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Aggregated Impact of EV Charger Type and EV Penetration level in Improving PV Integration in Distribution Grids

Saumitra Wagh, Yunhe Yu, Aditya Shekhar, Gautham Ram Chandra Mouli, and Pavol Bauer
DCE& S Group, Delft University of Technology

***Abstract*—Mass deployment of Electric Vehicles (EVs) can improve the loading characteristics of low voltage distribution grids with high Photovoltaic (PV) penetration. This impact is investigated in the paper from two point of views, namely, the EV charger type and the EV penetration level. Based on the measured usage data for home, public and semi-public EV chargers, it is highlighted that the ratio of the number of these charger types can influence the grid level impact of PV penetration. Using Monte-Carlo method with aggregated power balance model, it is suggested that the increase in percentage of public and semi-public chargers relative to home chargers can improve self-consumption of PV energy in the grid, thereby reducing the power mismatch due to excess local generation. A PowerFactory based simulation with real measurement based data on real German distribution grids reveals that the grids have no risk of congestion at all with 80% EV penetration , allowing for a possibility even higher EV penetration in the future. Furthermore, with the considered uncontrolled EV charging, it is observed that the grids experience reverse power flows due to excess PV generation. This excess PV energy reduces by about 5 % with high EV penetration, indicating a future potential for targeted smart charging application for improving these benchmarked results.**

I. Introduction

Increasing Photo-voltaic (PV) energy generation has presented operational challenges such as nodal overvoltages and reverse power flows in the low voltage distribution grids [1], [2]. These reverse power flows arise when the energy produced locally by the PV exceeds the downstream load demand, and there are three common methods to deal with this problem:

1) The reverse power can be exported to the upstream network. However, if the grid operators are dealing with a high PV penetration in future, all interconnected distribution grids may exhibit similar behaviour with net excess of generated energy.
2) Power mismatches can be reduced by employing distributed energy storage elements in the grid. While it is a popular research solution, challenges such as cost of ownership in European grids, high installation cost and space requirements need to be addressed [3], [4].
3) Local curtailment of excess power generated, but this can lead to losses in green energy savings.

A modified method 2) is an attractive approach for there is a rapid growth of Electric Vehicles' (EVs) employment [5], together with their natural features, EVs can be considered as perfect candidate for distributed, flexible storage units in the grid. For example, the synergistic integration of EVs for maximizing PV self consumption is studied in [6]–[8].

In this paper, the impact of uncontrolled EV charging on excess PV energy is benchmarked for different penetration levels using Monte-Carlo simulation based aggregate model as well as grid simulations performed with PowerFactory using actual grid data in Germany. The main focus of this paper is to show the impact of different charger types (home, public and semi-public) as well as the EV penetration levels, wherein measured data is used to define probability distribution of arrival time and EV energy demand at these chargers.

II. Power Mismatches with Increasing PV and EV Penetration Levels

The EV penetration in all grids varies from 0% to 80%. It is the percentage of total number of vehicles present in the grid. The mathematical representation is given by Equation (1), where γ_{EV} is EV penetration percentage and N_{EVs}, N_{cars} are the number of EVs and number of cars respectively.

$$N_{\text{EVs}} = N_{\text{cars}} \times \gamma_{\text{EV}} \tag{1}$$

In this paper, the EV penetration levels is also represented by the number of charging events. The charging event refers to the entire session that spans between the start time (t_{s}) when a given EV with a certain energy demand (E_{d}) connects to the charging point and the end time (t_{e}) at which it either becomes fully charged or disconnects due to departure. It can be inferred that the aggregated number of charging events per day on the distribution grid would increase with N_{EVs}. The PV penetration is calculated using Equation (2) where γ_{pv} is the PV penetration, $E_{\text{pv,yearly}}$ is the yearly PV generation and $E_{\text{load,yearly}}$ is the yearly load consumption.

$$\gamma_{\text{pv}} = \frac{E_{\text{pv,yearly}}}{E_{\text{load,yearly}}} \tag{2}$$

