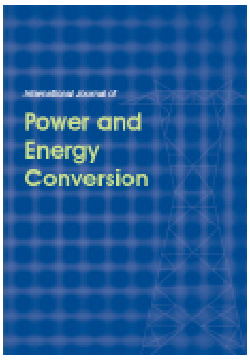

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Renewable compensatory measures to mitigate the grid stress after different penetration shares of electric mobility in urban environment

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Abstract: The need for a more secure green power supply and a wiser grid expansion demands thorough analysis of the electrical energy demand growth and also of future installations of renewable energy sources. In the present study the increase of electricity demand for a city due to electric mobility penetration has been estimated. Consequently, the expansion of renewables is also examined as possible mitigation measure against grid stress. During the simulation process several scenarios are considered and different grid indexes are calculated and applied as metric factors. Simulation results indicate that the electric mobility brings almost up to 20% increase in the total electricity demand of the chosen urban area by 2050. Moreover, outcomes show that the higher penetration levels of wind energy in the renewable energy mix result in a more reliable power supply by reducing great variations in the grid exchange and by leading to higher degrees of self-sufficiency.

Keywords: electric vehicles; renewables; grid; charging.

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1 Introduction

Transport sector is having a vital role during the decarbonisation era against the climate change. The greenhouse gas emissions from this sector in Germany should be reduced to 40%–42% towards 1990, according to the Climate Plan 2050 of the government (‘Klimaschutzplan 2050 der Bundesregierung’) (BMU, 2016). This target is in accordance with the European (EU) climate and energy framework that includes EU-wide goals (European Commission, 2014). To this respect, electric mobility can be hereby a significant contributor to this direction, since the use of battery electric vehicles (EVs) is responsible for lower emissions, especially for countries which tend to decarbonise their electricity generation (IEA, 2019). In particular, Germany has set a target for 1,000,000 EVs on the roads till 2020 (Die Bundesregierung, 2009), and the federal government is pursuing to increase the number of EVs in the upcoming years while the automotive industry strives also to this direction (Die Bundesregierung, 2011).

However, the required energy to charge all these vehicles may bring the power supply to its limits and can stress the grid extensively. In this context, several mitigation measures should be introduced, so as to balance the extreme supply conditions. Solar and wind energy are two renewable energy sources (RES) that can be further expanded in this case and succeed the desired output. A recent study, formed from the four German transmission system operators (TSO), shows the trend of the penetration of electric mobility in the German grid until 2035 (Rippel et al., 2023). Jochem et al. (2013) investigate methods to smoothly integrate EVs in the future German power supply system, while Engel et al. (2018) examine the same issue from a global point of view. Similarly, EVs share in European energy market is presented in study of Duran and the impact of smart charging is additionally analysed (Duran, 2015). A review on the issues that the integration of EVs poses for electrical networks is presented in Srivastava et al. (2023). Several other studies develop also green charging strategies (Schuller and Hoeffer, 2014; Codani et al., 2016; Horst et al., 2009; Ghofrani et al., 2014; Freire et al., 2010; Monigatti, 2017; An et al., 2017; Hoffmann, 2019), in which EVs charging procedure is allocated and matched to the available surplus of renewable energy, proving evidently the need for exploring possible synergies between electric mobility and expansion of renewables. Yu et al. (2022) analyse the impact of the EV penetration under the aspect of urban decarbonisation, while Zhang et al. (2021) examine the relation of the photovoltaic (PV) penetration quote and charging demand with respect to prices. In addition, Maurer et al. (2023) provide an analysis of the correlation of PV and EV grid intergation with focus on the voltage levels. These studies though did not analyse the effects of different renewable and EVs penetration shares on grid level. With respect to the planning of a reliable power supply both by policy and energy suppliers, it would be thus of great interest to evaluate the relation between EVs penetration increase and renewables' diversity in the energy mix of urban areas.

Target of this study is therefore to analyse the relation of different penetration shares of the electric mobility and renewables in the energy mix of a city. The rest of the paper is structured as follows. In Section 2 the developed methodology is described and chosen metric factors are also presented. In addition, the selected case study region is introduced. The results of the simulation are provided and analysed in Section 3 and finally in Section 4 conclusions are drawn.

