32nd Electric Vehicle Symposium (EVS32)
Lyon, France, May 19 - 22, 2019

Analysis of Intelligent Charging Strategies to Reduce the Need of Grid Reinforcement Measures Caused by the Market Ramp-Up of Electric Vehicles

Detert Bracht[1], Tim Montag[2], Timo Schürer[3]

[1]*P3 group (P3), Aachen (Germany), Detert.Bracht@p3-group.com*

[2]*P3 group (P3), Aachen (Germany), Tim.Montag@p3-group.com*

[3]*Main-Donau Netzgesellschaft (MDN), Nuremberg (Germany), Timo.Schuerer@main-donau-netz.de*

Executive Summary

The accelerating market ramp-up of electric vehicles in the sector of road-bound passenger and freight transport leads to an increase in the installation of charging infrastructure connected to the distribution grids. The additional power and energy demand of electric mobility affects the power flow through operating equipment. In case of high load caused by electric mobility, local grid congestion can occur. The presented case study reveals, that the implementation of intelligent charging strategies relieves the distribution grids significantly and costs for grid reinforcement decrease by up to 44 % compared to uncontrolled charging.

Keywords: EV (electric vehicle), market development, load management, smart charging, simulation

1 Introduction

Due to the increasing greenhouse gas concentration as the main driver for climate change, the German government facilitates, among other things, EV to reduce CO2 emission in the transport sector [1][2]. To ensure security of supply in the distribution grids in the long term and to avoid disinvestment in grid reinforcement measures, it is necessary to take the influence of electric mobility into account at an early stage when planning network expansion. Against this background, the long-term prognosis of the electric mobility market ramp-up and the grid relief potential of intelligent charging strategies is of high importance. Therefore, P3 developed a model to emulate the adoption decisions of potential buyers of electric vehicles. The resulting scenario for the market ramp-up is locally disaggregated based on an analysis of mobility data as well as socio-economic parameters. Considering the mobility behavior and the forecasted charging behavior local load time series for electric mobility are generated. These display cost-optimal integration of battery storage systems (BSS) in charging parks as well as intelligent strategies for global charging control. Subsequently, the developed methodology is applied on five representative medium voltage (MV) grid areas within the supply area of MDN and load flow simulations are performed. Subsequently, the potential of intelligent charging strategies to avoid needs of grid reinforcement and its costs are examined. The proposed methodology is schematically depicted in Fig. 1.

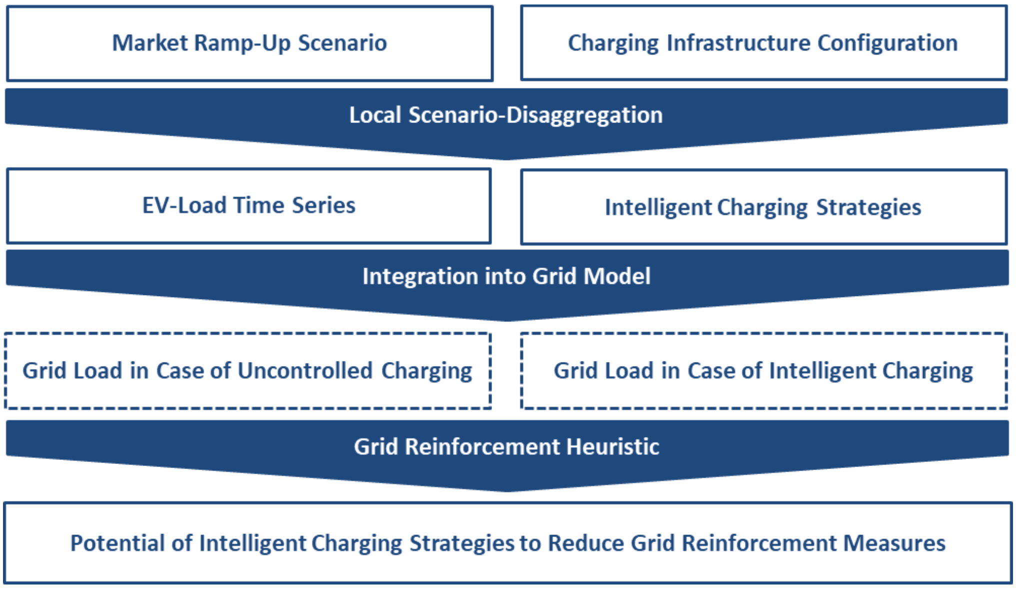

Figure 1: Schematic overview of proposed methodology.

2 Methodology

2.1 Market Ramp-Up Scenario

The forecast of the electric mobility market ramp-up is based on the diffusion process of the electric mobility innovation. The decision of purchasing a vehicle depends on the relative economic advantages of the available alternatives and the compatibility with existing mobility needs, as well as the technological risk of the drive type to be selected for both commercial and private costumers. In a first step, the forecasting model emulates the economic decision of potential users based on the economic advantages derived from a break-even analysis of the total cost of ownership (TCO).

