POTENTIAL FOR EV CHARGING FROM PV: A GEOGRAPHIC ASSESSMENT

Noémie Jeannin[1]*, Alejandro Pena Bello[1,2], Jérémy Dumoulin[1], David Wannier[3], Christophe Ballif [1,4], Nicolas Wyrsch[1]

[1]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.
[2]Institute of Energy and Environment, School of Engineering, University of Applied Sciences of Western Switzerland HES-SO, 1951, Sion, Switzerland.
[3] Institute of Informatics (II), HES-SO Valais/Wallis, CH-3960 Sierre, Switzerland
[4]Swiss Center for Electronics and Microtechnology, Rue Jaquet-Droz 1, 2002 Neuchâtel, Switzerland.
**noemie.jeannin@epfl.ch*

Keywords: GEOGRAPHICAL ANALYSIS, SOLAR COUPLING, VEHICLE-TO-X, ELECTRIC VEHICLE CHARGING, FLEXIBILITY.

Abstract

This paper investigates the potential of storing photovoltaic (PV) electricity in electric vehicle (EV) batteries and reinjecting the stored electricity into the grid (V2G) during high electricity demand periods. We developed a geographical methodology to quantify the mobility and EV charging needs across Europe. Scenarios of charging behaviour are then used to distribute the charging needs among locations corresponding to residential areas, workplaces, or points of interest (e.g., shops, restaurants, etc.). Resulting load curves and maps of the charging demand, with a resolution of one hectare, are then compared to a potential PV production obtained from typical meteorological data of irradiance, solar panel performance, and building coverage. This comparison is conducted hourly over one year, monitoring the evolution of the daily storage capacity of the EV fleet. Case studies were conducted on three cities in Switzerland: Sion, Neuchâtel, and Zürich. Three scenarios are used to compare home charging behaviour, balanced home and work charging behaviour, and charging at points of interest. Results highlight the impact of charging behaviour on the flexibility potential, with higher potential when charging at work and point of interest is privileged. The methodology is implemented in the online platform *citiwatts* [1].

1 Introduction

The electrification of the European vehicle fleet is a powerful lever for decarbonization. When coupled with renewable electricity production, it not only reduces emissions in the transport sector but also offers an opportunity to balance intermittent photovoltaic (PV) energy production with energy demand through vehicle-to-grid (V2G). The later enables discharging into the grid or a home when PV production is low. However, the potential of V2G systems to support this balance remains underexplored, particularly at small spatial scales where local factors play an important role. This paper presents a geographical method for estimating the potential of using electric vehicles (EVs) as daily storage for photovoltaic (PV) electricity. The EV batteries are then discharged into the grid as vehicle to grid (V2G) when the PV production is low. Previous studies have used mobility models [2], or gravity models [3] in complement of survey data to quantify mobility and charging needs of EVs, at a regional scale. The presented method estimates the mobility needs of the European population thanks to a self-calibrated gravity model developed by Lenormand et al. [4], without mobility survey data. The method calculates the charging needs of an EV fleet, the V2G potential, and the CO_2 emissions reductions within the selected area. Case studies are conducted in Sion, Neuchâtel and Zürich, three cities in Switzerland, against three different charging scenarios to compare the EV-PV coupling potential in different contexts. Three scenarios are used to compare high home charging behaviour, balanced home and work charging behaviour, and charging at points of interest (POIs). The method is based only on open-source data and can be applied over all of Europe through the online open-source tool for energy transition *citiwatts* [1]. It can be used by energy planners and municipalities to compare the effect of policies influencing the charging behaviour.

2 Methodology

The potential of V2G is obtained in three steps. The first step uses a self-calibrated gravity model to estimate the vehicle kilometre travelled (VKT) of the commuters living or working in the area of interest. Then, several charging scenarios are developed to dispatch the charging needs between home, work and POIs in space and time. Finally, the charging needs and available storage capacity are compared with the local solar potential. CO_2 emissions reduction obtained from V2G are also calculated. This method builds on previous work [5] and improves the estimation of the VKT.