High PV penetration can lead to reverse power flows in the distribution grid, as shown in Fig 1 (a). The negative power represents the instances where the aggregate PV generation is higher than the total demand and the corresponding unused grid energy (E_{pv}, shaded grey area) is given by Equation (3).

$$E_{\text{pv}} = \int_{0}^{T_{\text{final}}} \left(\sum_{\text{n=1}}^{\text{N}} (P_{\text{pv,n}} - P_{\text{load,n}} - P_{\text{EV,n}}) \right) dt \tag{3}$$

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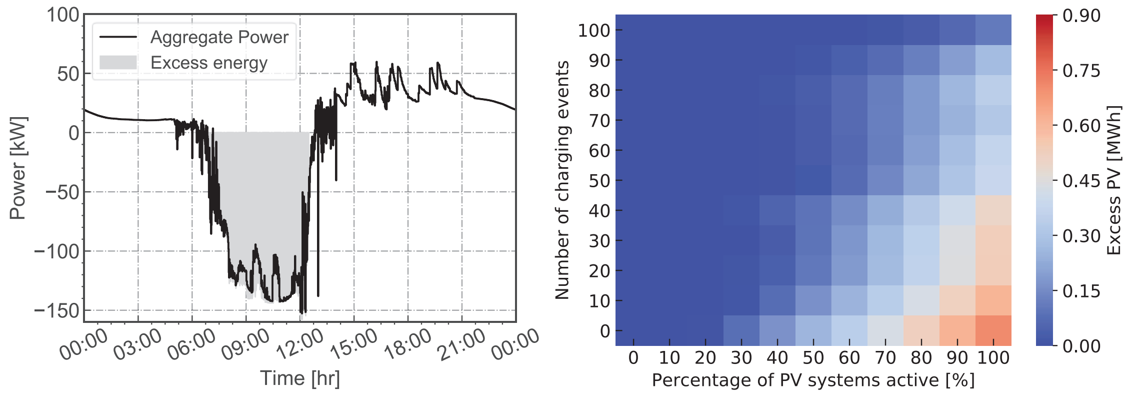


(a) Unused PV energy

(b) Heatmap: PV utilisation

Fig. 1: For a single day (a) Excess PV energy. (b) PV energy utilisation in presence of EVs

Herein, $P_{\text{load,n}}$, $P_{\text{EV,n}}$ and $P_{\text{PV,n}}$ are the load demand, EV charging power and PV power generation at n$^{\text{th}}$ node in the distribution grid, respectively. It can be inferred that the aggregated $P_{\text{EV,n}}$ increases as a function of N_{EVs}, which reduces E_{pv} for the given PV penetration level, as shown in Fig 1 (b). In case of uncontrolled charging, the aggregated $P_{\text{EV,n}}$ corresponding to the individual charging session times t_{s} and t_{e} is solely governed by the probability distribution of the EV arrival and departure times (t_{a} and t_{d} respectively) as well as their energy demand E_{d}. In the subsequent section, this data for different charger types is used to study the corresponding impact on excess PV energy.

III. Influence of EV Charger Type Ratio

The EV chargers used in this work are of three different types that indicates in which neighbourhood a charger is installed, namely home, semi-public and public. Each EV charger type has different probability distributions of t_{a}, t_{d} and E_{d} over the week, and therefore result in different charging behaviour in terms of t_{s} and t_{e}. For example, Fig 2 shows the probability distribution of EV arrival time for all the charger types and the corresponding $\sum_{\text{n=1}}^{\text{N}} P_{\text{EV,n}}$ when relative proportion of home chargers is varied. The probability distribution is derived from the EV mobility and charging model based on references [9], [10]. It is visible from Fig 2 (a) that the public and semi-public chargers have a higher probability of t_{a} during sun hours relative to home chargers and therefore a higher overlap with the PV generation. Consequently it can be seen from Fig 2 (b) that the aggregated grid charging power shifts towards morning hours when home chargers are reduced from 70 % to 25 %. It can be inferred from this observation that a lower proportion of home chargers in the grid can improve the self consumption of local PV energy in the grid even with uncontrolled charging.

