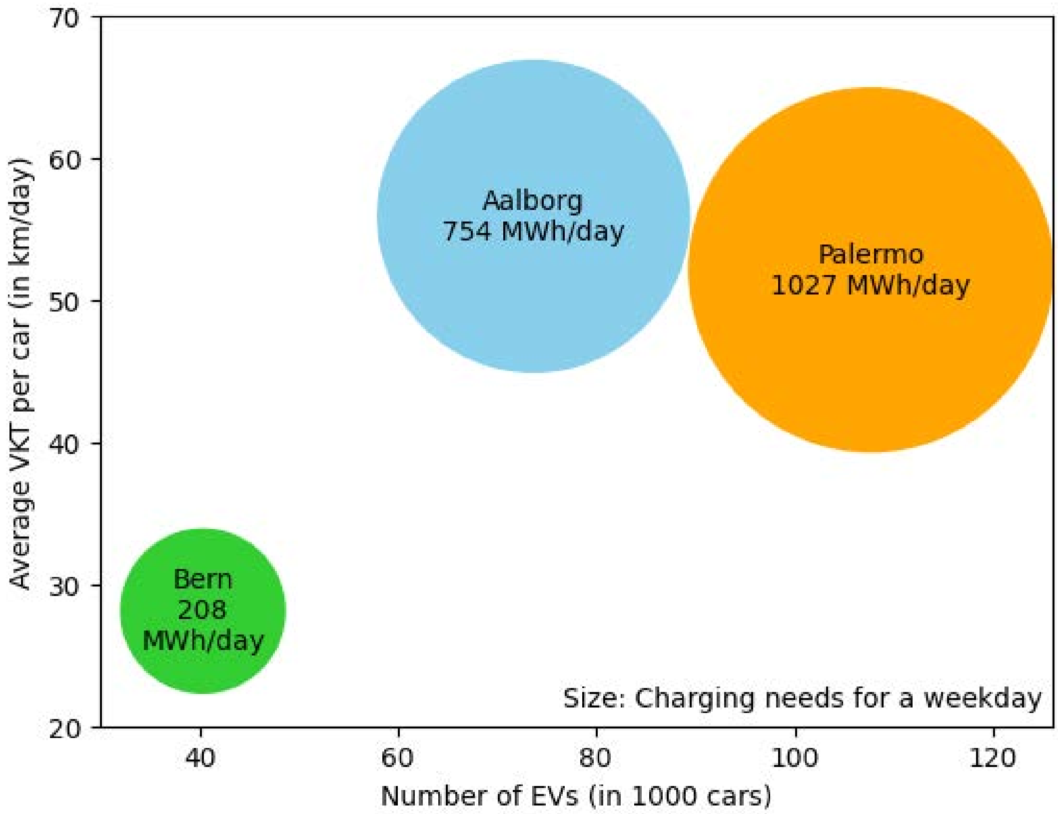

Figure 4: Charging demand on weekdays represented by the area of the bubbles, in relation to the number of EVs and the average VKT in each city.

the residential areas and the scenario "Flexible" shows higher demand in the city centres. As more EVs are charging at POIs in scenario "Flexible", the demand is more concentrated over pixels containing POIs than in scenario "Comfort". In Aalborg, in residential areas, the charging demand is from 10 to 20 kWh/hectare per day, while in the urban areas it reaches easily 200 kWh/hectare/day.

4.3 Charging EV from PV

Figure 5 illustrates the resulting load curves of the two scenarios in relation to an exemplary workweek of PV production in January, indicated in green, and July, indicated in red, derived from the PV model. It is observed that the "Flexible" scenario demonstrates a superior alignment with PV production, as the demand peak occurs during the PV production period. However, the variability of PV production is considerable, with some days failing to provide sufficient output to meet peak demand.

Figure 6 illustrates the proportion of daily charging demand that can be met through the utilisation of PV electricity determined by the model over the course of a year. In Aalborg, the PV production of a typical year can cover 53% of charging needs over the year, with a notable variation from 24% in January to 75% in July. In Bern, the PV production of a typical year can cover 61% of charging needs over the year, with a variation from 47% in January to 73% in July. In Palermo, the PV production of a typical year can cover 59% of charging needs over the year, with a variation from 49% in January to 68% in July. The production of electricity varies from one day to the next and may be zero on days with unfavourable meteorological conditions. Despite Palermo's greater potential for PV production, the elevated demand for charging reduces the proportion of charging from PV electricity. In Aalborg, the proportion of charging from PV electricity during the winter months is approximately half that observed in Palermo and Bern. Nevertheless, over the course of a year, the

