*35th International Electric Vehicle Symposium and Exhibition (EVS35)*
*Oslo, Norway, June 11-15, 2022*

# Future electricity flows and their impact on the power distribution grid on a decentralized level

Lukasz Brodecki[1], Christian Klinkhardt[2], Matthias Weinhold[3], Daniel Mayer[4], Martin Neuburger[3], Nadine Kostorz[2], Christian Körner[4], Markus Blesl[1], Martin Kagebauer[2], Ralf Wörner[3]

[1] *Institute of Energy Economics and Rational Energy Use (IER), University of Stuttgart, Hessbrühlstraße 49a, 70565 Stuttgart, Germany, lukasz.brodecki@ier.uni-stuttgart.de*

[2] *Institute for Transport Studies, Karlsruhe Institute of Technology (KIT), Otto-Ammann-Platz 9, 76131 Karlsruhe, Germany*

[3] *Institute of Sustainable Energy Engineering and Mobility, University of Applied Sciences Esslingen, Kanalstraße 33, 73728 Esslingen am Neckar, Germany*

[4] *Stuttgart Netze GmbH, Stöckachstraße 48, 70190 Stuttgart, Germany*

**Summary**

The increasing electrification of the heating and the transportation sector requires a long-term analysis regarding potential grid infrastructure adjustments. In the presented study, an approach for bottom-up household-load profiles (including photovoltaic profiles) is enriched with charging patterns from electric vehicles, generated by the travel demand model mobiTopp and used for a quasi-dynamic grid analysis on a low-voltage level. As a result, the need to expand the low-voltage power grid and the expected costs are identified. Finally, flexibility measures for load shifting are implemented, and their effects on the need for expansion are examined.

*Keywords: simulation, energy network, BEV, heat pump, load management*

## 1 Introduction

The development towards a sustainable energy supply, following the climate goals of the state of Baden-Wuerttemberg in Germany, requires a transformation of the energy system. The increasing electrification, especially in transportation and heating supply, increases the future demands on the urban power distribution grid. Hence, detailed examinations regarding the transition of the heating structure in buildings, the future usage of battery electric vehicles (BEV) as well as flows in the electricity distribution grid via a detailed grid simulation (low voltage) must be carried out [1].

This research proposes a methodology for a comprehensive analysis based on a model coupling approach consisting of a load simulation for residential buildings, a model for decentralized photovoltaic (PV) generation, a travel demand simulation, and a load flow model for electricity grid calculations. Therefore, the developed approach for the simulation under full consideration of the consumption side (including decentral heat supply and electric mobility) as well as the supply side in the form of PV in high time-resolution enables detailed and dynamic analyses of electricity loads within the electric distribution grids in the context of increasing electrification of the energy system. These effects are particularly of high interest, especially in urban areas with a high load density and meshed grid structure.

First, a literature review on studies in this field is given. Second, the simulation of the load profiles for BEV, PV, heat, and other household consumers is described. Also, the results of the respective simulations are explained. This research aims to determine future electricity flows of all electrical loads for balance areas with urban dominance in a scenario analysis. Thereupon, the simulation of the load flows is described. Further, the impact on the power distribution grid and the strain on the local infrastructure are identified. Finally, based on the results, recommendations will be given.

# 2 Literature

Various studies have been carried out on the effects of the electrification of the transport and heating sector on the generation and distribution of power in the low-voltage power grid. In the area of BEV, field trials are common in which varying numbers of BEVs are issued to residents of a spatially limited area [1, 2]. Gauglitz et al. simulate future electricity demand by BEV for a case study region. The results can provide a good basis for the respective neighborhoods but do not necessarily ensure representative transferability [3]. Wagner et al. have analyzed electric mobility power demand for Germany based on models [4]. Held et al. focuse on the effects of BEVs on low voltage grids regarding thermal overload of power lines and voltage characteristic [5]. Some studies focused only on the distribution substations transformers utilization [6]. Brinkel et al. show the trade between grid reinforcement and less flexibility in the charging process without considering other consumers and PV [7]. Another simulation study deals with load shift potential in relation to different amounts of the charging infrastructure at home and at work [8].

Besides these studies focusing on BEVs, several existing studies address the bottom-up simulation of residential electricity loads to analyze the increasing electrification of the energy system. Tjaden et al. investigate the impact of heat pumps (HP) and stationary battery storage for single-family buildings, but the approach simulates individual households [9]. Gährs et al. analyze different supply options in residential buildings at high temporal resolution but do not consider the impact on larger balance areas [10]. Richardson et al. develop an approach for the simulation of variable balance areas consisting of a variety of residential buildings with different characteristics under the integration of the decentral electricity supply side through PV, but do not consider detailed demand curves for electric mobility [11, 12]. Similarly, the impacts of heat pumps and PV on low voltage grids are investigated by various publications [13, 14]. There are also studies combining these power consumers and generators in an integrated approach [15, 16]. Werner did a simulation and a field trial with smart grid infrastructure and flexible power pricing in a single area [17]. Wintzek et al. assess the influence of BEVs, HPs and PVs on urban low voltage distribution grids in different scenarios. Therefore, grid simulation is based on static load flow analysis in defined operation points like peak load or peak generation. The interaction between loads and generators is estimated through simultaneity factors. The results give a good overview of the main effects, but for a detailed analysis of the duration and exact time periods of the overload as well as the flexibility, a time-based load flow analysis with time series must be considered [18].

# 3 Methodology of the load profile simulations

In the following, the essential components for the simulations of the electricity loads are discussed. The synthetic generation of the electricity load profile is based on a stochastic bottom-up building and resident simulation model and a travel demand simulation.