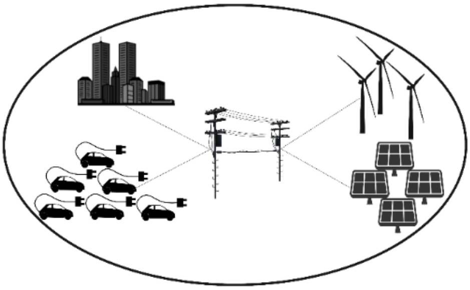
2 Methodology/system description

For the study of the relation of different RES shares to various EVs penetration levels a particular methodology is required, through which the future amounts of power demand and generation will be extracted and then compared. In this chapter this methodology as well as the selected case study are presented and thoroughly explained.

2.1 Case study

In this specific study, the effect of electric mobility on the electrical supply in an urban environment is examined (Figure 1). A municipality of 50,000 inhabitants, located in the central north part of Germany, has been considered as the chosen case study city. In 2018 the local annual electricity demand was 111.789 GWh and electric mobility penetration amounted to 0.33%, which corresponds to 100 EVs and is twice as high as the respective share of electric mobility for the whole Germany (Schuller and Hoeffer, 2014; Kraftfahrtbundesamt, 2019; Stadtwerke Wolfenbüttel, 2019). In addition, the PV installations in the area with a peak power of 6.2 MW succeeded for the same year a 3.58% penetration share in the electricity mix of the city (Stadt Wolfenbütte, 2018).

Figure 1 Examined case study



2.2 National targets

German federal state has set in its strategic roadmap for the upcoming future specific targets not only for the EVs increase in the transport sector but also for the expansion of the renewables towards a less carbonised environment. In particular, there is the aim of 6 million registered vehicles until 2030, which corresponds to an 11% penetration level, while for 2040 and 2050 several studies with different scenarios show a trend for possible

EVs penetration shares of 35% and 50% respectively (Die Bundesregierung, 2011; Vennegeerts et al., 2018). Moreover, according to the Federal Ministry for Economic Affairs and Energy certain quantitative goals for renewable energy in gross electricity consumption have been set for the decades 2030, 2040 and 2050 in the frame of the energy transition (BMWi, 2015). These data are presented in Table 1 altogether.

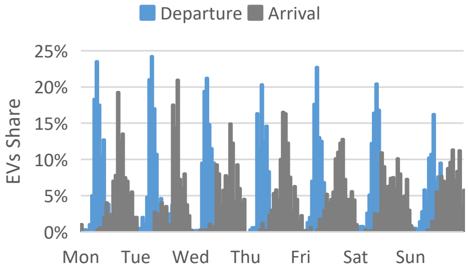
2.3 Simulation/methodology

- *RES penetration:* for the modelling and simulation part of the renewable energy production the national targets have been applied for the chosen urban area. The shares of PV and wind have been wisely selected, addressing the current trend towards energy transition. With a present 7% and 14% share of PV and wind energy in the electricity consumption of Germany nowadays, it is considered wiser to start examining respective ratios from 10% PV and 20% wind, based also on the study of the German Renewable Energy Federation (BEE, 2019). These quotas are then successively increased in 10% steps and the new respective energy mix is each time new defined till the desired RES target has been reached. The upper limits of PV and wind shares in the RES energy mix comply with a realistic expansion of RES during considered time spans, bounded to 50% for each one of them. Consequently, validated analytical PV and wind models have been used and respectively scaled up so as to reach the planned power output (Dimopoulou et al., 2019). These models accept as input weather data from a local weather station and the year 2018 has been considered as the reference year. The power outputs per time step are subsequently extracted as a time series in 15-minutes intervals and the accumulated RES power levels per time unit are calculated.

  This procedure is repeated for every RES penetration level and each time the new power curve over the year is generated.