2.1 Gravity model at the municipality scale

The gravity model aims to quantify the commuting flows between two areas (G_{start}^{dest}), from their populations (P_{start}, P_{dest}), the distance between the two locations ($d_{start\rightarrow dest}$) and a parameter (β). Equation 1 shows the core equation of the gravity model.

$$G_{start}^{dest} = P_{start} \times P_{dest} \times d_{start\rightarrow dest}{}^{-\beta} \quad (1)$$

The areas considered in this study are the local administrative units (LAU2) from the Eurostat Nomenclature of territorial units for statistics [6]. The online tool OpenRouteService [7] was used to compute the driven distance ($d_{start\rightarrow dest}$) between the centre point of each LAU2 unit and any other unit within a radius of 60 km.

The parameter β is calculated using the method of Lenormand et al. [3], from the average area of the LAU2 in each country (A), as shown in Equation 2.

$$\beta = 0.3 \times A^{-0.17} \quad (2)$$

The factor G was calculated for each couple of LAU2. Then, for each LAU2 A, the factors G to all accessible LAU2 are normalized and used as weight to dispatch the commuters to the surrounding LAU2s.

$$\hat{G}_{start}^{dest} = \frac{G_{start}^{dest}}{\Sigma_{dest}\, G_{start}^{dest}}$$

This calculation produces the number of commuters leaving and coming to each LAU2 and their driven distance, from which we can deduce the average VKT of the commuters leaving each LAU2 A (VKT_A), as shown in Equation 4, or coming to each LAU2 B (VKT_B), as shown in Equation 5. The number of commuters (C_B) coming to each LAU 2 B is calculated as in Equation 6.

$$VKT_A = \Sigma_{dest}\, \hat{G}_A^{dest} \times d_{A\rightarrow dest} \quad (4)$$

$$VKT_B = \Sigma_{start}\, \hat{G}_{start}^{B} \times d_{start\rightarrow B} \quad (5)$$

$$C_B = \Sigma_{start}\, \hat{G}_{start}^{B} \times P_{start} \quad (6)$$

The gravity model assumes that the whole population is going out of its unit area. To counterbalance that, only the active population is taken into account in our gravity model, excluding also the share of the active population which is not commuting. Moreover, only the population driving a car is considered.

The layer of the VKT of the population in Europe per hectare is based on the average VKT per LAU2 obtained from the gravity model, downscaled with a layer of the population density at the hectare level (P), multiplied by the motorization rate at NUTS2 level from Eurostat (MR) [8], and the share of the active population (α). The GHS POP layer [9] used is a projection of the population in 2030. The motorisation rate is from 2021, but is assumed to stay the same until 2030. The calculation is done for a fully electrified vehicle fleet.

2.1 Charging scenarios

The charging habits of the EV owners are considered to be split between the following locations: at home in the evening, at work during the day, at POIs at visiting time, at home while working remotely, or when they are not commuting. The charging needs at home (E_{home}) are located according to the population density as presented in Equation 4. The charging load profile is obtained from Sorensen et al. [10], normalized, and multiplied by the aggregated demand of the location of interest. The charging needs are obtained from the VKT by multiplying it with an average value of electricity consumption per km of c = 0.183 kWh/km [11].

The number of POIs and workplaces per hectare are obtained from OpenStreetMap [12]. The number of POIs and workplaces per hectare is then normalized by LAU2 and used as weights for splitting the incoming commuters of the LAU2 charging in the area. The load profile for charging at POIs is obtained from data collected in jerechargemonauto.ch [13] over one year. The load profile for charging at work is obtained from Lawson et al. [14].