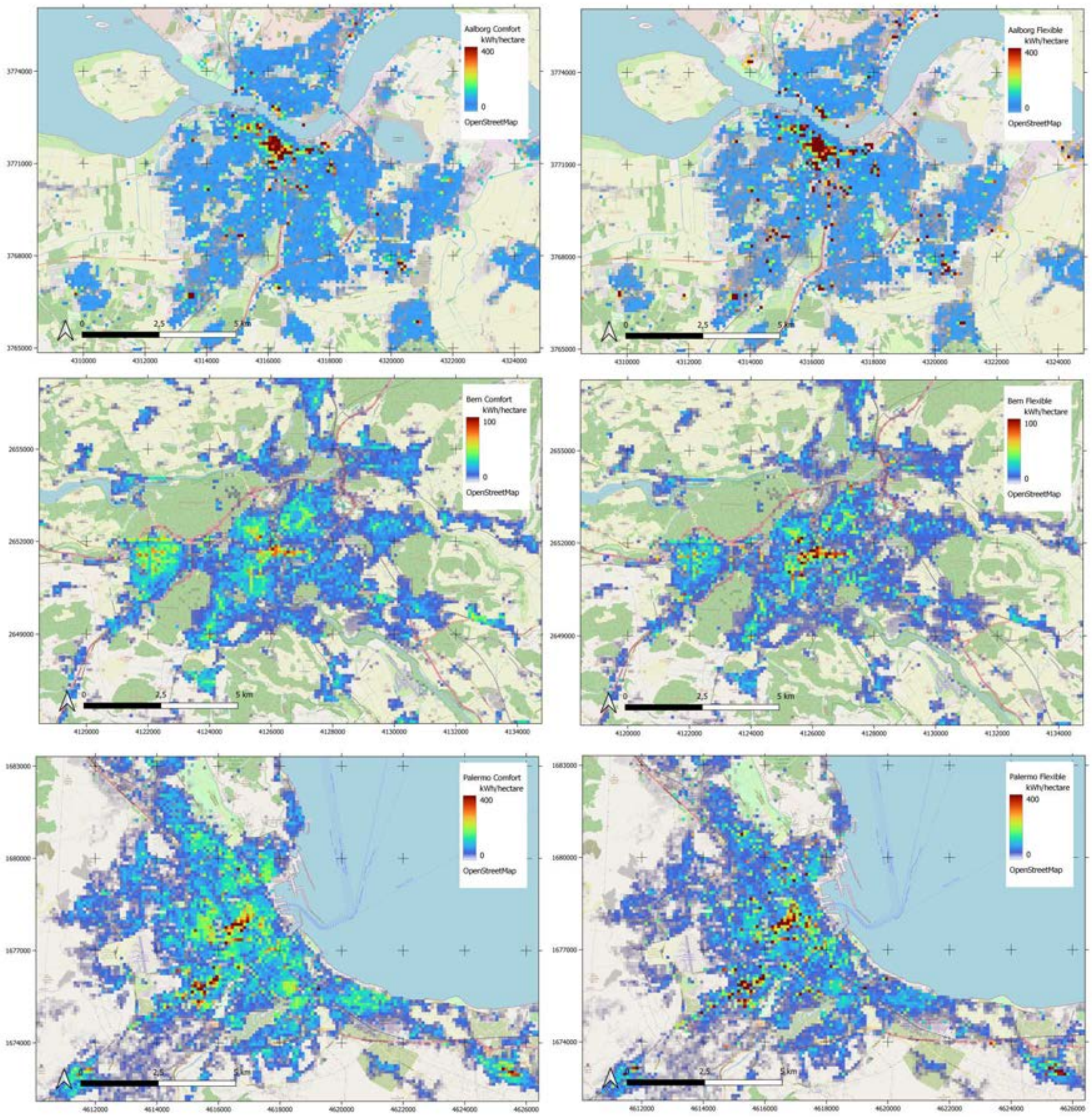

Figure 5: Comparative maps of the daily charging demand per hectare in the three cities in Aalborg, Bern and Palermo on each line, for the scenarios “Comfort” on the left columns and “Flexible” on the right column.

proportion of charging from PV is comparable between Aalborg, Bern and Palermo, around 60%.

4.4 Local flexibility from EV batteries

As detailed in Section 2.4, if all the EVs charging during the days are used as storage for the PV production, from 305 to 389 GWh of PV electricity can be stored over one year by the Alborg’s EV fleet in 2035. In Bern, the total stored electricity ranges between 224 and 295 GWh. Whereas in Palermo, the stored PV electricity reaches 671 to 921 GWh. Figure 8 displays the annual storage available for the two scenarios. The scenario “Flexible” shows a higher storage potential in the three cities (32% more in average). Despite longer VKT in Palermo, the large number of vehicles and the high solar radiation leads to higher storage potential compared to Bern and Aalborg.

The daily storage capacity is constrained by either the output of the PV system or the battery capacity of the available vehicles. Figure 9 illustrates the daily storage capacity for a typical year. As a higher number of EVs are connected to the electrical grid during the daytime in the “Flexible” scenario, the capacity of the available storage is increased. In the three cities, the