- *Mobility strategy:* the simulation of the charging load profile and the electric vehicle charge behaviour is based on the departure and arrival time data as well as the driving distance values for the EVs, which have been extracted from the VDE Study for EVs (2010) (Böcker et al., 2010) and from the research of Probst (2014). In Figure 2 the distribution of the departure and arrival times for private vehicles is graphically illustrated and in Table 2 the relation of the driven distance per vehicle share is depicted. It is assumed that the EVs charge always at the end of the last trip of the day until they are again fully charged. Moreover, different categories of EVs (small and middle class) have been taken into account (Table 2) and their distribution over the years in the EVs mix favours the middle class type the more long-term the prognosis is. Additionally, different charging power levels (2.3 kW, 3.7 kW, 11 kW and 22 kW) have been considered, assuming that the higher the driving distance and the longer the commuting time, the higher the demand in power charge level is. The consumption and battery capacity of the EVs are extracted as the average values of the available on market EVs in 2018 for each specific category. For small class EVs these are 12.5 kWh/100 km and 18.2 kWh, while for the middle class 15.7 kWh/100 km and 39 kWh respectively (Hoffmann, 2019).

Figure 2 Departure and arrival times of passenger cars (see online version for colours)



Source: Dimopoulou et al. (2019)

A stochastic procedure based on the existing weighted distributions is then developed to recreate a new sample of EVs and aggregate the charging behaviour on the existing load demand. In particular, for each EV *i* in each penetration level, which corresponds to *m* EVs, and for each day *d* of the year *Y* the algorithm chooses randomly the category to which the EV belongs to. This category (small and middle class) is related to the average consumption per km C_i. Then the charge power P_{EV_i} is selected, as well as the arrival time in day *d* and the departure time in day *d* + 1. Consequently, the required energy E_{EV_i} to fully charge the vehicle (1) and the charge duration T_i are calculated (2) and lastly, the aggregated load of the day P_{total} is created by adding the charge power to the existing load of the city P_c on time interval which corresponds to the arrival time and for *t* time steps which equal the planned charge duration (3).

$$E_{Ev_i} = d_i \times C_i \ \forall i \in m, d \in Y \tag{1}$$

$$T_i = \frac{E_{EV_i}}{P_{EV_i}} \forall i \in I, d \in Y \tag{2}$$

$$P_{total} = \sum_{i=1}^{m} P_{EV,t}^{i} + P_C, \forall t \in T, i \in m, d \in Y \tag{3}$$

With the performed simulations of the annual energy demand with EVs and renewable production for 2030, 2040 and 2050 is attempted to estimate the grid stress under different penetration shares of electric mobility and evaluate the ratio of PV and wind in the energy mix, which could give a better contribution to grid relief. The whole methodology is given as a flow chart in Figure 3.

Table 1 National targets and status quo

	2018	*2030*	*2040*	*2050*
Electric mobility penetration	0.33% (Hoffmann, 2019)	11% (Die Bundesregierung, 2011)	35% (Stadt Wolfenbüttel, 2018)	50%[a]
Renewable energy in gross electricity consumption	3.58% (Stadtwerke Wolfenbüttel, 2019)	50% (Vennegeerts et al., 2018)	65% (Vennegeerts et al., 2018)	80% (Vennegeerts et al., 2018)

Note: [a]Own calculation based on Stadt Wolfenbüttel (2018).