The final charging needs are a linear combination of the charging needs at each location with the share of people charging at home ($\gamma_{home}, \gamma_{home\_office}$), at POIs ($\gamma_{POI}$), and at work ($\gamma_{work}$).

$$E = (\gamma_{home}, + \gamma_{home\_office}) \times E_{home} + \gamma_{POI} \times E_{POI} + \gamma_{work} \times E_{work} \quad (7)$$

2.1 PV production and flexibility

The solar potential (S) at a location is calculated from the hourly typical meteorological year data of irradiance from PVGIS (IR) [15], an efficiency of solar panels (η = 0.2) and a performance ratio (PR= 0.8), following the Equation 8.

$$S = IR \times \eta \times PR \quad (8)$$

The load curves for charging and the PV production are then compared for every day of a typical year, as presented in Figure 1. In our model, the PV production is used in priority for charging EVs (yellow area). When the PV production is too low, the EVs charge form the grid (green area). When the PV production is higher than the charging demand, the overproduction is stored in the available EV batteries (blue area). For storage, only the EVs plugged during the PV production period are considered, i.e. EV charging at work, during home office or from people not using their cars for commuting. EVs charging at home in the evening and at POIs are excluded. The average battery capacity of the EVS is considered to be 50 kWh. The use of V2G is assumed to discharge the battery up to a state of charge of 20% every day. .

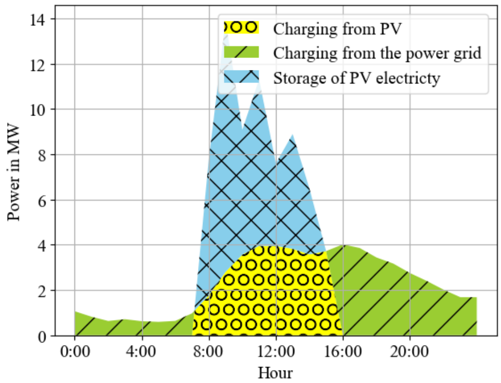

Figure 1: Example of load curves compared to an example of PV electricity production

3 Case Studies

Sion, Neuchâtel, and Zürich have diverse profiles. Zurich is the centre of a metropolitan area, Neuchatel and Sion are mid-size cites with a dynamic industry. Sion is located in the Rhône Valley, with an Alpine environment.

3.1 Parameters and scenarios

The coverage of PV panels is supposed to be 30% of the building footprint. For this case study, the vehicle fleet is considered to be 100% electrified. Three different charging scenarios are used to compare the EV-PV coupling potential in different contexts. In Switzerland, 10% of the active population is working mainly at home and is not commuting [16]. Only 36% of the dwellings are occupied by the owner in Switzerland [17]. EV owners who own their homes can easily install a private charging infrastructure and are likely to charge at home, especially if they also own a PV infrastructure. We explore three scenarios for EV charging infrastructure. In Scenario A, the 64% of the population living in rented dwellings [17] can recharge at home if private charging infrastructure is well-developed in rental properties. In Scenario B, they can charge at work if companies and workplaces have robust charging infrastructure. Finally, in Scenario C, if charging infrastructure is not readily available at home or work, EV owners are expected to rely on public charging stations at POIs to recharge. Moreover, 16% of the Swiss population works from home once or twice per week. It is assumed that this share of the population charges during home office two days per week if they don't have a charging point at work. The Scenarios A, B and C are detailed in Figure 2.