The hypothesis stated above can be corroborated by doing a Monte-Carlo analysis with variation in percentage of home chargers. Fig 3 depicts the Monte-Carlo simulation results representing the change in Excess PV Energy trend with respect to the number of charging events happening in a grid in one day. The percentage of public and semi-public chargers is divided equally. It is observed that with a decreasing home charger percentage, the excess PV energy is utilised more. For example, for a 100 charging events the spread of the excess PV energy for 70% home chargers is from 0.2 to 0.6 MWh , whereas for 25% home chargers it is from 0.02 to 0.4 MWh.

IV. German Grid Simulations and Results

A. *Simulation setup:*

The simulations were accomplished on three different German distribution grids with PowerFactory. The grid details are shown in Table I, and the simulation time was one week with a time step of one minute. The charging of EVs in the simulation happen without any algorithm i.e. in this research work only the effect of uncontrolled charging of EVs is addressed.

Grid Type	Installed PV capacity [kW]	Total load [MWh]	Home charger percentage [%]
Rural Grid	193.89	213.5	70 %
Urban Grid	214.73	518	50 %
Sub-Urban Grid	1039.68	1414	25 %

TABLE I: German distribution grids

The loads in each grid are divided into three categories namely, household, agriculture and commercial. The load profiles applied in the simulation are calculated based on the standardized load profiles obtained from German Association of Energy and Water Industries, BDEW *(Bundesverband der Energie-und Wasserwirtschaft)*. All the profiles provided are for a normalized load of 1000 *kWh/year*. Hence, depending upon the yearly consumption of different loads, the profiles were generated with respect to it. Fig 4 shows the sample profiles from each type of loads used for the grid simulations. Agricultural load has an identical behaviour throughout the entire week as weekends do not affect the agricultural operations. Residential and commercial loads, behave differently. They have a similar trend on working days and a different trend on weekends. The distribution of types of loads in the grid is also an important factor in assessing the grids. For example, agricultural loads consume more power as compared to residential and commercial loads. So if a grid has more

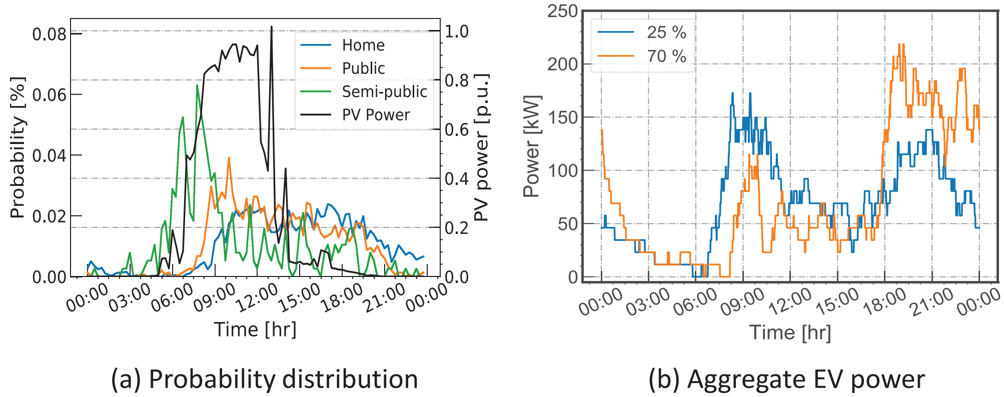


Fig. 2: (a) Probability distribution of EV arrival time for different charger types. (b) Aggregate EV power with respect to home charger variation.

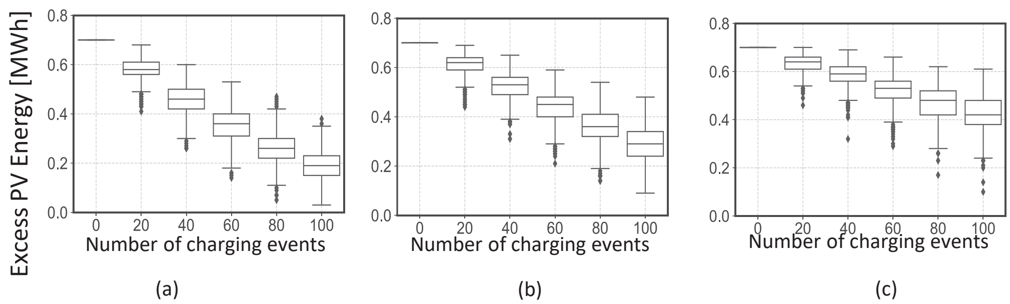


Fig. 3: Effect of Home Charger Variation on Excess PV energy. (a) 25% home chargers, (b) 50% home chargers, (c) 70% home chargers