## 3.1 Building and Resident Simulation Model

The building model consists of separate modules (occupancy, lighting, equipment, and heating/cooling), which individually simulate the electricity consumption of all electric appliances for each household in a quarter-hourly time resolution. The sum of all appliances adds up to the total load per household.

Due to the increasing electrification of the heating system via heat pumps the developed methodology has been extended by simulating heating and cooling. The heating and cooling module is designed to consider future electricity load profiles in an urban energy system with an increasing share of heat pumps. Therefore, all considered households are assigned to residential buildings with characteristics consisting of the building type, building size, year of construction (age), degree of modernization, the outdoor air temperature and the implemented heat pump technology. Air-to-water heat pumps and ground source heat pumps are simulated separately. Based on these specifications the space heating and hot water supply can be provided with electrically driven heat pumps, thus, influencing the future loads in the electricity grid on distribution level [10]. The thermal load management is calculated accordingly to the ambient heat temperature of the selected case studies and is therefore also part of the input data for the simulations.

Furthermore, to address the ongoing and future expansion of PV, the supply side in residential buildings is simulated as well in a stochastic bottom-up simulation model. Therefore, a similar stochastic bottom-up simulation model based on a Monte Carlo Markov-Chain approach for solar radiation is implemented. This is coupled with varying building roof orientations and roof area potentials, leading to building specific PV generation time series in a high time resolution [11].

## 3.2 Travel Demand Model

Further, the additional electric loads caused by domestic charging processes in residential buildings are added to the total via a separate simulation model. The microscopic agent-based travel demand model mobiTopp is used to simulate all trips of the inhabitants of a city within one week resulting in detailed charging patterns from electric vehicles [19]. Within mobiTopp, inhabitants and cars are represented by agents, with respective characteristics like gender, age, and possession of mobility tools (e.g., car or public transit pass) for people as well as e.g. segment, type of drive, and range for cars. They perform activities and trips according to their given activity schedule. Each trip requires two simulated decisions which are destination and mode choice. Whenever an electric vehicle falls below a given state of charge (SOC) and reaches a destination with an available charging station, the charging process is started. It is interrupted as soon as the car is fully charged or the activity at the destination ends. In this study, the focus lies on private charging points at home at a power of 11 kW. They can only be used by agents belonging to a household which can install private charging points because of the availability of private parking facilities. Other charging options include semi-public charging points (22 kW), which can be used during working or shopping at specific locations. In addition, the existing and future public charging infrastructure (11kW – 145 kW) planned by the authorities for the analyzed urban area is available to all agents at the respective location during any activity. The provided power of private charging points may be reduced by charging management strategies implemented in the simulation on the grid operator level. Possible restrictions occur time-based. Vehicle to grid technology (V2G) is not modeled implicitly but can be evaluated qualitatively thanks to the microscopic representation of the vehicles.

## 3.3 Study cases and scenario definition

Together with the energy system analysis and the agent-based transport demand model, the approach results in typical urban supply tasks at a neighborhood level based on which the future need for action is determined. The described load profile simulations are therefore applied in the following three case studies. Structural data of the consumer side of the example balance areas are listed in Table 1. In the context of the analysis, an observation area consisting mainly of single-family houses (SFH), one with multi-family housing (MFH) and a mixed-use area (MIX) are considered.

Table 1: Overview of the simulated case studies and their structural data in the initial condition

| | Number of inhabitants [#] | Number of households [#] | Share of single-family housing | Share of multi-family housing | Installed capacity of transformer on distribution level [kVA] |
|---|---|---|---|---|---|
| SFH | 1086 | 462 | 89,8% | 10,2% | 785 kVA (1 transformer) |
| MIX | 2450 | 1171 | 40,8% | 59,2% | 1792 kVA (4 transformers) |
| MFH | 2845 | 1372 | 30,4 % | 69,6% | 1570 kVA (2 transformers) |

Within the framework of a scenario analysis, different conditions are assumed for the simulation of the electricity consumers, leading to several different electricity load profiles. A flexible and holistic electricity load simulation can be conducted for varying energy systems with variable degrees of electrification. The following four scenarios have been defined for the application of the methodology. Table 2 offers an overview of the characteristics of the different case studies and scenarios. Three long-term scenarios with a time horizon of 2050 and one intermediate scenario for 2030 are analyzed:

**2030 scenario**
The 2030 scenario is intended to show an interim status of the transformation of the energy system in the future. The 2030 scenario allows based on the initial state (2019) for estimation of which measures or grid adjustments will already be necessary at this intermediate development stage. Therefore, comparatively lower electrification rates in the heating supply and mobility sector are analyzed.

**High Load scenario**
The High Load case represents a deep electrification rate in both the heating and transport sector with a time horizon of 2050 on the consumer side. It serves to identify the effects of further 2050 scenarios and intends to present the range of possible outcomes. Therefore, characteristics of the parametrization that negatively impact the low-voltage grid are assumed. The electricity consumption thus takes the maximum market share of BEVs of 100 % as well as high penetration of heat pumps within the heat supply into account. In addition, increased specific electricity consumption of electric BEVs is assumed. At the same time, a comparatively low heat refurbishment of the building stock resulting in high heating demand and low feed-in of electricity by PV is applied. Accordingly, this scenario serves to identify the maximum possible grid load resulting from high electricity loads.