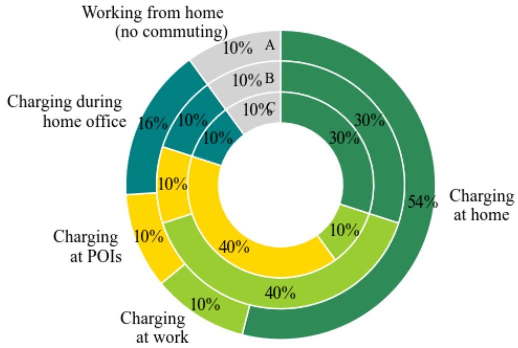

Figure 2: Chosen scenarios for the study

3.2 Results

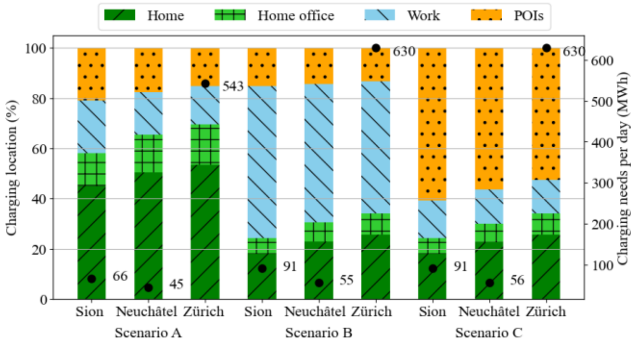

Figure 3: Charging needs per day per and type of location for each scenario and city, on the right scale, and share of charging at each location on the left.

Figure 3 shows the average charging needs per day for each location and scenario. The three cities are the centre of commuting areas and thus have higher charging needs when EVs are charged at work and POIs (13 to 26% more in Scenarios B and C compared to Scenario A).

Despite a similar population in Sion and Neuchâtel (35'000 inhab.), the charging demand per day is higher in Sion (66 - 91 MWh/day) compared to Neuchatel (45-56 MWh/day). This can be explained by the Alpine environment around Sion, where commuters have longer distances to drive.

Figure 4 presents the results of the charging demand by hectare per day for Scenarios A, B and C in Neuchâtel, Sion and Zürich. In Scenario A, in the 3 cities the charging demand is distributed over the whole city, while in Scenarios B and C, the demand is concentrated over fewer hectars. In Sion and Zürich, the differences from Scenario B, focussing on charging at workplaces and Scenario C, focussing on charging at POIs are clearly visible. The high-demand hectares of Scenario C are in the city centres while the high demand pixels in Scenario B are not only in the city centres but also in the industrial areas at the surrounding of the city.

In Scenario A, PV production meets 40% of charging needs in January and rises to 68% in June. In Scenario B, PV production covers 51% of charging needs in January, increasing to 81% in June. The maximum daily storage of PV electricity available in EV batteries varies across scenarios and locations: in Sion, it ranges from 331 MWh/day in Scenario C to 554 MWh/day in Scenario B; in Neuchâtel, from 274 MWh/day in Scenario C to 554 MWh/day in Scenario B; and in Zürich, from 2,911 MWh/day in Scenario C to 4,142 MWh/day in Scenario B. For the three scenarios, this maximal value is reached more than 50% of the days over one year. Consequently, the limitation in the storage comes from the number of cars available for charging during the day, and highlights the necessity to incentive charging during the day to maximise the potential of V2G.

The CO_2 emission reductions from EV-PV coupling are the result of three contributions. The first contribution is the switch from using oil-powered vehicles to using EVs. The second contribution is the use of PV electricity for charging instead of using only electricity from the electric grid. Finally, the third contribution is resulting from V2G, which enables the use of the PV electricity stored in the EV batteries instead of the electricity from the grid.

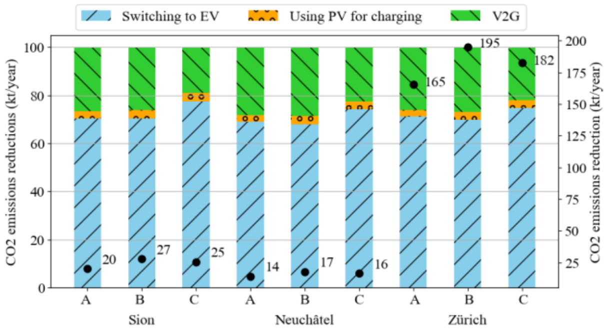

Figure 5: Contributions in the CO_2 emissions reductions in Sion, Neuchâtel and Zürich, for Scenarios A, B and C on the left axis, and potential of CO_2 emissions reductions per year on the right scale.