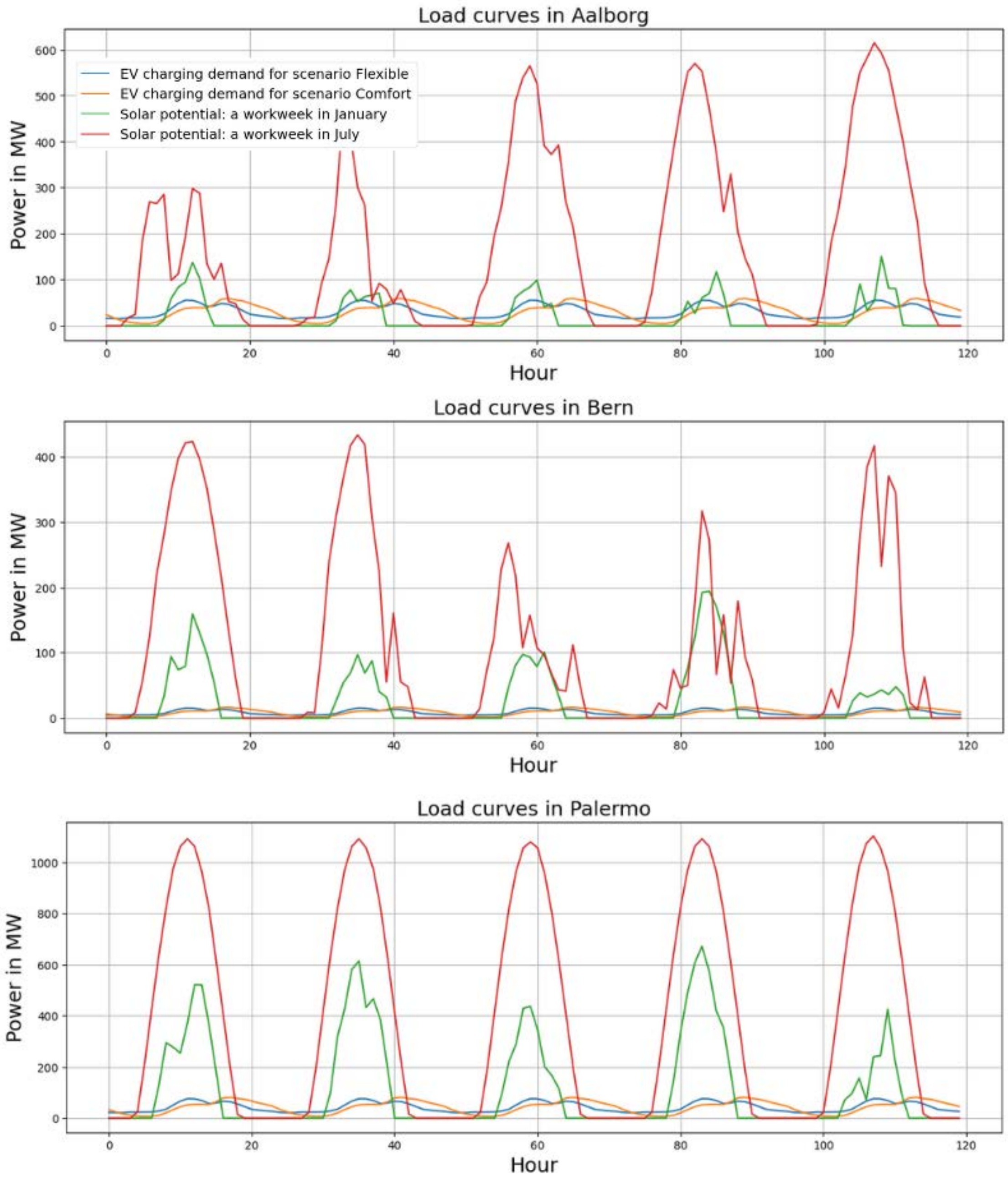

Figure 6: Example of PV production in one week in July and one week in January compared to the resulting load curves for the two scenarios.

maximum daily storage capacity is reached in spring and summer (from April to October), with 2.0 GWh in Aalborg, 1.05 GWh in Bern and 2.98 GWh in Palermo. However, even during the summer months, the daily storage capacity may be significantly reduced due to low irradiance levels. During winter, the maximum storage capacity in Bern can only be reached in exceptional circumstances. In Aalborg, the winter storage capacity is below 20% of the maximal value, which is likely due to the limited duration of sunlight during this period. In Palermo, the maximum storage capacity can be reached throughout the year, but with a higher probability in the summer. TMY data are created to represent the variability of the solar irradiance from one day to another and through the year. Therefore, the results give an overview of

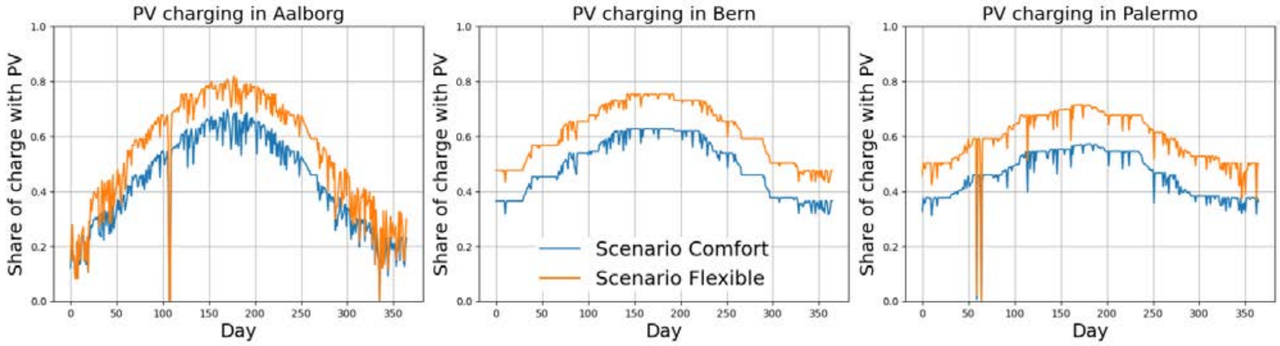

Figure 7: Share of charge from PV production from a typical year and both scenarios.