For this purpose, the existing vehicle market is analysed regarding available EV models and corresponding reference vehicles with internal combustion engines (ICEV). Subsequently, the EV models are categorized and average TCO-annuities as functions of the annual mileage are determined for each drive type r and vehicle category s. For purchasing a vehicle in year t those values can be calculated according to formula (1) to (3).

$$TCO^{a}_{r,s,t} = a^{r,s,t}_{capex} + a^{r,s,t}_{opex} \quad (1)$$

$$a^{r,s,t}_{capex} = \left(AC_{r,s,t} * (1+i)^{T} - RV_{s} * AC_{r,s,t}\right) * \frac{i}{(1+i)^{T}-1} \quad (2)$$

$$a^{r,s,t}_{opex} = AM * (s_{e_r} * c_{e_{r,s,t}} * k_{e_t} + (1 - f_{e_r}) * c_{v_{r,s,t}} * k_{v_{r,t}} + k_{w_{r,s}}) + K_{s_{r,s,t}} \quad (3)$$

$TCO^{a}_{r,s,t}$ annuity of total cost of ownership

$a^{r,s,t}_{capex}$ annuity of capital expenditures

$a^{r,s,t}_{opex}$ annual operational expenditures

$AC_{r,s,t}$ acquisition cost

i interest rate

T holding period

RV relative residual value at end of the holding period

AM annual mileage

s_{e_r} electric driving share

$c_{e_{r,s,t}}$ electricity consumption

k_{e_t} electricity cost

$c_{v_{r,s,t}}$ fuel consumption

$k_{v_{r,t}}$ fuel cost

$k_{w_{r,s}}$ annual cost for maintenance and repair

$K_{S_{r,s,t}}$ annual contribution to the motor vehicle tax

After calculating the TCO-basis for the current vehicle market, all relevant factors influencing its future development are exemined. This includes future mobility needs, energy industry framework and possible political measures. Thus, the parameters influencing the TCO are forecasted until 2050 and a plausible range for future TCO values is determined. Based on those forecasted TCO-values, break-even analyses are conducted to calculate the proportion of ICEV that can economically be substituted by Battery Electric Vehicles (BEV) or Plug-In Hybrid Electric Vehicles (PHEV). Fig. 2 depicts the break-even-analysis for short-range BEV in the year 2025 by showing the forecasted ranges of the TCO-annuity as well as the distribution of the annual mileage within this vehicle category. By determining the break-even-mileage and the corresponding share of drivers reaching it, optimistic, medium and pessimistic scenarios regarding economic substitutability can be derived.

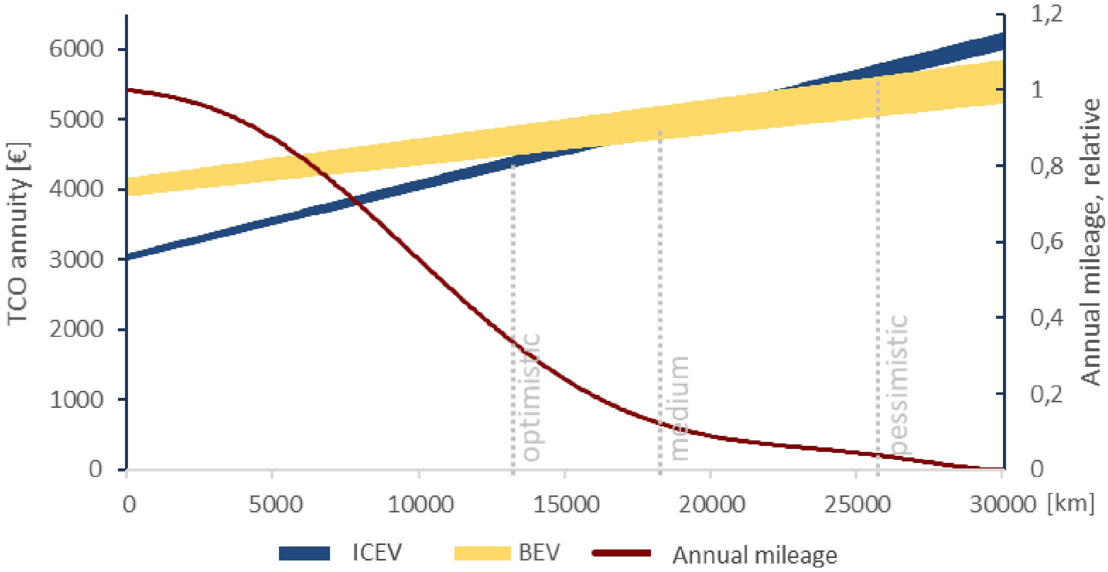

Figure 2: Break-even analysis for short-range BEV in 2025.