Figure 3 Flow chart of the applied methodology

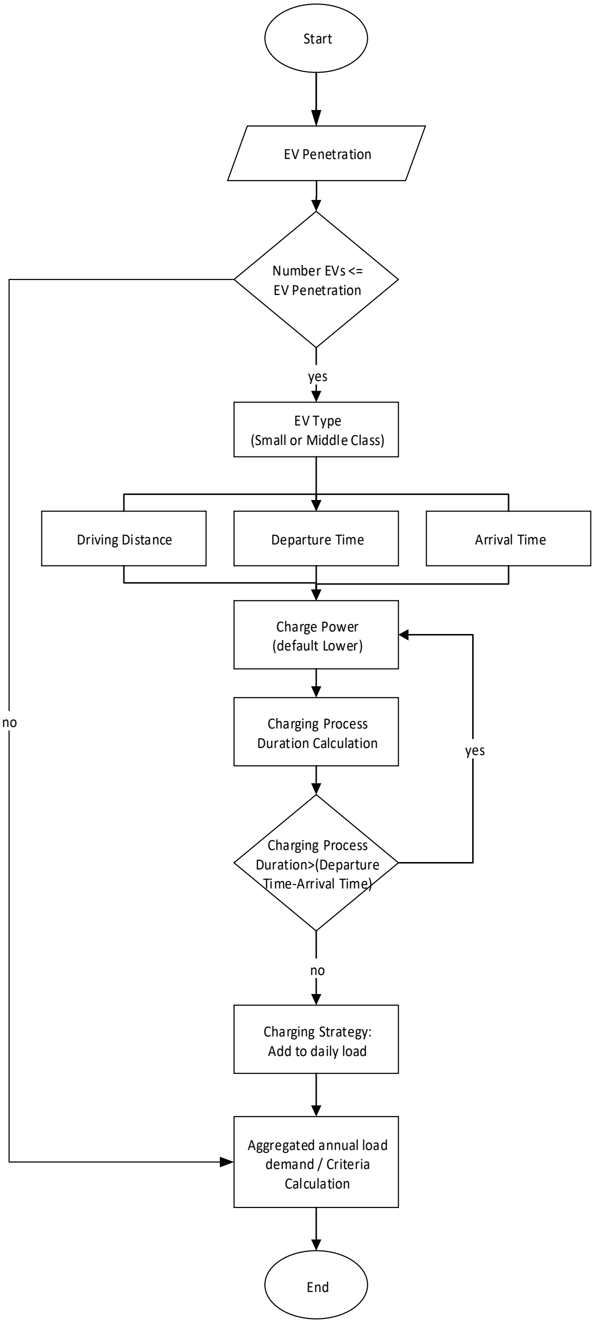


Table 2 Distribution of the average daily driven distance from passenger cars

Distance in km	0–1	1–10	10–20	20–40	40–65	65–100
Share in %	3.96	27.52	20.39	23.67	14.61	9.85

Table 3 EVs distribution per category

	2030	*2040*	*2050*
Small class	80%	40%	20%
Middle class	20%	60%	80%

2.4 *Grid factors*

Finally, the annual load demand is then analysed in terms of key factors and grid indexes, so as to examine possible synergy effects from integration of renewable energies and e-mobility. These factors are the load cover factor F_{load}, or level of self-sufficiency (4), the supply cover factor F_{supply}, which describes the self-consumption of the locally produced renewable energy (5) and the grid interaction index I_{grid}, which depicts the variability of the exported or imported energy (6) (Salom et al., 2013):

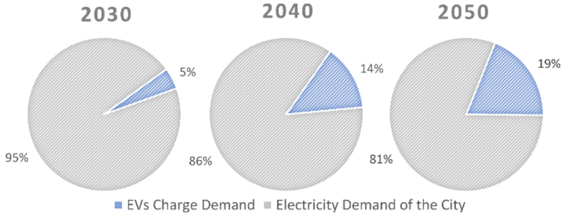
$$F_{load} = \frac{\int_{\tau_1}^{\tau_2} \min\left[P_{RES}(t), P_{total}(t)\right] dt}{\int_{\tau_1}^{\tau_2} P_{total}(t) dt} \tag{4}$$

$$F_{supply} = \frac{\int_{\tau_1}^{\tau_2} \min\left[P_{RES}(t), P_{total}(t)\right] dt}{\int_{\tau_1}^{\tau_2} P_{RES}(t) dt} \tag{5}$$

$$I_{grid} = \sigma\left(\frac{E_{Grid\_Exchange}}{\max\left(\left|E_{Grid_{Exchange}}\right|\right)}\right) \tag{6}$$

where $\tau_2 - \tau_1$ is the examined time period, $E_{Grid\_Exchange} = E_{Feed} - E_{Draw}$ is the net exported energy, E_{Feed} is the energy surplus, E_{Draw} is the energy deficit drawn from the grid, $P_{RES}(t)$ is RES power generation, $P_{total}(t)$ is the accumulated load demand.

Figure 4 EVs charging energy demand share in the total electricity mix (see online version for colours)



3 Results

The extracted outputs, as depicted in Figure 4, show that the electric mobility brings almost up to 20% increase in the total electricity demand of the chosen urban area by 2050, highlighting thus the urgent need for green solutions and higher penetration levels of RES in the energy mix of a medium sized city, in order to charge EVs with green power. In 2030, the increase due to EV charging is though rather limited, arising to 5% of the annual total electricity demand while in 2040 the respective ratio amounts to 14%.