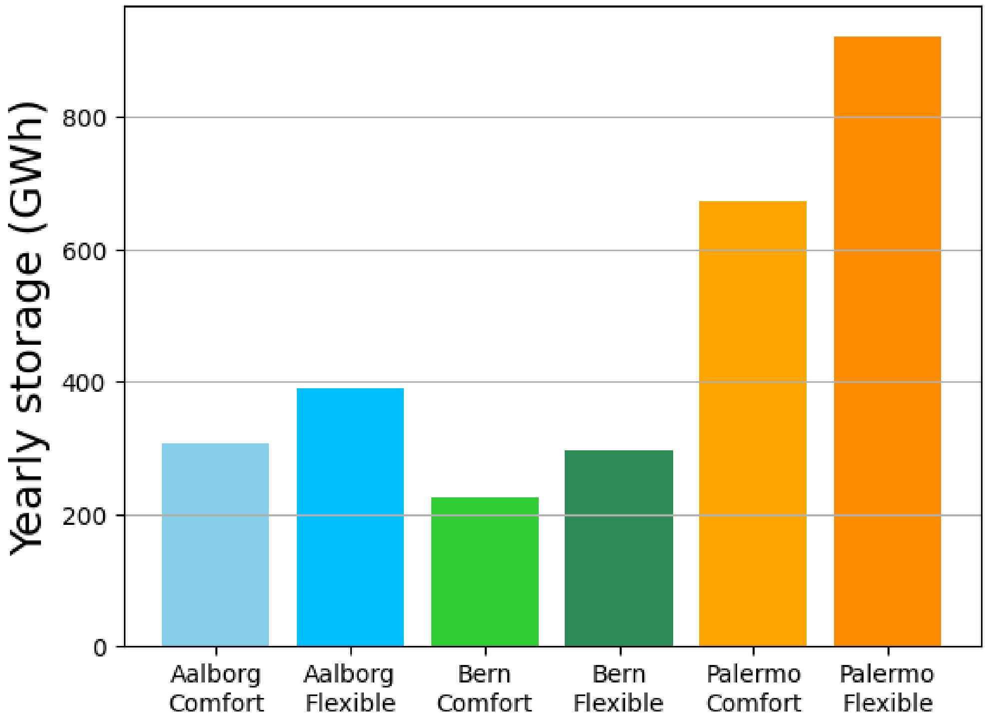

Figure 8: Annual storage in GWh obtained in Aalborg, Bern and Palermo for the two scenarios.

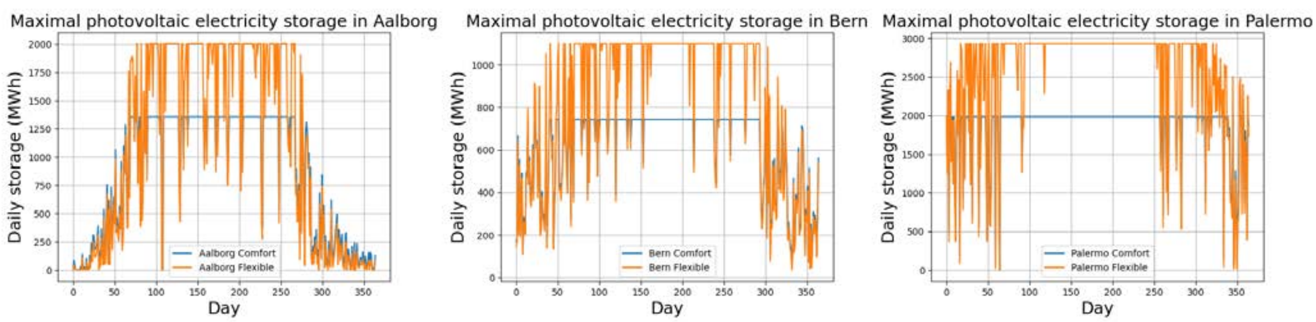

Figure 9: Daily storage over the year in Aalborg, Bern and Palermo for the two scenarios.