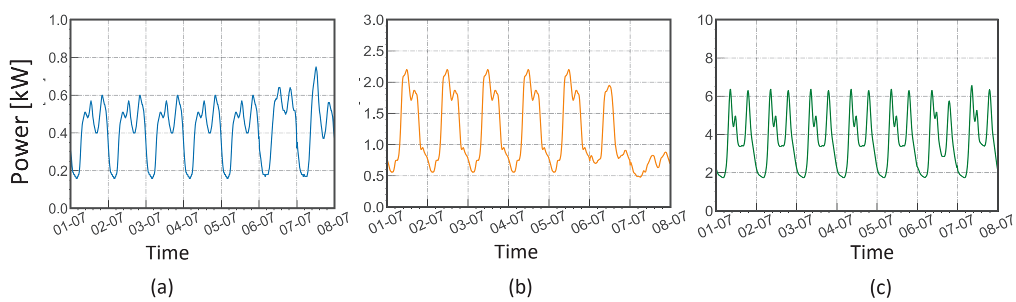


Fig. 4: Load profiles of different load types.(a) Residential load, (b) Commercial load, (c)Agriculture load.

agriculture loads then it is more prone to overloads when introduced with new loads like EVs as the charging of multiple EVs can happen at the peak time adding to the overall grid consumption.

Each of these grids were simulated in two distinct PV penetration scenarios, namely 'High PV' and 'Low PV'. The only difference between them is number of activated PV systems in the grid. These two scenarios are provided by German DSO together with the grid models. In which the low PV scenario represents the current installation status and the high PV scenario is a prediction of future PV installations. For obtaining the PV profile a standard generation profile of a 1 kW is assumed. The profile used is obtained using Meteonorm software. The software also provides the values of the ambient temperature, wind speed which affect the PV generation and are taken into account by using the Duffie and Beckman model [11]. The profile for each PV system is calculated by multiplying the rating of the system to the standard generation profile. The rating of each PV system is provided together with the grid models by German DSO.

B. Simulation results:

The simulations of two PV penetration scenarios were first carried out without the presence of any EV, in order to assess the effects of PV generation. Fig 5 shows the effect of PV penetration on the transformer loading of the rural grid. Low PV scenario reduces the transformer loading as compared to the no PV scenario. But in case of higher PV penetration there is a mismatch of local generation and consumption and the

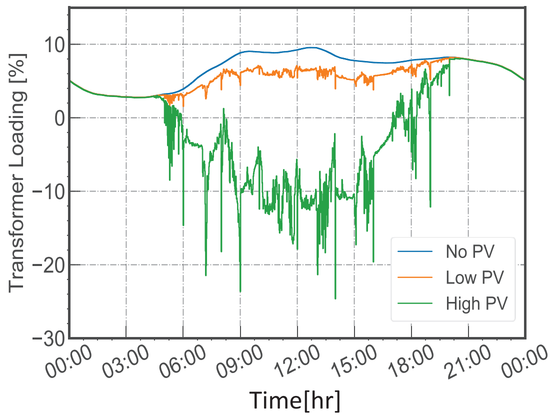


Fig. 5: Transformer loading of rural grids in different PV scenarios.

excess energy flows upstream in the network giving negative loading value. A great number of PV systems are present in the high PV scenario, and every unit would reach its full-rating generation during noon when the sun irradiation is perfectly high. This combination could lead to a quite noticeable over-voltages and overloading phenomena in the grids. Fig 6 is the heat map of the sub-urban gird with high PV scenario at the time of peak PV generation, depicting the effect of high PV generation. The grid experiences overloading of transformer, lines and also nodal overvoltages.