For the estimation of the diffusion process over time, the economic substitutability is a main influencing parameter but is not sufficient on its own. Individual factors influencing the purchase decision of customers are also relevant. The proportion of new vehicle registrations substituted by electric vehicles, for the year under consideration, is therefore calculated by taking the state of the market penetration into account. Fig. 3 shows the resulting market ramp-up scenario for the category of passenger vehicles. For each year until 2050 the share of new registrations of electric vehicles and the resulting number of electric vehicles in the total vehicle population of Germany are depicted. In the context of this study, a full-electrification scenario by the year 2050 is considered.

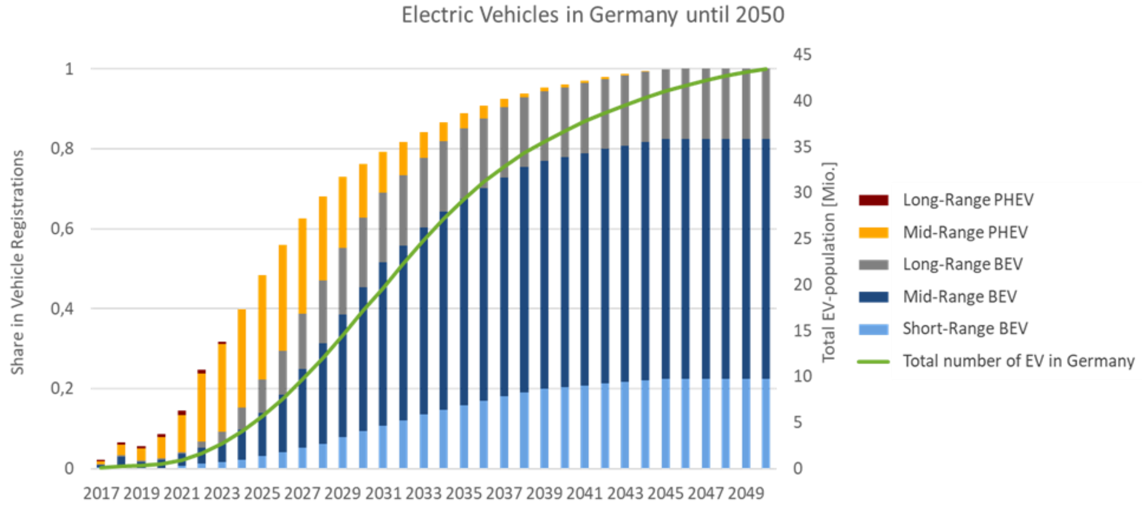

Figure 3: Prognosis of EV market ramp-up in Germany.

2.2 Charging Use Cases

The local effects in the distribution grids and therefore the need of grid reinforcement measures is determined by the number of electric vehicles in each vehicle category and by the characteristics and use of the charging infrastructure deployed for the expected penetration of electric vehicles. The configuration of the charging infrastructure depends on the mobility behaviour and charging needs of the electric vehicle users that determine energy and power demand for each charging session. Depending on the owner group and vehicle category different use cases for charging electric vehicles can be distinguished according to the potential charging location.

For privately used vehicles two main categories are to be distinguished. The first category is "Private Charging". This refers to electric vehicles being charged at a designated parking lot that is not publicly accessible for other electric vehicles. This includes the locations "Home" and "Workplace".

- "Home": the car owner charges the EV at the place of residence where a charging point is available at a designated rented or owned parking lot.
- "Workplace": charging infrastructure is installed at the employees designated parking lot and used during working hours.

The second category refers to charging processes at central locations in urban areas. The charging points are usually operated commercially and are open to the public or potential customers. Possible charging locations are as follows:

- "Car Park": in underground or high-rise garages, for example at points of interest (POI) located in the city centre. Charging points might be provided by the parking lot operators or other commercial entities.
- "Supermarket": the charging infrastructure is located at shops that are frequented by the customers on a routine basis.
- "Filling Station": similar to ICEV users today, the electric vehicle customer drives to a designated high-power charging location to satisfy existing charging needs.

For commercially used vehicles, a division according to vehicle category is necessary due to different mobility requirements and vehicle parameters. The first category corresponds to commercial passenger vehicles for which the use case "Car Fleet" is defined. The electric vehicles are charged at the respective company location and outside of the operating hours. The use case “Truck Fleet” corresponds to vehicles primarily used for inner-city distribution transport that take a daily round trip starting and ending at the respective company premises. The third relevant use case that is considered for commercially used vehicles within this study is “Bus Fleet” and refers to public transport motorbuses that charge at a central depot. For every use case, the installed maximum power of the charging infrastructure sufficient to satisfy the customers charging needs is determined by the energy to be recharged and the assumed average length of stay at the charging location as well as consumer preferences.