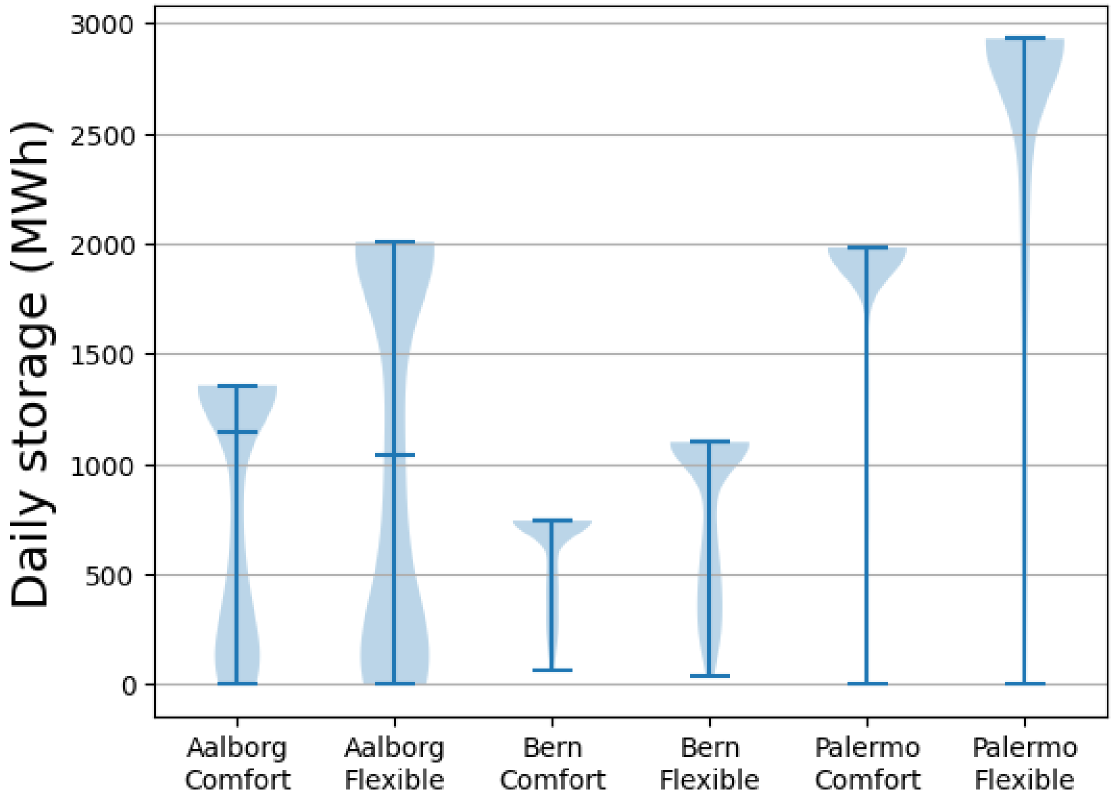

Figure 10: Violin diagram of the daily storage capacity reached in Alborg, Bern and Palermo for the two scenarios.

the coupling potential but the irradiance of year 2035 may vary from the TMY data.

Figure 10 displays a violin plot of the daily storage reached for each scenario in each city. The width of the curve indicates the number of days for which the daily storage reached each value. In Palermo and Bern, the maximum storage capacity for each scenario is reached on more than half of the days. In Aalborg, the median value is approximately 1 GWh, which is approximately 50% of the maximum value. The average battery capacity may increase in the future with the electrification of sport utility vehicles. Consequently, the 50-kWh value is a quite conservative hypothesis. If the average capacity increases, the total storage available for flexibility will increase proportionally until it reaches the daily solar production (as shown Figure 9). In our methodology, all the cars charging during the day are considered available for V2X. Consequently, the given potential is the maximal storage capacity. In practice, the availability of bidirectional charging stations near EV owners' residences and their willingness to contribute to V2X are limiting the real potential.

4.5 Results on CO_2 Emissions

The results of CO_2 emissions reductions are obtained with the current values of carbon intensity of the energy mix and carbon intensity of the PV electricity. Higher CO_2 emissions reductions could be obtained by decarbonizing the electricity production and the PV infrastructure production. In Aalborg, in the scenario "Flexible", the electrification of transport in 2035 reduces CO_2 emissions by 17%, using the current energy mix. Furthermore, the integration of PV technology for EV recharging results into an additional 2%pt. reduction in emissions, bringing the total reduction to 19%. In Bern, the adoption of EVs results in a 23% reduction in emissions when coupled with the prevailing energy mix. Given that the current energy mix in Switzerland is already relatively decarbonised, the use of photovoltaics for EV charging does not result in a significant further reduction in emissions. Nevertheless, further decarbonised electricity generation will be necessary for EV charging. PV electricity generation can meet most of these needs. In Palermo, the adoption of EVs results in a 17% reduction in emissions under the existing Italian