**High Feed-in scenario**
In addition to the load on the grids due to increasing electricity consumption, negative residual loads due to PV-related electricity feed-in can also lead to high loads on the electricity infrastructure, especially in the summer months. Therefore, in this scenario, contrary to the heavy load case, a low electricity demand combined with high PV generation is assumed. This scenario includes a complete thermal refurbishment of the building structure as well as a relief of the local electricity infrastructure by shifting charging processes of electric mobility towards the employer location, which is not part of the simulated residential case studies. The electricity consumption of electric vehicles is based on a market share of BEVs of 70%.

**Preventive Charging Management scenario**
In this scenario, based on the High Feed-in case in combination with low thermal refurbishment rate of the building stock as in the High Load case, the BEV charging strategy is adjusted. The effects achievable with a flat time-controlled reduction of the charging power of all charging points are to be shown. In this scenario, the load of all private charging points is reduced to 50% of the maximal charging capacity (11 kW) in the period between 4 p.m. and midnight.

Table 2: Overview of the considered scenarios and their characteristics

| | | Share of HP in heating supply | Installed PV capacity [kWp] | BEVs with domestic charging opportunity |
|---|---|---|---|---|
| SFH | 2030 | 65,4 % | 584 | 123 |
| | High Load | 100,0 % | 1297 | 382 |
| | High Feed-in | 100,0 % | 2992 | 285 |
| | Preventive Charging Man. | 100,0 % | 2992 | 285 |
| MIX | 2030 | 17,0 % | 468 | 298 |
| | High Load | 59,5 % | 1255 | 1231 |
| | High Feed-in | 59,5 % | 2764 | 822 |
| | Preventive Charging Man. | 59,5 % | 2764 | 822 |
| MFH | 2030 | 19,5 % | 534 | 366 |
| | High Load | 64,9 % | 989 | 1610 |
| | High Feed-in | 64,9 % | 2192 | 822 |
| | Preventive Charging Man. | 64,9 % | 2192 | 822 |

# 4 Results of the load profiles simulations

In the following chapter, the results for the simulations of each model are presented.

## 4.1 Simulated load profiles from mobiTopp

The effects of different market penetrations of BEVs and measures to reduce peak loads of BEV charging are to be worked out. Therefore, the load profiles resulting from the travel demand model are discussed on their own before they are combined with other consumers. Figure 1 shows example load profiles for the MIX study area. In general, differences can be observed between weekdays and weekends. On weekdays, a barely discernible morning peak is followed by a strong peak in the afternoon, which begins at around 16:00 and continues into the evening. This peak also coincides with the main time of use of other household appliances and must therefore be analyzed in the neighborhood analysis in conjunction with all consumers. On weekends, on the other hand, charging operations are distributed throughout the day and thus, the load peaks are lower. In general, the days and the exact times peaks occur in the evening are strongly influenced by chance. The maximum values of the power peaks, on the other hand, are not significantly determined by chance.

Figure 1 (left) shows the effects of the different market shares of BEVs in the MIX area. As expected, the total energy demand and the maximum power peaks increase with a higher market share of BEVs in this balance area. However, it is striking that the increase of the peaks is not linear with the number of BEVs. One reason for this is that in all three scenarios the same number of public and semi-public charging points is assumed. In the scenario with 100% BEVs, these charging options are consequently more heavily utilized. Thus, more charging processes are postponed during the course of a day and are carried out at the end of the of a tour at the place of residence. This leads to disproportionately higher required energy quantities at the private charging points considered in the grid islands.

In addition to the varying market share, various measures for reducing and shifting peak loads are simulated. In these cases, the share of BEVs is assumed to be 70 %. Figure 1 (right) shows the resulting load profiles. In the High Feed-in scenario, the number of charging points available at workplaces was increased. The differences from the default are small. One reason is that even in the default case, many semi-public charging points are available, which cover the demand to a large extent.

In the Preventive Charging Management scenario, a drop in performance is noticeable at 4 p.m. and at midnight. The reason is the technical process approach of the simulation, in which all vehicles are "unplugged" and "plugged in" again to activate and deactivate the charging strategy. During the time frame, all vehicles only charge at 50 % of the maximum power. This measure reduces load peaks in the period between 4 p.m. and midnight. However, the effect is offset by a higher number of vehicles plugged in at the same time due to longer charging processes. Thus, at the grid island level a large proportion of the reduction due to the power restriction is compensated. After the end of the restriction, a peak can be seen at midnight, which in most cases is even higher than the peak in the evening in the base scenario. However, at this time, loads of other consumers are lower, which leads to an lower overall load on the grid infrastructure. With this strategy still almost all the charging processes are completed during the night in the grid islands despite the restrictions. This means that there are only minor restrictions on the use of BEVs as due to the preventive charging management constraints.