Figure 5 shows the three contributions in the CO_2 emissions reductions in Sion, Neuchâtel and Zürich. In all cases, the largest contribution comes from the switch to EVs. As the electricity mix is already partially decarbonized in Switzerland (78 gCO_2/kWh [18]), using PV electricity (35 gCO_2/kWh [18]) for charging has not a high impact compared to charging from the grid. However, using the PV electricity stored in the EV batteries instead of the one from the grid could contribute to a high reduction of the CO_2 emissions in all the scenarios, particularly Scenario B with more EV owners charging at work.

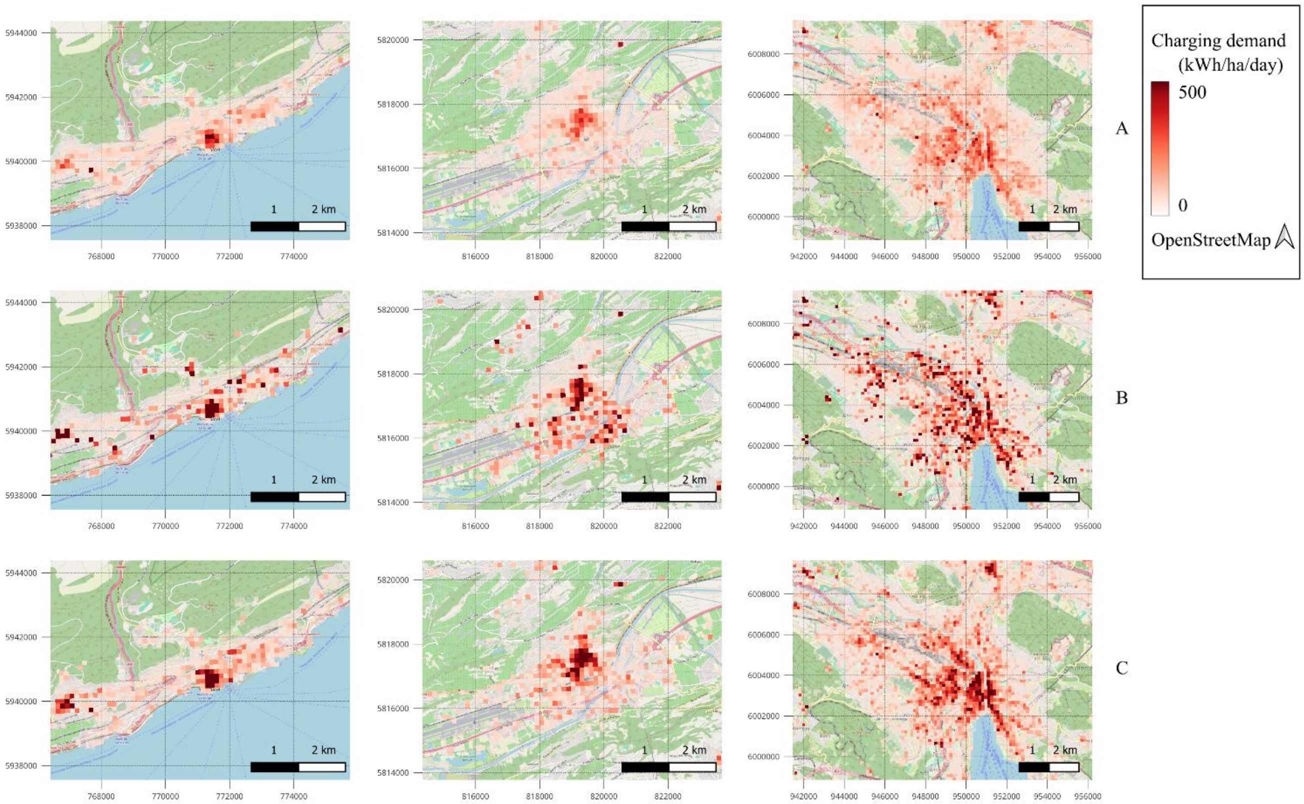

Figure 4: Map of the charging needs per hectare for Neuchâtel (on the left), Sion (in the centre), and Zürich (on the right), for Scenario A (on the top), Scenario B (in the middle), and Scenario C (at the bottom).