2.3 Local Electric Mobility Scenarios

The local load flow caused by the charging of electric vehicles is determined by the local characteristics of the charging infrastructure for each use case as well as the local energy demand of the electric vehicles. The aim of the local electric mobility scenario disaggregation is to determine the significance of the use cases for a specific grid area and to derive specific parameters that influence the local power and energy demand.

At first, an individual market ramp-up scenario for each community within the supply area of MDN is derived based on socio-economic parameters like housing and income structure by conducting regression analyses. Fig. 4 visualizes the number of registered passenger EV by the year 2050 for each community within the grid area of MDN.

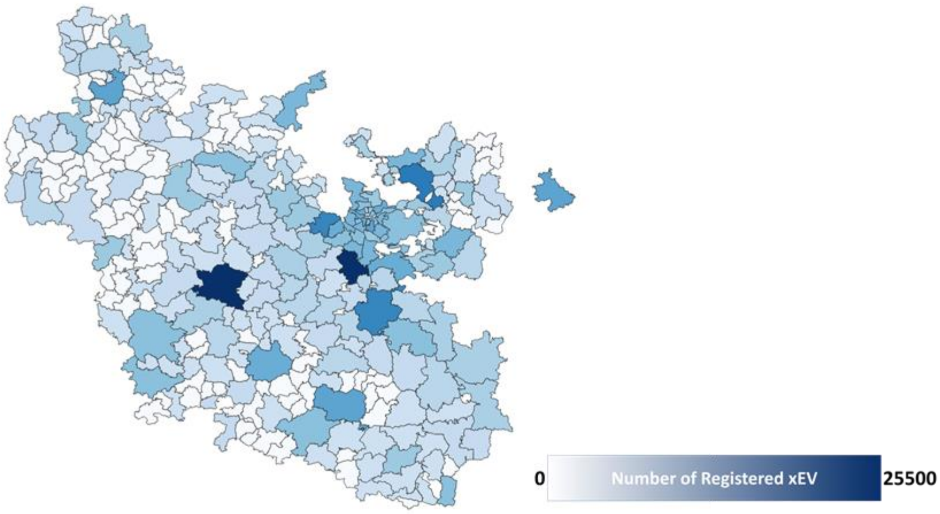

Figure 4: Registered passenger EV within supply area of MDN by 2050.

In addition to the locally registered vehicles, the local balance of commuters inter- and intra-area is particularly relevant for the utilization of “Workplace” charging within a specific grid area. To determine the commuter hotspots within any grid area to be investigated, P3 applies a developed model that calculates the probability for commuters to enter or leave the grid area based on statistical input data such as [3]. Furthermore, potential charging locations for “Central charging” are identified and site-specific data is collected to determine the extent to which these are utilized within the specific grid area. The relevant number of vehicles within the catchment area and the average distance travelled to the charging location are analysed and then used as input parameters to determine the local power and energy demand of the electric vehicles.

Following this methodology to derive local electric mobility scenarios, all relevant use cases for specific grid areas and thus the local characteristics of the charging infrastructure can be determined for each studied year. Also, specific input variables regarding the local power and energy demand are derived to simulate local load time series for electric mobility.

2.4 Local Load Time Series

Possible network congestion is caused by the characteristic of local peak loads. The local simultaneity factors and the time pattern of the required power per use case are of crucial importance [4]. In this context, a P3-model for simulating individual load curves for each charging point is used. The individual power demand of each electric vehicle depends on vehicle-specific parameters, local parameters of the examined area and the selected use case. These factors determine both the vehicle battery state-of-charge (SOC) at the time of arrival and the required charging power at the charging point and thus the charging curve assigned to the vehicle.

The start and end time of each individual charging process is also relevant for the time profile of the total load [5][6]. It is assumed that the charging process will start immediately upon arrival at the charging point. Hence, a probability distribution for the arrival times at the respective charging location is defined for each use case. Depending on the SOC at the beginning of the charging session and the power rating of the charging infrastructure, a potential charging curve is assigned to each vehicle, which is derived from real time series in the database of P3. Fig. 5 shows an overview of this simulation model.