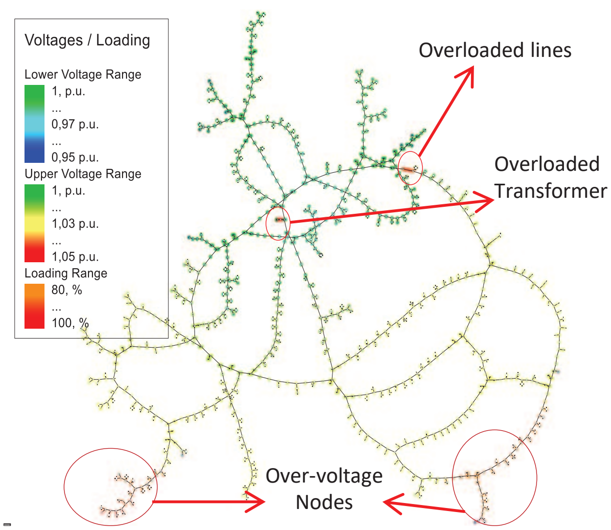


Fig. 6: Heat map of sub urban grid showing the effect of High PV generation

Similarly, the simulations were carried out for different EV penetration scenarios without the presence of PV systems in order to assess the effects of increasing EVs on the grid elements. The EV penetration increases from 0% (EV_0) to 80% (EV_80). The method of EV fleet and charging profile generation is based on and updated from [12]. The difference in this research is that, the EV types are selected from the top selling EVs in the German market [13]. In addition, all the EVs are considered to be 3-phase.

Fig 7 and Fig 8 are the plots of transformer and maximum line loading of the rural grid. It shows that even with the highest level of EV inclusion, there is an absence of overload. The peaks in the curve are affected by the type of chargers in the grid. Here, as the rural grid has more home chargers more charging events are observed after 15:00 in the noon, when the EVs arrive at the house and are plugged in. It is evident that a large number of chargers does not affect the grid operation drastically.

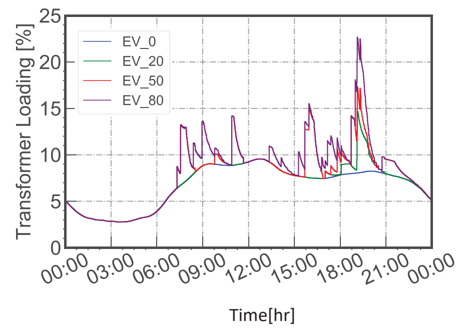


Fig. 7: Transformer loading in different EV scenarios for rural grid.

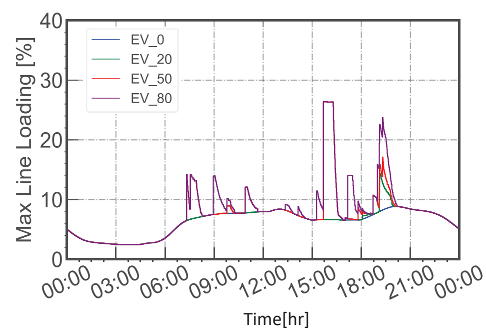
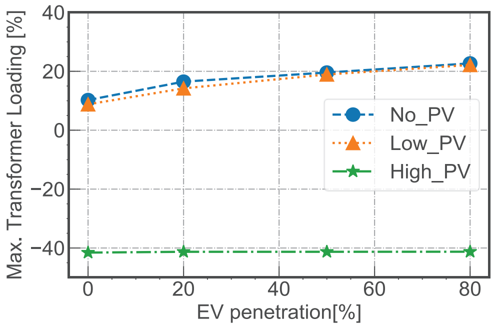


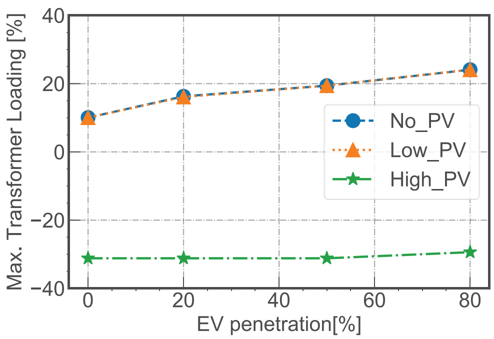
Fig. 8: Maximum line loading in different EV scenarios for rural grid.