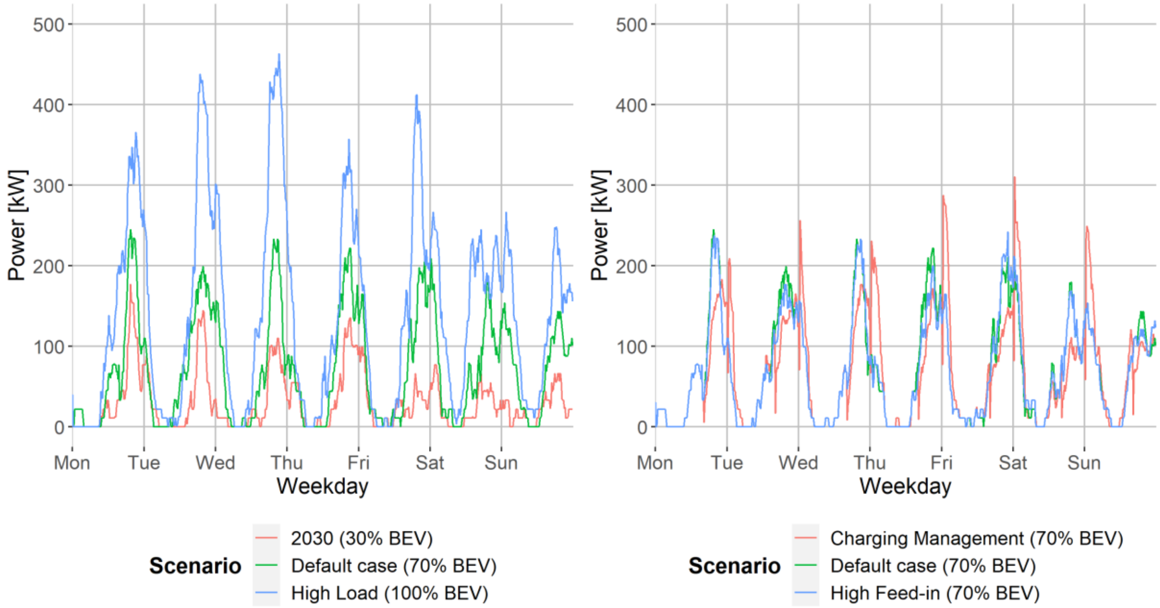


Figure 1: Electricity load profiles with different shares of BEVs (left) and load profiles with strategies for peak load reduction (right)

## 4.2 Integrated load profiles

To show the influence of the scenario definitions on the total loads for the selected case studies, the outputs of the stochastic simulations are shown below. The results are presented as an ordered load duration curve in descending order of the residual load. The duration curve of the residual load is evaluated for the area in a quarter-hourly resolution for the entire year. Under the category "electric heating", the loads of circulating pumps, electric storage heaters, and heat pumps are summarized. Under warm water, the electric appliances that provide hot water are aggregated. This applies to small storage tanks, water heaters, instantaneous water heaters, as well as the electricity consumed by heat pumps for the provision of hot water. Electricity consumption of air conditioners is included under electric cooling. The charging process of the electric mobility is represented by the group electric mobility. All remaining electrical appliances are grouped under household.

Figure 2 shows the development of the maximum load between the scenarios 2030 and the high load case for the multi-family housing case study. The overall increase in the electricity demands (positive axis) can be observed through electrification within the energy system. The high electric mobility share (100 %) as well as the increase through electrification of the heating supply side lead to a doubling of the resulting maximal residual loads and thus to higher stress on the electricity infrastructure. The proportion of electric mobility during hours with high loads increases with the rising share BEV. In the High Load case up to 25 % of the maximum load can be attributed to the charging processes of electric vehicles. The increased specific electricity consumption of BEVs in the High Load scenario leads to comparatively longer charging hours, thus increasing the simultaneity of charging processes in different households. This overlap induces an increase in load in this segment over the full time horizon. The increased PV expansion and the corresponding PV generation (negative axis) cannot compensate for the increase in loads in the High Load case. The highest positive loads in the residential sector typically coincide with low PV generation, commonly in the period between 7-9 p.m., whereas high negative residual loads can be expected during the summer days around noon, leading to a reversal of the electricity flow rates at the transformers and high export rates leading therefore to a negative residual load. In the analyzed High Load scenario in the MFH case only a few hours within the year are expected with low negative residual loads (see right Figure 2).

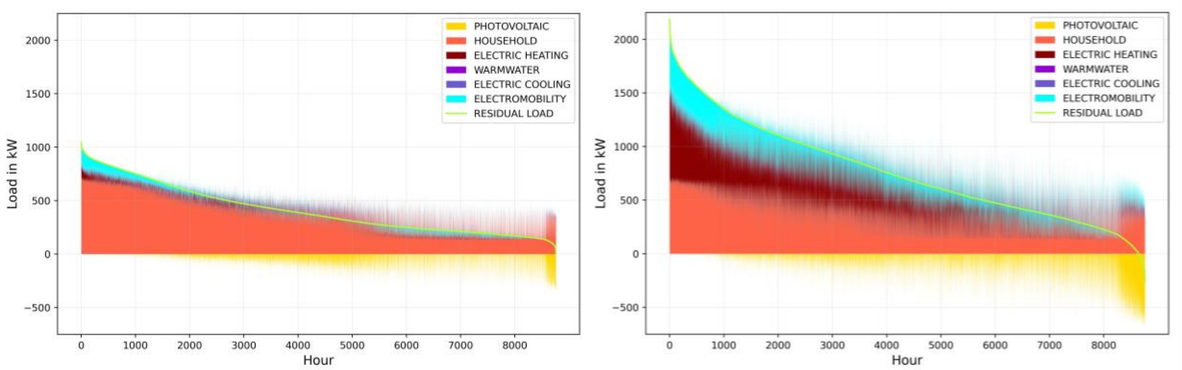


Figure 2: Load duration curves for the scenarios 2030 (left) and High Load (right) for MFH case study

To evaluate the influence of a substantial expansion of PV compared to the High Load case, Figure 3 shows the High Feed-in scenario for the SFH case (left) and the MFH case (right). The high installed capacities of PV lead in the SFH case to a negative residual load in about 3000 hours per year. The high feed-ins, therefore, lead to a in reference to electricity consumption disproportionate increase in the export flows within the considered electrical infrastructure. At the same time, it can be seen that the thermal refurbishment rate of the building stock can significantly reduce the maximum loads caused by the electric heating (i.e. heat pumps). Thus, despite a 70% share of electric mobility, the maximum positive residual load in the MFH case (Figure 3 right) can be reduced to the level of the 2030 scenario (see Figure 2 left). In addition, the thermal refurbishment share of the building topology also contributes to the reduction of the load peaks in the transitional seasons, but here the influence is smaller. Nevertheless, in this case, it remains to be noted that the loads in the electricity infrastructure, as well as the countermeasures for grid expansion to be taken must be oriented to the installed PV capacities since the feed-ins into the public electricity grid exceed the power imports.