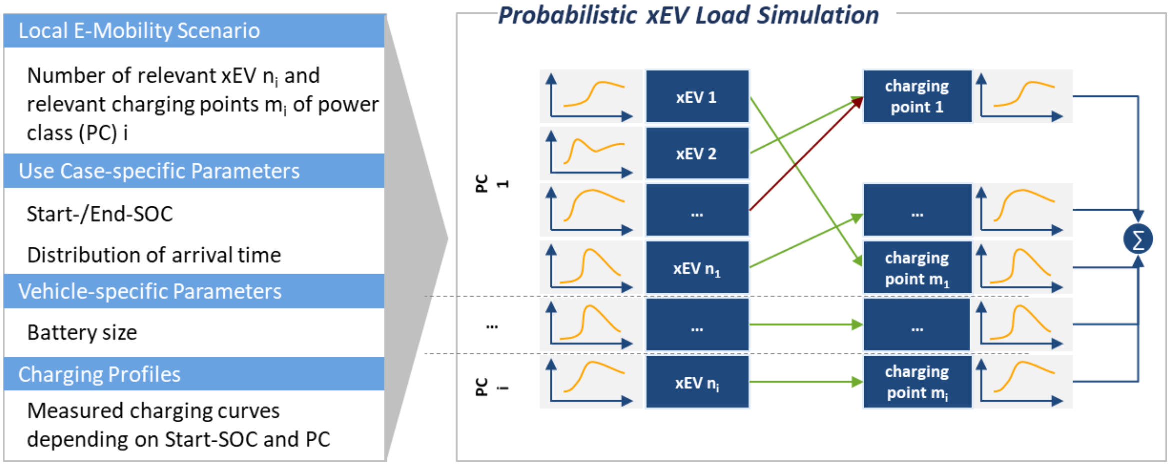

Figure 5: Schematic overview of probabilistic load simulation model.

2.5 Intelligent Charging Strategies

The need for additional grid reinforcement arises due to the power drawn at the charging infrastructure facilities at times of high grid load. By implementing intelligent charging strategies, the maximum electric mobility load and thus the number of necessary grid reinforcement measures can be reduced [5]. At first, the possibility of integrating BSS in a commercially viable manner is examined for each potential charging park in the given grid area by applying a developed optimization model out of the toolbox of P3. This model is further described in [7].

In addition to BSS, the aggregated maximum power drawn from the grid can also be decreased by reducing the number of charging sessions at times of critical grid load. This can either be achieved by conditioning the EV-owners to expand the intervals between charging sessions or by implementing intelligent strategies for charging control. To implement the latter option in real-world applications, communication between the EV, vehicle users, electric vehicle supply equipment (EVSE), energy suppliers, the distribution system operator (DSO) and billing service providers is necessary. These parties exchange data to control the charging process, such as the power demand and the SOC, as well as customer preferences and payment information. As a communication node, the EVSE is of crucial importance for the implementation of intelligent charging strategies. The model developed within the scope of this study takes intelligent charging control strategies into consideration that could already be implemented based on the current regulatory framework.

For charging the lithium-ion batteries of EV the CCCV-method (Constant Current Constant Voltage) is most commonly used. Hence, the charging power reaches its maximum value just after the start of the charging session and decreases afterwards. Thus, the total aggregated electric mobility load is high especially at times when many charging sessions are started simultaneously. Therefore, the aim of the implemented charging control strategies is to limit the number of simultaneously starting charging sessions. In this way, charging sessions are shifted from times of critical grid load to non-critical periods. Fig. 6 shows the dependency of increasing number of shifted charging sessions and decreasing simultaneity factor.

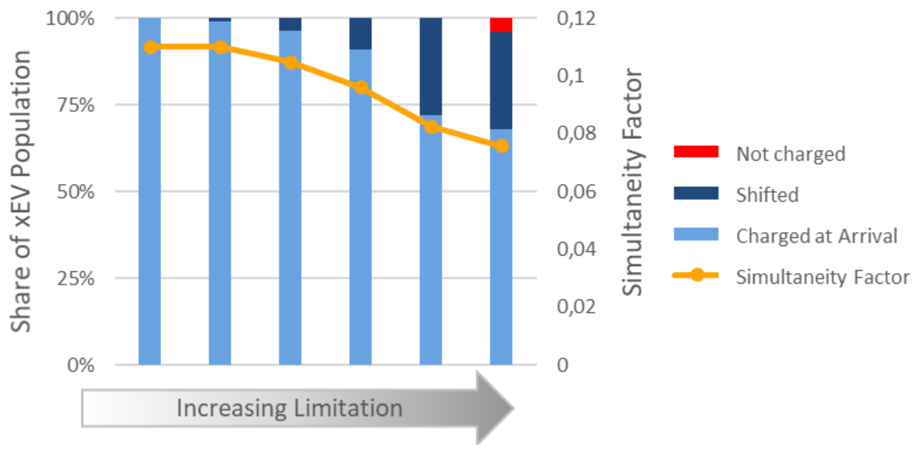

Figure 6: Simultaneity factor depending on the share of shifted charging sessions.

For the simulations in this study, global charging control is considered. The developed load shifting algorithm is therefore applied for the entire EV population so that the simultaneity factor is minimized while at the same time ensuring that the charging need of all customers are satisfied.

3 Case Study

3.1 Examined MV Grid Areas

To examine the grid load under increasing penetration of electric vehicles, local electric mobility scenarios are derived according to the methodology described in chapter 2. Based on these scenarios, local electric mobility load time series representing the electric mobility impact in 2025, 2030 and 2050 are generated. The charging infrastructure facilities are mapped as additional loads in models of real-world distribution grids supplied by MDN. To comprehensively map all relevant charging use cases and charging infrastructure configurations for electric vehicles, exemplary studies of the power flow within MV grids are carried out in this study. Fig. 7 shows the geographical location of the examined MV grid areas in the context of this study.