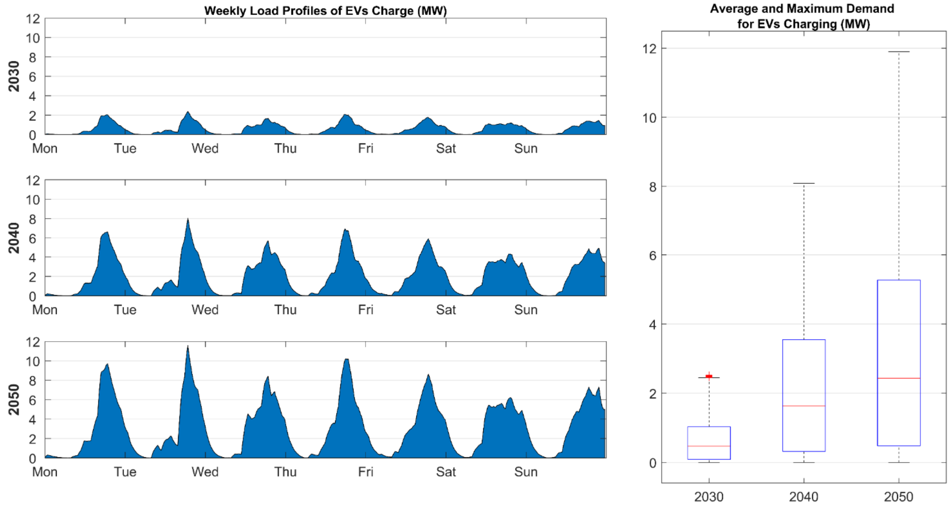
In Figure 5 the weekly load charge profiles for the three different years are additionally graphically presented, as well as the average and maximal load in each examined year. It is noticed that although for 2030 the load increase due to electric mobility is not significant, this is not the case for 2040 and definitely for 2050. Peak loads up to almost 12 MW are spotted in 2050 due to simultaneous charge demand late at the afternoon creating great power needs from the grid site. This equals a 50% load increase, indicating thus the need for mitigating measures to cover such great peaks. In 2040 this increase arises to 35% while in 2030 this is just over 10%.

In addition, as depicted in Figure 6 and Figure 7, the calculated grid interaction index is growing with higher penetration of PV shares and is steadily reduced with greater wind ratios in the energy mix over the years. The deviation of the grid exchange is increasing due to great amounts of PV energy that are daily produced but are not able to be consumed and must be fed to the grid, while wind shres are smoothly distributed over the day, and are more straightforward drawn from loads.

The supply cover factor is as expected reduced with the increase of both PV and wind shares, which is a result of great load mismatching (renewable energy production does not coincide load demand).

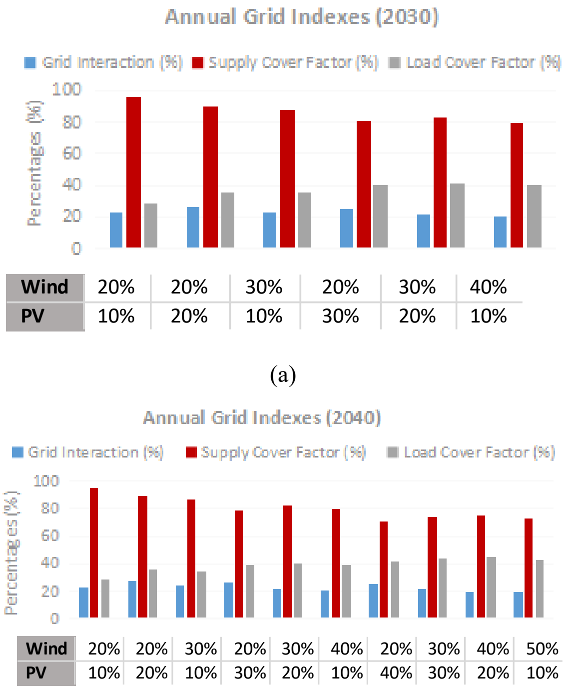
When no storage system is considered the higher renewable energy production does not lead to higher amounts of self-energy consumption, as the production is not controlled to agree with the demand, though rather dependent on intermittent weather conditions.