Further, the comparison between the SFH and MFH case study shows that the MFH building structure implies a significantly lower expansion of PV. The potential here correlates with the corresponding available roof areas, which leads to a lower PV capacity in the case of an MFH settlement. While the maximum generation from PV in the EHS is approx. three times the maximum loads, this ratio is 1.3 in the MFH case. In addition, this also results from the higher load densities in consumption in MFH settlements. While the relative heat demands are lower in the MFH settlement, the importance of electric mobility on the electricity load increases. The higher population density in the MFH case leads to higher peak loads from charging processes at comparable electrification of the transport sector. This is why the share of the electric mobility of the total load is usually higher in MFH in comparison to SFH. Accordingly, for MFH areas, attention must be paid to peak loads with respect to the utilization of the charging infrastructure. High power densities in MFH settlements are often limited with respect to electric mobility due to a lack of parking spaces and thus charging locations. Nevertheless, a focus should be placed on the charging infrastructure in MFH settlements with regard to the load in the distribution grid infrastructure.

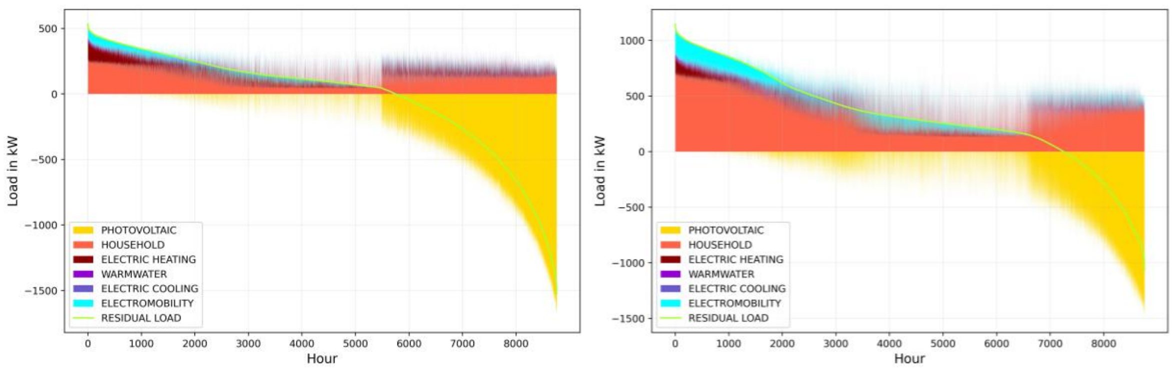


Figure 3: Load duration curves for the scenario High Feed-in for the SFH case (left) and MFH case (right)

Figure 4 illustrates the influence of a complete thermal refurbishment of the building stock for the mixed building topology. The resulting maximum residual load can be almost halved compared to the High Load case. This corresponds to approx. 1000 kW in the considered scenario. Accordingly, thermal building refurbishments are an efficient measure not only to achieve a reduction of heating energy consumption, but also to achieve a significant reduction of absolute load peaks in a highly electrified heat supply system. Furthermore, also for the MIX case study, it can be observed that with the load reduction, PV surpluses of high PV capacities lead to high negative residual loads. These must also be avoided regarding potential electricity infrastructure overloads.

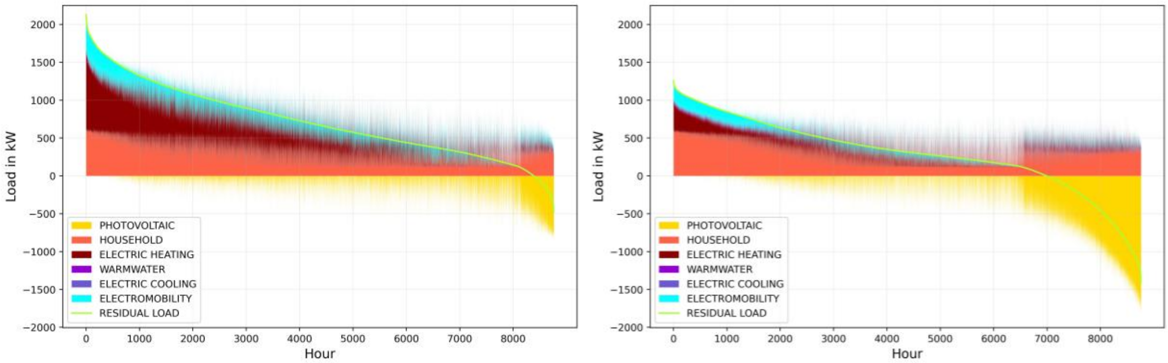


Figure 4: Load duration curves for the scenarios High Load (left) and High Feed-in (right) for the MIX case

## 5 Grid Simulation and analysis

Finally, the low-voltage grid is simulated quasi-dynamically in quarter-hourly intervals. Electricity flows - caused by the generated building-specific load profiles - are simulated in grids consisting of nodes (prosumers, cable distribution cabinets, and transformers) and edges (powerlines). For these case studies, several areas within the city of Stuttgart are implemented in the software application PowerFactory according to actual cable grid plans. The time resolution of the data is determined by overheating time constants of installed power converter transformers and low voltage lines. As a result, the level and frequency of overload of individual components can be evaluated. In addition, violations of the voltage band, described in DIN EN 50160, can also be detected [20].