Figure 7: Examined rural and urban MV grid areas of MDN.

In cooperation with MDN, five representative MV distribution grids – two urban MV grids and three rural MV grids – were selected to analyze the impact of electric mobility. These grid areas are characterized by distinct structural prerequisites and supply tasks, so that in the context of this study a comprehensive picture of potential grid impacts of increasing electric mobility load can be mapped. As Fig. 7 shows, all of he grid areas are located in northern Bavaria. Among the two urban grid areas grid No. 4 is located right in the city center of Nuremberg and No. 5 covers a residential district close to the city center which leads to differing utilization and availability of charging use cases as well as differing relevance of commuters.

3.2 Grid Load in Case of Uncontrolled Charging

To determine the grid load under increasing electric mobility load until 2050, power flow simulations within the MV grids are conducted and in addition, the power exchange with the high voltage (HV) grid as well as the subordinate low voltage (LV) grids is analyzed. Based on these simulations, possible overload of operating equipment as well as voltage range violations at relevant grid nodes are investigated for the years 2025, 2030 and 2050. The permissible supply voltage within the MV grid is specified by EN 50160. Restrictions on equipment load are determined by the applicable grid planning principles of MDN. The data resulting from the power flow simulations is evaluated regarding these restrictions and subsequently a developed heuristic is applied to determine and the necessary grid reinforcement measures and its cost. Fig. 8 shows the results of these analyses for 2025, 2030 and 2050 and each of the five MV grid areas examined in the context of this case study.