4 Conclusion

The model presented in this study uses a geographical approach to compute the charging needs of EV owners in Europe using only open-source data. Case studies in Sion, Neuchâtel, and Zürich, compare three different scenarios of charging behaviours corresponding to three different deployments of the charging infrastructure: in residential areas (Scenario A), at workplaces (Scenario B) and at POIs (Scenario C). Results highlight a higher potential of charging at work for reducing CO_2 emissions thanks to a higher potential of storing PV electricity for V2G. The model is implemented as a calculation module in the online open-source tool *citiwatts* [1]. It can be used by local governments, policymakers or energy planners to compare the effect of different scenarios of charging behaviour and support the most suitable one for CO_2 emissions reductions.

5 Acknowledgements

This project Open GIS for Energy Transition (OpenGIS4ET) has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Digital Transformation for the Energy Transition, with support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883973, financed for the Swiss partners, by the Swiss Federal Office for Energy.

6 References

[1] 'Citiwatts'. https://citiwatts.eu/map
[2] F. Straub, O. Maier, D. Göhlich, and Y. Zou, 'Forecasting the spatial and temporal charging demand of fully electrified urban private car transportation based on large-scale traffic simulation', *Green Energy Intell. Transp.*, vol. 2, no. 1, p. 100039, Feb. 2023, doi: 10.1016/j.geits.2022.100039.
[3] 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, doi: 10.1016/j.segan.2024.101379.
[4] M. Lenormand, A. Bassolas, and J. J. Ramasco, 'Systematic comparison of trip distribution laws and models', *J. Transp. Geogr.*, vol. 51, pp. 158–169, Feb. 2016, doi: 10.1016/j.jtrangeo.2015.12.008.
[5] 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, doi: 10.54337/ijsepm.8151.
[6] Eurostat, 'NUTS - Nomenclature of territorial units for statistics'. https://ec.europa.eu/eurostat/web/nuts/background
[7] 'Open Route Service'. https://openrouteservice.org/
[8] 'Stock of vehicles by category and NUTS 2 regions', eurostat. https://ec.europa.eu/eurostat/databrowser/view/tran_r_vehst/default/map?lang=en
[9] C. European Comission, 'GHSL - Global Human Settlement Layer'. https://ghsl.jrc.ec.europa.eu/copernicus.php#inline-nav-1
[10] 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, doi: 10.1016/j.enbuild.2021.110923.
[11] 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, doi: 10.1016/j.trd.2017.04.013.
[12] 'Open Street Map'. https://www.openstreetmap.org/
[13] 'jerechargemonauto.ch'. https://map.geo.admin.ch/?lang=fr&topic=energie&bgLayer=ch.swisstopo.pixelkarte-grau&zoom=0&layers=ch.bfe.ladestellen-elektromobilitaet
[14] C. Lawson, O. Asensio, and C. Apablaza, 'High-resolution electric vehicle charging data from a workplace setting'. Harvard Dataverse, 2020. doi: 10.7910/DVN/QF1PMO.
[15] J. I. for E. and T. European Comission, 'Photovoltaic Geographical Information System (PVGIS)'. https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en
[16] Swiss Federal Office for Statistics, 'Teletravail'. https://www.bfs.admin.ch/bfs/fr/home/statistiques/culture-medias-societe-information-sport/societe-information/indicateurs-generaux/economie-nationale/teletravail.assetdetail.32289944.html
[17] Swiss Federal Office for Statistics, 'Conditions d'habitation'. https://www.bfs.admin.ch/bfs/fr/home/statistiques/construction-logement/logements/conditions-habitation/locataires-proprietaires.html
[18] 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, doi: 10.1016/j.joule.2023.09.010.