Figure 5 shows a static perspective of an excerpt of the analyzed distribution grid with the nodes and edges as well as overloaded powerlines and components (left graph). Also visible in this graphic is the topology of a typical, tightly meshed urban grid, which all examined grids in this study feature. The right illustration displays loads of four transformers within the subgrid for an exemplary week with its fluctuating stress level. It can be seen that for the selected case, due to the increased electrification of the energy system, several overloads in the transformers appear at different times.

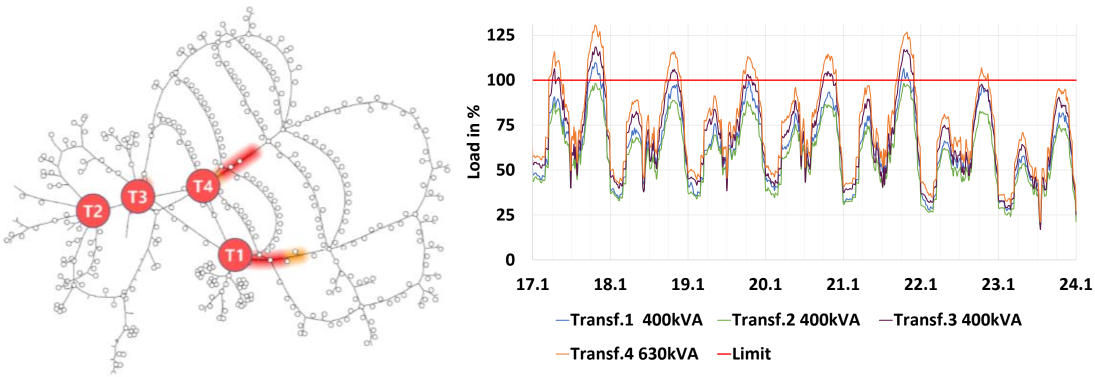


Figure 5: Low voltage subgrid topology and relative transformer load

Further analyses provide insight that the reoccurring overloads result from charging processes of the electric cars during evening hours combined with a simultaneous operation of a large number of heat pumps. In the three tables below the time of the maximum load of the entire grid for each scenario, in which overloads appeared, was determined. Consequently, it is possible that the identified point in time is not for all grid components the interval with the highest load.

For the scenario definition in the 2030 case, no overloads within the lines or transformers appeared, thus leading to the conclusion, that the current grid infrastructure contains reserve capacities, which can be utilized for further energy system electrification. The High Load scenario shown in Table 3 results in an overload in every grid studied between 7 and 9 p.m. in the winter months. Each transformer in the individual subgrids is also overloaded by at least 29 % of the allowable load. The powerlines are not as affected as the transformers in this scenario in terms of level and intensity of load. In the SFH grid, no line exceeded its maximum capacity levels. Overloads appear only in the MIX and MFH case.

Table 3: Overview of grid state for High Load scenario

| | Timeslice of highest grid load | Number of lines with overloads | Average level of overloads of affected lines | Number of transformers with overloads | Average level of overloads of affected transformers | Max. electric load for heating supply [kW] | Max. kW for BEV [kW] |
|---|---|---|---|---|---|---|---|
| SFH | 25. Dec 19:15 | 0 out of 815 | - | 1 out of 1 | 137% | 699 | 156 |
| MIX | 16.Jan 19:00 | 8 out of 895 | 133 % | 4 out of 4 | 129% | 1340 | 657 |
| MFH | 18.Feb 20:45 | 4 out of 603 | 103 % | 2 out of 2 | 160% | 1161 | 463 |

For the High Feed-in scenario, the opposite can be observed (see Table 4). Here the typical grid overload times appear in the summer with high PV feed-in. The maximum load occurs between noon and 2 p.m.. Grid components are also overloaded in the High Feed-in scenario. However, in this case the powerlines are affected in particular, whereas only one transformer is overloaded. The strongest influence of this configuration appears in the SFH case study. In comparison to the MIX and MFH case studies, more than 3 % of the total grid length of the SFH is overloaded in the interval with the highest grid load. At the same time, the only located transformer there is also heavily overloaded (199 % of its maximum capacity). The transformers in the other grids do not show signs of overload in this scenario. The reason for the specific timing of the occurrence of the maximum overloads and their seasonal variation is based on the development of PV and the share of thermal refurbished residential buildings, according to the scenario definitions. High electricity demand due to electrification of the energy system combined with low local electricity generation results in high loads. So in this case, a centralized power supply is more likely to overload the transformer infrastructure in the evenings during the winter months than to overload the line infrastructure. A decentralized electricity generation in the low-voltage grid during the day in the summer, in this case via PV, affects the lines to a greater extent.

Table 4: Overview of grid state for High Feed-in scenario

| | Timeslice of highest grid load | Number of lines with overloads | Average level of overloads of affected lines | Number of transformers with overloads | Average level of overloads of affected transformers | Max. electric load for heating supply [kW] | Max. electric load for electric mobility [kW] |
|---|---|---|---|---|---|---|---|
| SFH | 24. Jun 13:00 | 26 out of 815 | 120 % | 1 out of 1 | 199% | 237 | 124 |
| MIX | 29. May 13:15 | 11 out of 895 | 130 % | 0 out of 4 | - | 273 | 253 |
| MFH | 21. Jun 12:00 | 0 out of 603 | - | 0 out of 2 | - | 287 | 242 |

The results for the Preventive Charging Management scenario in Table 5 show that an intervention in the charging strategy can implement benefits within the grid stability. In comparison to the High Load scenario in the case studies MIX and MFH a drop in overloaded components and load intensity can be observed. Still, both case studies show their maximal overloads in the winter.