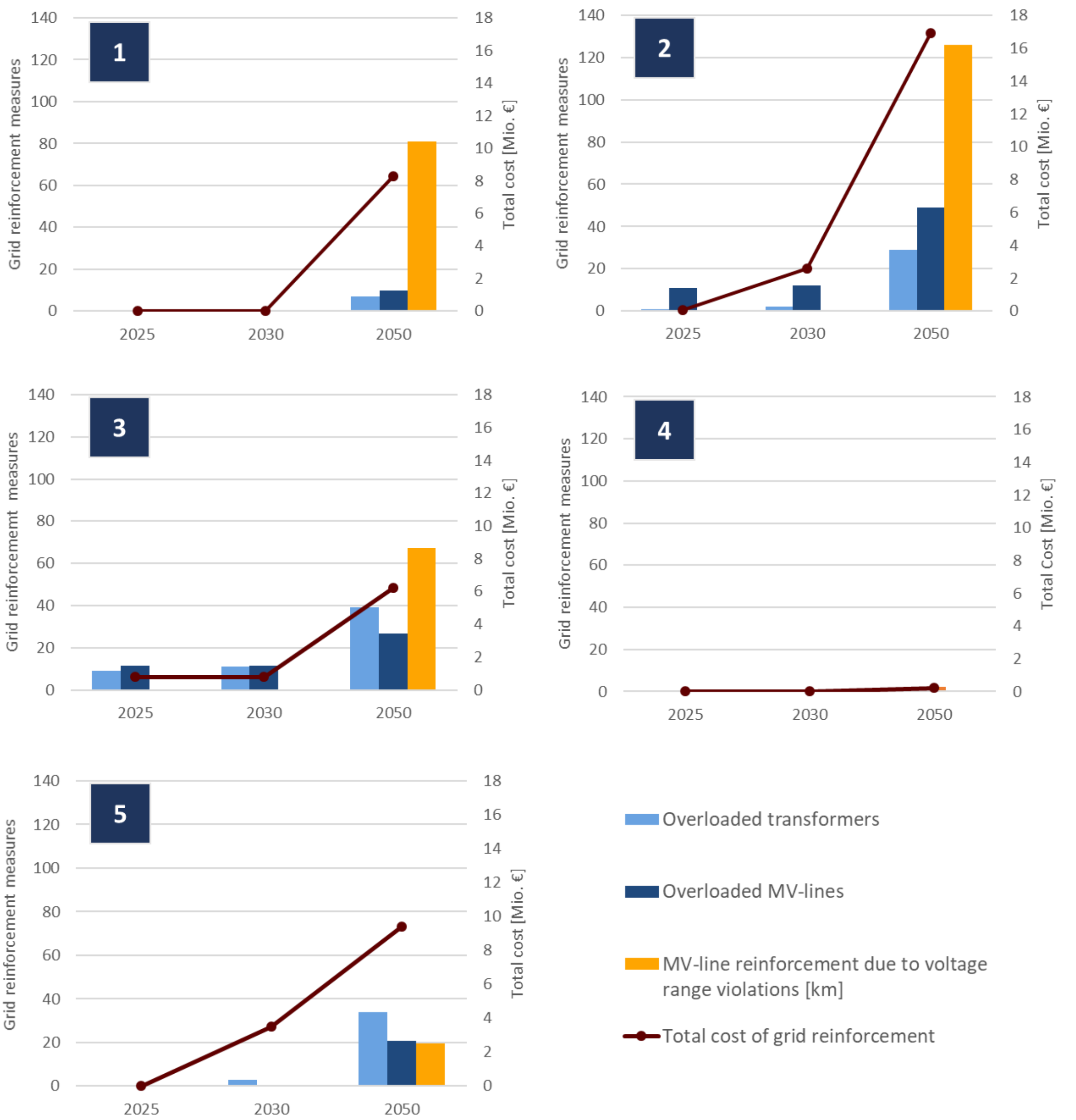

Figure 8: Necessary grid reinforcement measures and its cost for examined MV grids.

The simulations reveal that in case of uncontrolled charging, for every examined grid area except grid No. 4 a significant amount of grid reinforcement measures have to be taken by 2050 due increasing electric mobility load. In addition, it can be observed, that the gradient from 2030 to 2050 is very high. This applies in particular to MV grid No. 2. While in 2030 grid reinforcement costs of 2.6 million euro arise due to overloaded transformers and MV-lines, these multiply by factor 6.5 to a value of 16.9 million euro until 2050. This value arises due to 29 overloaded transformers, 49 overloaded MV-lines and especially due to voltage range violations at 126 of the 264 installed transformer substations within the grid area which lead to necessary MV-line reinforcement of 147 km.

Necessary line reinforcement due to voltage range violations appears to be one of the key drivers for the rise-up of grid expansion cost by 2050 in particular for rural MV grids. Fig. 9 shows the installed transformer substations within the rural MV grids No. 1 to No. 3 and their local distribution. Those substations with violations of the permissible supply voltage in the year 2050 are highlighted in yellow.

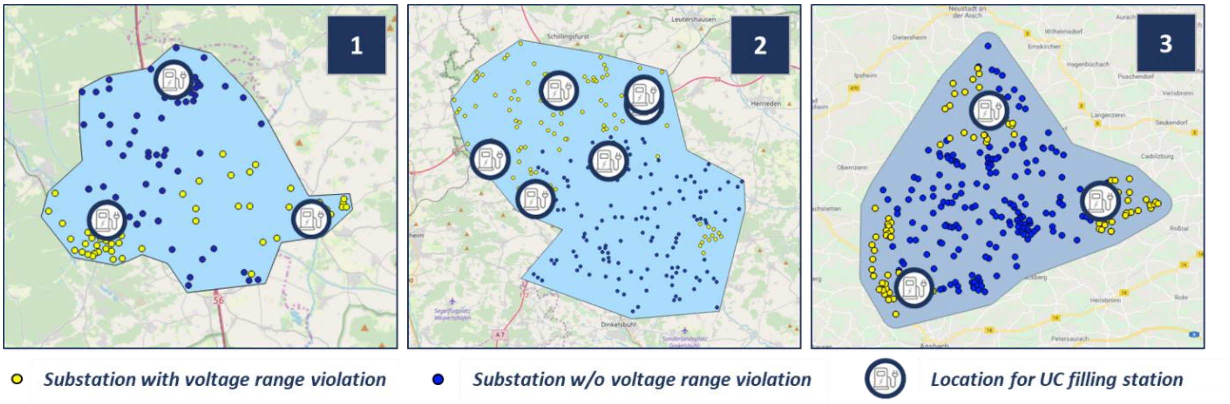

Figure 9: Location of occurring voltage range violations within rural MV grids in 2050.

As the figure shows, voltage range violations within the three examined rural MV grids occur especially near locations for the use case "filling station" due to high peak load. This leads to a high necessity for grid operators to take suitable countermeasures regarding this use case. However, load shifting is not a suitable option to avoid conventional grid expansion and the accompanying high cost because of the fact that for this use case the customer demands high availability and short charging times. Thus, the integration of BSS as mentioned in chapter 2.5 represents a key factor to be evaluated when considering grid integration of high-power charging parks.

3.3 Grid Relief Potential of Intelligent Charging Strategies

In order to investigate the impact of intelligent charging strategies, MV grid No. 2 is further examined in the following as it represents the grid area with the highest amount of necessary grid reinforcement measures accompanied by the highest cost. The grid load as forecasted in the year 2050 in case the proposed intelligent charging strategies are implemented is illustrated in Fig. 10. The amount of overloaded operating equipment and occurring voltage range violations in case of uncontrolled charging is compared to the case of applied global charging control as well as to the case of cost-optimized integration of BSS in charging parks combined with implementing global charging control.