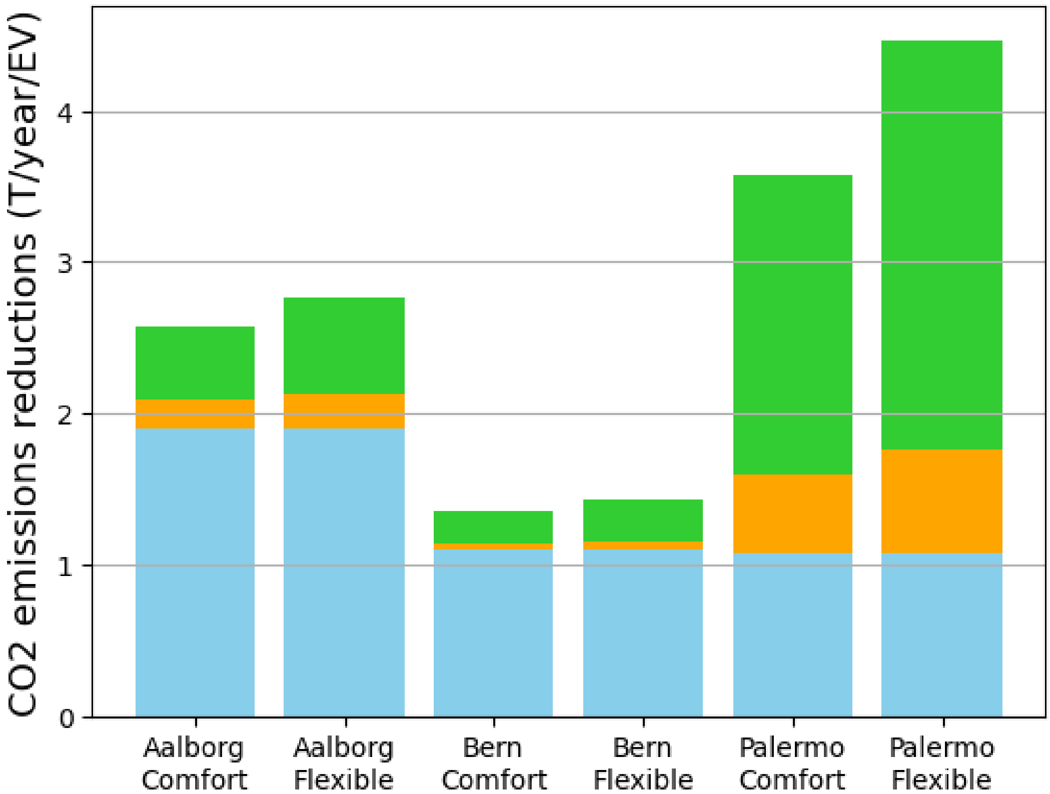

Figure 11: Reduction in the CO_2 emissions per car for the scenarios "Comfort" and "Flexible" in Aalborg, Bern and Palermo per year from switching to EV (in blue), using PV electricity for charging (in orange) and V2X (in green).

energy mix, while the integration of PV electricity for EV recharging leads to a 28% reduction.

Figure 11 highlights the contribution of switching to EV (in blue), using PV electricity for charging (in orange) and V2X (in green) in the CO_2 emissions reductions per EV. The CO_2 emissions reductions per EV reach 2.8 TCO_2/EV/year in Aalborg, 1.52 TCO_2/EV/year in Bern and 4.6 TCO_2/EV/year in Palermo for the scenario "Flexible". In Aalborg, the high VKT lead to a high impact of switching from ICEV to EV on the CO_2 emissions per car (1.90 TCO_2/EV/year). In Bern, the low carbon intensity of the energy mix results in the lower impact of the V2X and the use of PV for charging EVs. In Palermo, the combination of a highly carbonated electricity mix and a high solar potential results in a very high contribution of the V2X to the CO_2 emissions reductions per EV (2.8 TCO_2/EV/year in the scenario "Flexible").

If the decarbonization of the electricity grid in each countries follows the "Net Zero" scenario of the International Energy Agency, it reaches a carbon intensity of 37.5 gCO_2/kWh in 2035. With this electricity mix, the reductions of the CO_2 emissions due to the VKT of the cars are reduced by 21% in Aalborg, 25% in Bern and 36% in Palermo compared to the current fleet.

5. Conclusion

This article presents a methodology for quantifying the potential for integrating EVs and PV in a system that enables the charging of EVs from PV electricity and the utilisation of EV batteries for storing PV electricity. The PV electricity stored into the EVs can be reinjected into the grid or a house when the electricity demand is high. A methodology based on the geographical estimation of the daily VKT driven by EVs is applied to scenarios of charging behaviour in order to obtain load curves of EV charging. Subsequently, the load curves of charging are compared to the PV production curves, which are modelled from TMY data and a PV scenario that incorporates roof coverage of PV panels and panel performance. A comparison of the load curves allows for the calculation of the amount of electricity that can be charged from PV electricity, the potential storage capacity of vehicle batteries, and the reduction in CO_2 emissions.

The methodology is applied to three case studies on three European cities with different solar irradiance: Aalborg in Denmark, Bern in Switzerland and Palermo in Italy. The research compares two scenarios of charging behaviour: "Comfort" and "Flexible". The results demonstrate a notable impact of charging behaviour on the potential for storage and CO_2 emissions reduction. The scenario involving higher EV charging during the day (at work, POIs or during home office) results in higher storage and a considerably higher share of charging from PV electricity. It is projected that by 2035, the EV fleet could be charged from PV electricity sources for up to 61% of the typical year in Bern, 59% in Palermo and 53% in Aalborg, with only 10% of the gross floor area of each city covered with PV. The transition to electric vehicles has the potential to reduce the CO_2 emissions from 17%, in Aalborg, to 23% in Bern in 2035 with the current energy mix. Furthermore, the utilisation of PV electricity for EV charging has the potential to reduce CO_2 emissions by 19% in Aalborg to 28% in Palermo in comparison to the actual ICEV fleet.

It is assumed in this study that the battery of the cars used for storage is discharged to a state of charge of 20% on a daily basis. Future work could simulate the discharge of the battery over several consecutive days in order to take account of the variability of PV electricity production. This would yield more realistic results with regard to the potential for storage. Further research could also incorporate electricity demand curves from households or load curves from the grid, with the aim of optimising the allocation of PV electricity among consumers. Finally, an economic assessment of the V2X will be addressed in a future work.

As this study uses a geographical approach, it can better model the disparities between city centres and peri-urban areas in term of mobility. The EV-PV coupling simulations over one year allow to take into account the variability of the PV production and give a realistic overview of the variation in the flexibility potential. As this study is based on open data, it can be reproduced anywhere in Europe or in areas where similar data are available. The integration of the methodology in the online tool citiwatts [17], developed during project OpenGIS4ET, makes it available for public institutions and energy actors. Datasets containing open data are integrated in the platform to make the methodology directly available to any European city from user. The results of the methodology can help municipalities to better plan the deployment of distributed PV systems or to design policies and incentives to foster the use of EVs as flexibility assets for the local PV production.

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References

[1] European commission, 'Climate Action', Road transport: Reducing CO_2 emissions from vehicles. Accessed: Dec. 04, 2024. Available: https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles_en

[2] S. M. G. Dumlao and K. N. Ishihara, 'Impact assessment of electric vehicles as curtailment mitigating mobile storage in high PV penetration grid', *Energy Rep.*, vol. 8, pp. 736–744, Apr. 2022, https://doi.org/10.1016/j.egyr.2021.11.223.