Simulation results of increasing EV penetration in two different PV scenarios depicts a similar outcome in both summer and winter seasons. Fig 9 shows the seasonal comparison of transformer loading of rural grid and Fig 10 shows the behaviour of the sub-urban grid transformer in summer season. It can be seen that even with increasing EV chargers the PV energy is not completely consumed in the high PV scenario. The negative transformer loading in both figures indicate that there is still a significant amount of PV energy flowing upstream.

The high PV generation also results in overvoltages as previously seen in the heat map. The sub-urban grid experiences many instances where the maximum values come close to the allowable limit of 1.1 p.u. [14]. It might be argued that, the addition of EVs should help with this issue. The EVs do complement this behaviour but its not visible. The reason being two-fold. Firstly, there is large number of PV systems in all the grids. Secondly, high EV penetration percentage does not necessarily mean a high absolute number of EVs. Besides,



(a) Summer Season



(b) Winter Season

Fig. 9: Maximum transformer loading in a) Summer season, b) Winter season for rural grid

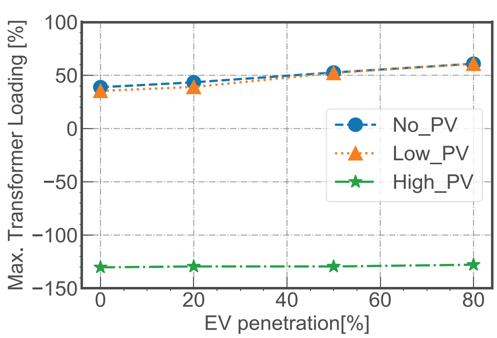


Fig. 10: Maximum transformer loading for increasing EV penetration in different PV scenarios for sub-urban grid in summer season

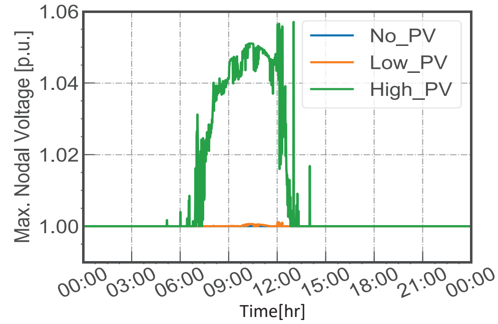
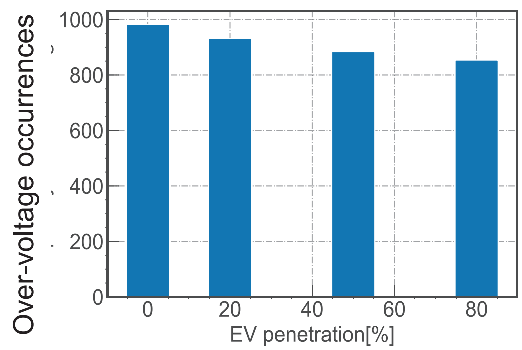
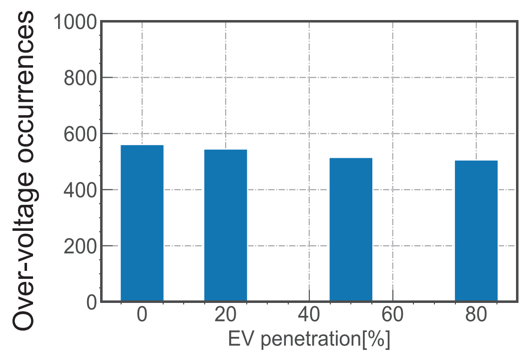


Fig. 11: Maximum nodal voltages for increasing EV penetration in different PV scenarios for sub urban grid



(a) Summer Season



(b) Winter Season

Fig. 12: Decrease in the occurrence of over-voltages of rural grid due to increasing EV penetration. a) Summer season, b) Winter season

most of the overvoltage moments occur when PV reaches maximum generation, but the energy cannot be consumed locally since every few EVs are in charging during that time.