The SFH grid contains a distinct characteristic. Due to the stochastic generation of the load profiles, even marginally more lines are affected by congestion in this case compared to the High Feed-in scenario. Here, the challenge of the inherent simultaneity of PV generator output in a local SFH type grid becomes apparent. Since the Preventive Charging Management scenario and the High Feed-in scenario do not differ in terms of the PV systems, the summer midday period is still the most critical interval for this grid.

Table 5: Overview of grid state for Preventive Charging Management scenario

| | Timeslice of highest grid load | Number of lines with overloads | Average level of overloads of affected lines | Number of transformers with overloads | Average level of overloads of affected transformers | Max. electric load for heating supply [kW] | Max. electric load for electric mobility [kW] |
|---|---|---|---|---|---|---|---|
| SFH | 03. Jul 13:30 | 29 out of 815 | 120% | 1 out of 1 | 199% | 699 | 192 |
| MIX | 16.Jan 19:30 | 3 out of 895 | 153% | 4 out of 4 | 113% | 1340 | 322 |
| MFH | 17. Jan 19:15 | 0 out of 603 | - | 2 out of 2 | 126% | 1161 | 311 |

After identifying the limit violations according to the grid simulation for each subgrid, it is investigated how the overloads can be resolved with conventional planning measures from the perspective of the electricity grid operator. As a first step, real measured values are recommended in addition to the simulation values for secured design data. These can be obtained specifically through measurements on exactly those critical components identified in the simulation. In the case of highly meshed urban grids, these are primarily transformers and the lines connecting them. When the design data are available, a decision should be made on a case-by-case basis between a replacement or additional local grid transformers operated in parallel. This also applies in the same way to the affected supply lines. The conventional measures are used as a reference planning variant to calculate the grid extension costs for each simulated low voltage subgrid. Further, flexibility measures are simulated to show the possible reduction in investments. In the investigated use case, system loads can be decreased through the intelligent combination of PV generation if - and only if - connectively designed and operated with the demand side.

# 6 Summary and recommendations

In this work, a methodology is presented how data-based recommendations can be derived from household-specific load and generation curve analysis regarding low-voltage grids. Despite high market shares of electric mobility in all long-term scenarios (at least 70%), a comparatively small share of the future total load can be attributed to BEVs in 2050. Instead, the electricity loads of heat pumps for the supply of space heating and hot water contribute to the significant increase in the total load. This is why time-controlled charging of BEVs as a grid-supporting measure can only mitigate the effects of overloads and do not resolve the effect completely. Furthermore, it should be noted that the definition of blocking times for larger electrical consumers like charging processes of electric mobility but also heat pumps should be chosen with caution. An unsuitable off-period of electric loads can lead to an opposite time-shifted grid overload in the distribution grid.

For the electricity distribution grid, it has been shown that an uncontrolled expansion of heat pumps and charging infrastructure for electric mobility in the analyzed scenarios leads to an overload of the electricity infrastructure. Therefore, if the goals of decarbonization of the energy system at the local level are to be met successfully, infrastructural expansion measures must be implemented, at best accompanied by regulatory adjustment steps.

The overload situations shown in the scenarios for the investigated case studies can be remedied by conventional grid expansion. In the balance areas dominated by residential buildings, the expected electricity line expansion is about 2 % to 3 % of the existing cable lengths. The overloads will mainly occur in the area of the outgoing lines around the substations. Particularly in the area of transformer stations, possible expansion potential must be examined in advance and the resulting necessary space requirements for new transformer stations must be coordinated with the grantor of the concessions.

Further measures can include a flexibilization of the consumption side, especially in subgrids with expected high energy densities (in this analysis in MFH). This primarily concerns the dispatch of heat pumps, where operating times can be comparatively easy coupled to the generation from PV in private households, whereas the electric mobility offers lesser potential for this strategy due to lower concurrency of PV generation in households and availability of electric mobility.

Generally, the analyses show that there is no need for action in the short term (until 2030) for the respective case studies, but rather in the medium to long term (15 years and more) to maintain grid stability. However, since conventional grid expansion measures require long lead and implementation times due to the space requirements, civil engineering and the necessary coordination with other disciplines, the measures must be planned and initiated by the distribution grid operators at an early stage.

It can be observed, that the High Feed-in case is relevant and decisive for low-voltage grid design and operation, particularly in areas dominated by single-family homes due to the comparatively high PV expansion potential. In multi-family residential areas with specifically higher consumer load densities, on the other hand, the High Load case is dominant for grid design. Nevertheless, both cases should always be examined at the local level.

Further, research should analyze the decision making on the time and place of charging processes of the electric mobility in more detail. However, for a better representation of the charging behavior, real data of the observed decisions are needed. Besides, the future availability of the different charging point types, which is currently uncertain, plays a curial role. In particular, the development of semi-public charging points located in parts of the low-voltage grid at shopping opportunities or at workplaces must be monitored. In this work, urban areas without commerce and industry were primarily investigated. Consequently, there is a need for further research for these types of areas, since other load peaks are likely to occur. Also, V2G technology in the context should be examined in more detail.

## Acknowledgments

This work was supported by the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Wuerttemberg (reference no. L75 21105).