[3] M. Pasetti, M. Longo, S. Rinaldi, P. Ferrari, E. Sisinni, and A. Flammini, 'On the Sustainable Charging of Electric Vehicles in the Presence of Distributed Photovoltaic Generation', in *2022 IEEE Sustainable Power and Energy Conference (iSPEC)*, Perth, Australia: IEEE, Dec. 2022, pp. 1–5. https://doi.org/10.1109/iSPEC54162.2022.10033024.

[4] D. Gudmunds, E. Nyholm, M. Taljegard, and M. Odenberger, 'Self-consumption and self-sufficiency for household solar producers when introducing an electric vehicle', *Renew. Energy*, vol. 148, pp. 1200–1215, Apr. 2020, https://doi.org/10.1016/j.renene.2019.10.030.

[5] I. Mendek, T. Marentič, K. Anžur, and M. Zajc, 'A Case Study on Electric Vehicles as Nationwide Battery Storage to Meet Slovenia's Final Energy Consumption with Solar Energy', *Energies*, vol. 17, no. 11, p. 2733, Jun. 2024, https://doi.org/10.3390/en17112733.

[6] A. Syla, D. Parra, and M. K. Patel, 'Assessing flexibility from electric vehicles using an open-source energy system model: trade-offs between smart charging, vehicle-to-grid and an extensive charging infrastructure', *Energy*, vol. 326, p. 136236, Jul. 2025, https://doi.org/10.1016/j.energy.2025.136236.

[7] Z. Fu, X. Liu, J. Zhang, T. Zhang, X. Liu, and Y. Jiang, 'Orderly solar charging of electric vehicles and its impact on charging behavior: A year-round field experiment', *Appl. Energy*, vol. 381, p. 125211, Mar. 2025, https://doi.org/10.1016/j.apenergy.2024.125211.

[8] H. Turnell, C. Marques, P. Jones, C. Dunham, A. Revesz, and G. Maidment, 'Driving success towards zero carbon energy targets for UK's Local Authorities', *Int. J. Sustain. Energy Plan. Manag.*, vol. 38, pp. 83–96, Jul. 2023, https://doi.org/10.54337/ijsepm.7548.

[9] F. Straub, S. Streppel, and D. Göhlich, 'Methodology for Estimating the Spatial and Temporal Power Demand of Private Electric Vehicles for an Entire Urban Region Using Open Data', *Energies*, vol. 14, no. 8, p. 2081, Apr. 2021, https://doi.org/10.3390/en14082081.

[10] Q. Jiang, N. Zhang, B. Yueshuai He, C. Lee, and J. Ma, 'Large-scale public charging demand prediction with a scenario- and activity-based approach', *Transp. Res. Part Policy Pract.*, vol. 179, p. 103935, Jan. 2024, https://doi.org/10.1016/j.tra.2023.103935.

[11] G. Yousefi, A. Dimovski, L. Radaelli, and M. Merlo, 'Estimating the impact of electric mobility on distribution networks through GIS techniques', *Sustain. Energy Grids Netw.*, vol. 38, p. 101379, Jun. 2024, https://doi.org/10.1016/j.segan.2024.101379.

[12] C. Gschwendtner, C. Knoeri, and A. Stephan, 'The impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load', *Sustain. Cities Soc.*, vol. 88, p. 104263, Jan. 2023, https://doi.org/10.1016/j.scs.2022.104263.

[13] F. Straub, O. Maier, D. Göhlich, and K. Strunz, 'Sector Coupling through Vehicle to Grid: A Case Study for Electric Vehicles and Households in Berlin, Germany', *World Electr. Veh. J.*, vol. 14, no. 3, p. 77, Mar. 2023, https://doi.org/10.3390/wevj14030077.

[14] A. J. Alrubaie, M. Salem, K. Yahya, M. Mohamed, and M. Kamarol, 'A Comprehensive Review of Electric Vehicle Charging Stations with Solar Photovoltaic System Considering Market, Technical Requirements, Network Implications, and Future Challenges', *Sustainability*, vol. 15, no. 10, p. 8122, May 2023, https://doi.org/10.3390/su15108122.

[15] C. D. W. Wanninayaka Mudiyanselage, K. N. Hasan, A. Vahidnia, and M. T. Rahman, 'Probabilistic coupled EV-PV hosting capacity analysis in LV networks with spatio-temporal modelling and copula theory', *IET Smart Grid*, vol. 7, no. 6, pp. 917–928, Dec. 2024, https://doi.org/10.1049/stg2.12189.

[16] T. Yi, C. Zhang, T. Lin, and J. Liu, 'Research on the spatial-temporal distribution of electric vehicle charging load demand: A case study in China', *J. Clean. Prod.*, vol. 242, p. 118457, Jan. 2020, https://doi.org/10.1016/j.jclepro.2019.118457.

[17] 'Citiwatts'. Accessed: Nov. 19, 2023. Available: https://citiwatts.eu/map

[18] N. Jeannin, A. Pena-Bello, J. Dumoulin, D. Wannier, B. Christophe, and N. Wyrsch, 'From PV to EV: Mapping the Potential for Electric Vehicle Charging with Solar Energy in Europe', *Int. J. Sustain. Energy Plan. Manag.*, vol. 41, pp. 45–57, Jun. 2024, https://doi.org/10.54337/ijsepm.8151.