To understand how the EV penetration affects the maximum voltage values, the occurrence of over-voltage is plotted in Fig 12. As described in the simulation setup, the simulation was carried out for one week with one minute time resolution, resulting in 10080 instances for one whole cycle. During these simulation instances, the moments of overvoltage occurrences were counted. Therefore, the occurrence of overvoltage is defined as the number of instances when there is any nodal voltage surpasses the allowable limit which is set according to each grid. For the rural grid the maximum limit in summer season was set to be 1.04 p.u. and for winter season it was 1.03 p.u. From Fig 11 it is noticeable for 0% EV penetration the overvoltages occur close to 9.5% of the total simulation instances in summer season and up to 7.5% in winter season. As the EV penetration increases, the occurrence of overvoltages decreases. With the maximum EV penetration, in summer season the occurrence drops to 8.3% and in winter season it is close to 6.5%. Thus, increment in EVs aids in reducing overvoltage occurrences.

Since all grids have different parameters including PV installation capacity, the excessive PV energy is then converted to normalised value $E_{\text{PV normalised}}$ for a fair comparison and it is calculated by Equation (4) where τ_{PV} means the actual installed PV capacity.

$$E_{\text{PV normalised}} = \frac{E_{\text{PV}}}{\tau_{\text{PV}}} \tag{4}$$

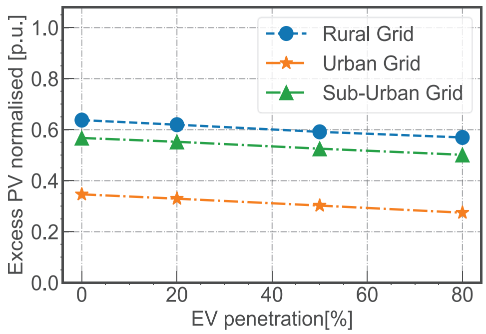


Fig. 13: Excess PV in each grid type.

Fig 13 displays the curve of normalised excessive PV energy versus EV penetration level in three grids. It can be observed that the excess PV energy decreases as the penetration of EVs increases. The trend of all three lines is the same and rural grid has the highest excessive energy due to a large PV penetration percentage. However, for every grid with increasing EVs the $E_{\text{PV normalised}}$ decreases, showing the potential of EVs in reducing power mismatch in the grid. It is to be noted that the reduction in $E_{\text{PV normalised}}$ happens even with uncontrolled charging. Hence one can make an hypothesis that with a proper algorithm, this decrease can happen to a greater extent.

V. Conclusions and Future Work

The main conclusion of this study is that a higher EV penetration level, which is greater charging events, would help with decreasing the excessive PV energy even without any charging coordination strategy. Besides, no overloading or under-voltage problems were observed with the PowerFactory based simulations of three real German grids.

Using data driven approach, Monte-Carlo analysis based simulations on aggregate model of 100 EV charging events were conducted. The result shows the distribution of EV charger type plays a significant role in this process that a higher ratio of public and semi-public charger could drastically improve the excessive PV decreasing procedure. Specifically, the median of excess PV energy reduces by almost 50 % from 0.4 to 0.2 MWh on a given day when home charger ratio is declined from 70 % to 25 % within this 100 charging events.

Furthermore, none of the grids experience overloads or under-voltage issues with the introduction of EVs even without any presence of any PV. It can be inferred from this that all three simulated grids can manage EV penetration beyond the maximum level set in this research work. If closely looked at the rural and urban grids, it is seen that the grids were operating at low loading values to begin with. Hence, in order to make them function near its technical limits, would mean addition of very large loads. The number of EVs to make such an impact would be very significant. Hence the overloading was absent in each of the grids. All the grid are oversized, robust and operationally efficient with the given simulation conditions.

In the High-PV scenario, all the grids experience power mismatch which results in excess unused energy. Furthermore, the occurrences of overvoltage caused by the PV generation is reduced as number of EVs increases in the grids. However, the number of EVs used in this research work is not enough to mitigate the overvoltages. Further research is required to solve this issue. Nonetheless, it can be deduced that, EV and PV appear to be complementary to each other. Both tend to balance each other out, albeit imperfectly.

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