Figure 5 Weekly load profile of EVs charging procedure and annual mean and max. load EVs charging load values (see online version for colours)



Moreover, load cover factor is higher with higher shares of wind in the local energy mix. As previously explained for the grid interaction index, higher self-sufficiency rates are accomplished when wind outbalances PV as this particular renewable energy source is not so dramatically affected from the intraday weather conditions and the greater power peaks that occur late in the afternoon can be partially covered from it.

Figure 6 Key factors for different RES penetration shares in (a) 2030, (b) 2040 (see online version for colours)



(a)

(b)

It can be also noticed that in the same total RES share in the energy mix the ratio of PV and wind affects the grid indexes substantially. Differences up to 30% are detected, when the wind rate outbalances in relation to the PV percentage, when the overall RES percentage remains the same, since wind energy succeeds lower variation in grid interaction and higher self-consumption and self-sufficient rates due to its versatility, which is over the day more evenly spread.

Figure 7 Key factors for different RES penetration shares in 2050 (see online version for colours)

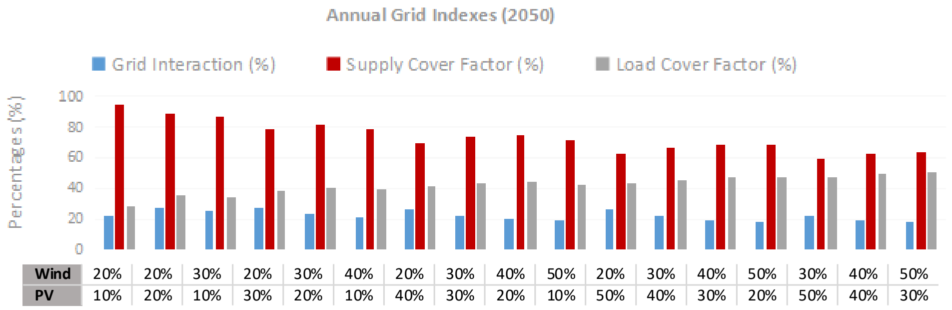


Figure 8 Weekly profile of the charging methods and the power difference, resulting from the regional electricity demand (without EVs) and local renewable generation (see online version for colours)

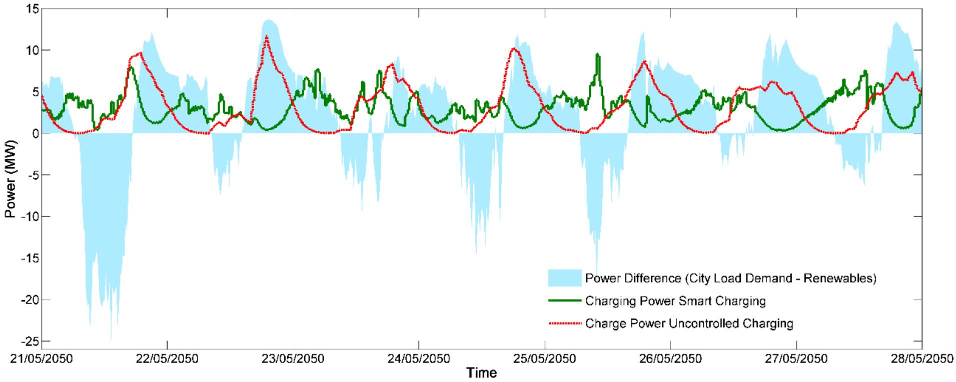
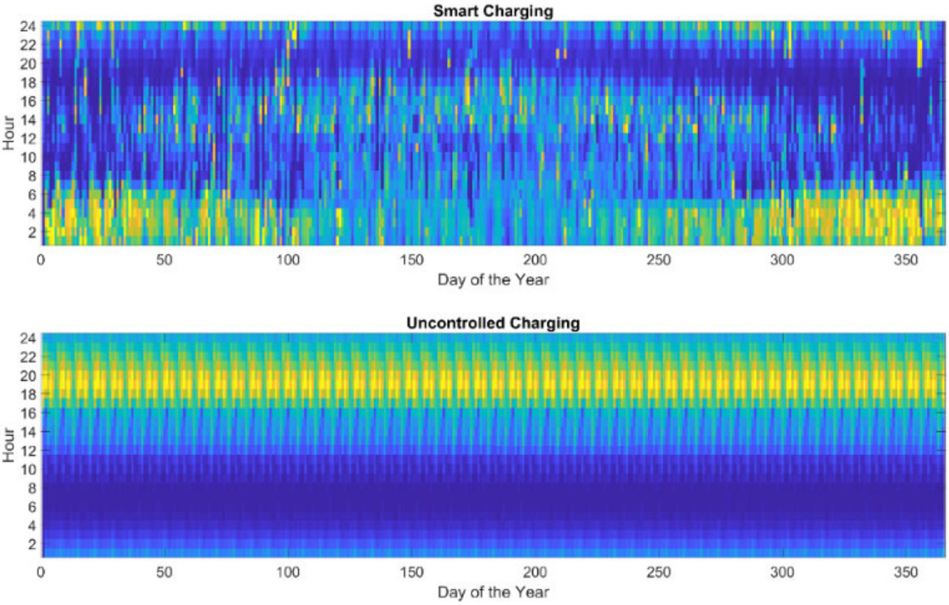