[19] Andreas Mueller, 'Population map for the EU28 + Switzerland, Norway and Iceland for the year 2012'. Available: https://gitlab.com/hotmaps/pop_tot_curr_density/blob/master/README.md

[20] European Parliament, 'EU ban on the sale of new petrol and diesel cars from 2035 explained'. Accessed: Nov. 19, 2023. Available: https://www.europarl.europa.eu/news/en/headlines/economy/20221019STO44572/eu-ban-on-sale-of-new-petrol-and-diesel-cars-from-2035-explained

[21] Eurostat, JRC and European, Commission, Directorate-General, and Regional and Urban Policy, 'Cities and commuting zones (LAU 2016)', Eurostst. Accessed: Oct. 27, 2022. Available: https://ec.europa.eu/statistical-atlas/viewer/?config=RYB-2022.json&mids=BKGCNT,BKGNT02021,CNTOVL,CITYCOMMZONE2018&o=1,1,0.7,1&ch=C01,TRC,CITYCOMMZONE&center=51.55492,18.58786,3&lcis=CITYCOMMZONE2018&

[22] G. M. Fetene, S. Kaplan, S. L. Mabit, A. F. Jensen, and C. G. Prato, 'Harnessing big data for estimating the energy consumption and driving range of electric vehicles', *Transp. Res. Part Transp. Environ.*, vol. 54, pp. 1–11, Jul. 2017, https://doi.org/10.1016/j.trd.2017.04.013.

[23] Å. L. Sørensen, K. B. Lindberg, I. Sartori, and I. Andresen, 'Analysis of residential EV energy flexibility potential based on real-world charging reports and smart meter data', *Energy Build.*, vol. 241, p. 110923, Jun. 2021, https://doi.org/10.1016/j.enbuild.2021.110923.

[24] 'jerechargemonauto.ch'. Accessed: Jul. 01, 2022. Available: https://map.geo.admin.ch/?lang=fr&topic=energie&bgLayer=ch.swisstopo.pixelkarte-grau&zoom=0&layers=ch.bfe.ladestellen-elektromobilitaet&catalogNodes=2419,2420,2427,2480,2429,2431,2434,2436,2767,2441,3206&E=2660000.00&N=1190000.00

[25] 'Estimated average battery capacity in electric vehicles worldwide from 2017 to 2025, by type of vehicle', Statista. Accessed: Nov. 17, 2023. Available: https://www.statista.com/statistics/309584/battery-capacity-estimates-for-electric-vehicles-worldwide/

[26] A. Virtuani, A. Borja Block, N. Wyrsch, and C. Ballif, ‘The carbon intensity of integrated photovoltaics’, *Joule*, vol. 7, no. 11, pp. 2511–2536, Nov. 2023, https://doi.org/10.1016/j.joule.2023.09.010.

[27] N. Scarlat, M. Prussi, and M. Padella, ‘Quantification of the carbon intensity of electricity produced and used in Europe’, *Appl. Energy*, vol. 305, p. 117901, Jan. 2022, https://doi.org/10.1016/j.apenergy.2021.117901.

[28] IEA, ‘Global average carbon intensity of electricity generation in the Stated Policies, Sustainable Development and Net Zero scenarios, 2000-2040’. Accessed: Dec. 15, 2024. Available: https://www.iea.org/data-and-statistics/charts/global-average-carbon-intensity-of-electricity-generation-in-the-stated-policies-sustainable-development-and-net-zero-scenarios-2000-2040

[29] J. I. for E. and T. European Comission, ‘Photovoltaic Geographical Information System (PVGIS)’. Accessed: Nov. 19, 2023. Available: https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en

[30] S. C. Federal Office for Spatial Development ARE, ‘Mobility and Transport Microcensus (MTMC)’, Federal Office for Spatial Development ARE. Accessed: Jan. 05, 2023. Available: https://www.are.admin.ch/are/en/home/mobility/data/mtmc.html

[31] Statistics Denmark, ‘Statbank Denmark’. Accessed: Nov. 15, 2023. Available: https://www.dst.dk/en/Statistik/emner

[32] Eurostat, ‘Passenger mobility statistics’. Accessed: Nov. 19, 2023. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=541810#Travel_mode

[33] ‘Stock of vehicles by category and NUTS 2 regions’, eurostat. Accessed: Feb. 16, 2023. Available: https://ec.europa.eu/eurostat/databrowser/view/tran_r_vehst/default/map?lang=en

[34] Eurostat, ‘New passenger cars by type of motor energy’. 2024. Accessed: Apr. 25, 2024. Available: https://ec.europa.eu/eurostat/databrowser/view/road_eqr_carpda/default/table?lang=en&category=road.road_eqr

[35] Ladepunkt, ‘Recharge-au-point.ch’. Accessed: Apr. 17, 2024. Available: https://www.recharge-au-point.ch/fr/outils/comprendre-l-infrastructure-de-recharge-2050/

[36] J. Schardt and H. Te Heesen, ‘Performance of roof-top PV systems in selected European countries from 2012 to 2019’, *Sol. Energy*, vol. 217, pp. 235–244, Mar. 2021, https://doi.org/10.1016/j.solener.2021.02.001.