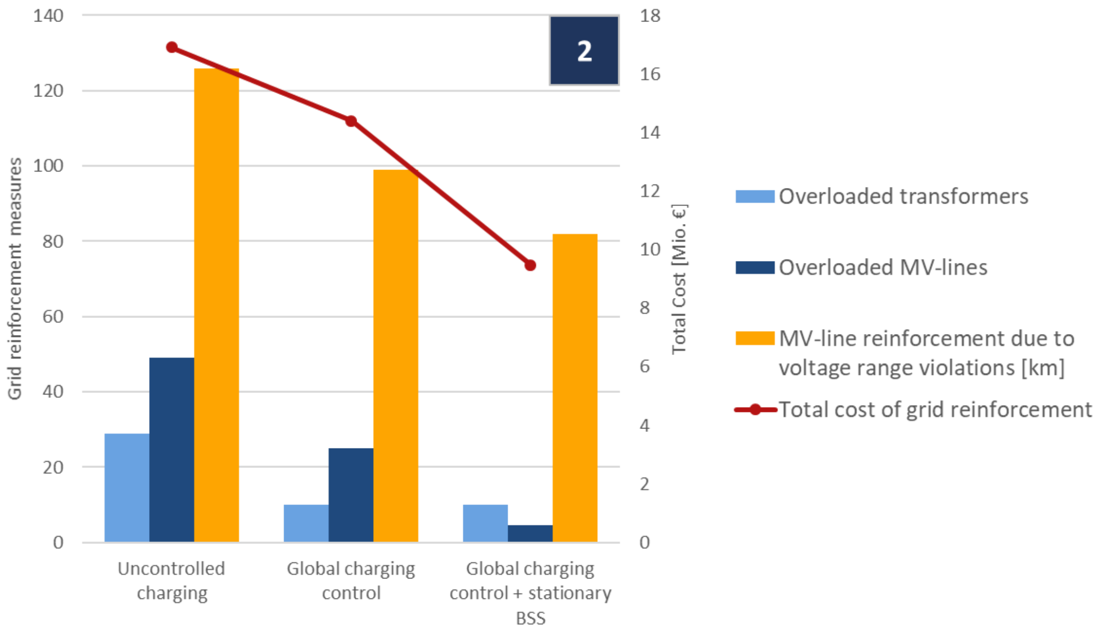

Figure 10: Grid reinforcement measures and cost considering intelligent charging strategies for MV grid No. 2 in 2050.

As the figure illustrates, grid load and thus the costs for necessary grid reinforcement measures are significantly reduced by implementing the proposed intelligent charging strategies. Especially the number of overloaded transformers and MV-lines decreases. While in case of uncontrolled charging 29 transformers as well as 49 MV-lines are overloaded, implementing global charging control drops these values to 10 overloaded transformers and 25 overloaded MV-lines. Given the case that BSS are integrated in high power charging parks in addition, even only five MV-lines are to be reinforced. Regarding voltage range violations especially the integration of BSS reduces necessary grid reinforcement measures to a high extend. Thus, the cost for grid reinforcement due to the market ramp-up of EV can be decreased by 44 % in total. However, even in this case of global charging control combined with the integration of BSS in charging parks, the extension of MV lines with a total length of 82 km is still necessary within MV grid No. 2 due to violations of the required supply voltage. Against this background, especially the implementation of intelligent reactive power control strategies is to be considered in further studies since they offer additional potential for grid relief due to voltage-supporting effects.

References

[1] Umweltbundesamt, *Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2018*, 2018.

[2] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, *Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung*, 2016.

[3] R. Follmer, D. Grunschwitz, B. Jesske, S. Quandt, B. Lenz, C. Nobis, *Mobilität in Deutschland 2008 - Ergebnisbericht – Struktur – Aufkommen – Emissionen - Trends,* 2010.

[4] Deutsche Kommission Elektrotechnik Elektronik Informationstechnik, *Der Technische Leitfaden Ladeinfrastruktur Elektromobilität*, 2016.

[5] I. Frenzel, J. Jarass, S. Trommer, B. Lenz*, Erstnutzer von Elektrofahrzeugen in Deutschland Nutzerprofile, Anschaffung, Fahrzeugnutzung*, 2015.

[6] M. Nicholas, G. Tal, T. Turrentine, *Advanced Plug-in Electric Vehicle Travel and Charging Behavior Interim Report,* 2017.

[7] R. Scholdan, S. Schrader, C. Bussen, *Analysis of the potential of stationary batteries to reduce the grid connection power and costs of high power charging (HPC) parks for battery electric vehicles (xEV*s), EVS32, 2019.

Main Author

Detert Bracht (M.Sc.) studied Energy Technologies and Business Administration at RWTH Aachen (Germany). As a consultant in the team of P3 he is currently focussing on the grid integration of electric vehicles as well as charging infrastructure rollout and the development of future charging concepts. In addition, he is responsible for the prognosis of both global and local electric mobility deployment.