Figure 9 Annual illustration of the charging procedure with smart and uncontrolled technique (see online version for colours)



Finally, it can be also identified that for the case study 2050, although the maximal penetration of renewables in the energy mix reaches 80% only half of it can be annually direct consumed. This fact in combination with the ineffectiveness of the RES to cover such type of load demand and inability to shave peaks should be carefully examined and considered for the design of the future power supply. The intermittent nature of the wind and PV makes it impossible to displace the conventional energy sources, without the confrontation with critical power supply issues. As alternative, other options should be considered. First storage of RES excess, when the demand is low, either through power-to-X systems, via stationary storage batteries or pumped-storage hydroelectricity systems is the one direction that not only the prosumers but also the power utility companies should turn to in order to succeed a better and more secure supply regime. In addition, efficiency measures, as well as demand response and peak shaving should be extra planned and fostered. This endeavour will assist towards reduction of load peaks and energy demand, mitigating thus the need for extreme expansion of RES installations. Financial incentives for users and EV drivers, such as charging when energy is cheaper are also of great importance und may contribute to expansion of the synergy space between electric mobility and RES. A charging control strategy for EVs may in this sense entail better intraday load allocation based on smart-designed time-of-use rate structures, with which EV charging load may be displaced to lower cost periods.

4 Conclusions

It can be concluded that the increased penetration of EVs causes greater grid stress, despite the parallel expansion of renewables, which counteract and partially compensate the further grid strain. However, the wind energy has in Germany apparent advantages to grid relief in comparison to the PV, since the evenly intraday distributed wind energy share can be better directly consumed for EVs charging purposes. The expansion of PV installations should be in future wisely planned, so as to avoid greater grid stress, while an intelligent designed charging technique oriented to shave peaks and exploit renewable energy surplus would contribute to this direction, if a significant enhancement in grid security and stability is required.

5 Outlook

With the increasing penetration of electric mobility and the associated rise in the number of vehicles that need to be connected to the power grid, charging strategies will become increasingly important. Currently frequently discussed charging strategies control the charging process on the basis of grid parameters (charging voltage, reactive power, etc.), the electricity price development or the availability of electricity from renewable energies. Due to the research focus of this working group, a charging strategy based on the surplus of renewable energies will be developed for future studies. First results show that the smart charging technique is successively shifting the charging procedure of every car that is arriving to its initial location, based on the already accumulated load demand and on the forecast renewable production (Figure 8). The charging procedure is thus finely dispersed during day and night (Figure 9), succeeding thus peak shaving and matching the time intervals of high surplus of renewable energy and low energy demand. In the future, more detailed simulations will be carried out to identify the influence on the power grid more precisely.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

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