## References

[1] Wörner et. al, *Analysis and Prediction of Electromobility and Energy Supply by the Example of Stuttgart*, World Electric Vehicle Journal, 2021, 12, 78, https://doi.org/10.3390/wevj12020078

[2] Busse, J.; *Hundertwasserstraße wird zum Reallabor der Verkehrswende*; Netze BW; Press Release; 29.10.2021; https://www.netze-bw.de/News/Hundertwasserstrasse-Reallabor-der-Verkehrswende; accessed on 24.04.2022

[3] Netze BW; *Wir elektrifizieren eine Tiefgarage. NETZlabor E-Mobility-Carré;* 2021; https://downloads.ctfassets.net/xytfb1vrn7of/oGRGcuHKm3eaKEA2LDGic/695aa0b65161a9f1cee8da9718a703ce/NetzeBW_E_Mob_Carre_Abschlussbericht_digital.pdf*;* accessed on 28.04.2022

[4] Gauglitz, P.; Ulffers, J.; Thomsen, G.; Frischmuth, F.; Geiger, D.; Scheidler, A.; *Modeling Spatial Charging Demands Related to Electric Vehicles for Power Grid Planning Applications*. ISPRS International Journal of Geo-Information; 2020, 9(12), 699; https://doi.org/10.3390/ijgi9120699

[5] Wagner et al.; *Kurzstudie Elektromobilität - Modellierung für die Szenarienentwicklung des Netzentwicklungsplans*; Forschungsstelle für Energiewirtschaft e.V.; https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/20202027_NEP_Kurzstudie_Emob_Abschlussbericht_1.pdf; accessed on 24.04.2022

[6] Held, L.; Märtz, A.; Krohn, D.; Wirth, J.; Zimmerlin, M.; Suriyah, M.R.; Leibfried, T.; Jochem, P.; Fichtner, W.; *The Influence of Electric Vehicle Charging on Low Voltage Grids with Characteristics Typical for Germany;* World Electric Vehicle Journal; 2019, 10(4), 88; https://doi.org/10.3390/wevj10040088

[7] Brinkel, N.B.G.; Schram, W.L.; AlSkaif, T.A.; Lampropoulos, I.; van Sark, W.G.J.H.M.; *Should we reinforce the grid? Cost and emission optimization of electric vehicle charging under different transformer limits*, Applied Energy; Volume 276, 2020, 115285, https://doi.org/10.1016/j.apenergy.2020.115285.

[8] Gnann, T. Klingler, A.L.; Kühnbach, M.; *The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure*, Journal of Power Sources, Volume 390, 2018, pp. 20-29, https://doi.org/10.1016/j.jpowsour.2018.04.029.

[9] Tjaden, T.; Weniger, J.; Bergner, V. Quaschning, F.; *Beitrag von Solarspeichersystemen zur autarken Strom- und Wärmeversorgung von Gebäuden in Niederspannungsnetzen*, Solarspeichersysteme;31. Symposium Photovoltaische Solarenergie; pp. 9-11; 2016; Bad Staffelstein

[10] Gährs, S.; Wieckowski, E.; von Braunmühl, J.; Wolfmaier, A.; Hirschl, B.; *Private Haushalte als neue Schlüsselakteure einer Transformation des Energiesystems*; Institute for Ecological Economy Research (IÖW); 2015; Berlin

[11] Richardson, I.; Thomson, M.; Infield, D.; Clifford, C.; *Domestic electricity use: A high-resolution energy demand model*, Energy and Buildings, 42(10), pp. 1878–1887, 2010, doi: 10.1016/j.enbuild.2010.05.023

[12] Richardson, I.; Thomson, M.; *Integrated simulation of photovoltaic micro-generation and domestic electricity demand: a one-minute resolution open-source model*, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 227, Nr. 1, pp. 73–81, 2013, doi: 10.1177/0957650912454989

[13] Kleinertz, B.; Gallet, M.; Müller, M.; Samweber, F.; *Optimierung der Netzrückwirkungen dezentraler Power-to-Heat-Anlagen im Niederspannungsnetz*; Dritte Dialogplattform Power to Heat; Verband der Elektrotechnik; 2017; Berlin

[14] Brunner, M.; Rudion, K.; Tenbohlen, S.; *Voltage Support in Distribution Grids Using Heat Pumps*; 23rd International Conference on Electricity Distribution, Lyon, 15th-18th June 2015

[15] Wintzek, P.; Ali, S.A.; Monscheidt, J.; Gemsjäger, B.; Slupinski, A.; Zdrallek, M.; *Planungs- und Betriebsgrundsätze für städtische Verteilnetze – Leitfaden zur Ausrichtung der Netze an ihren zukünftigen Anforderungen*; Neue Energie aus Wuppertal, Band 35, Bergische Universität Wuppertal, Wuppertal, 2021.

[16] Rehtanz, C.; Greve, M.; Hager, U.; Hagemann, Z.; Kippelt, S.; Kittl, C.; Kloubert, M.-L.; Pohl, O.; Rewald, F.; Wagner, C. *Verteilnetzstudie fur das Land Baden-Wurttemberg;* Technical Report; ef.Ruhr GmbH, 2017

[17] Werner, *Demonstration project „SoLAR" in Allensbach - Successful energy system transformation by intelligent energy sector coupling;* https://solarlago.de/solar-allensbach/; accessed on 28.04.2022

[18] Wintzek, P.; Ali, S.A.; Zdrallek, M.; Monscheidt, J.; Gemsjäger, B.; Slupinski, A.; *Development of Planning and Operation Guidelines for Strategic Grid Planning of Urban Low-Voltage Grids with a New Supply Task*. Electricity 2021, 2, pp. 614-652; https://doi.org/10.3390/electricity2040035

[19] Mallig et. al, *mobiTopp – A Modular Agent based Travel Demand Modelling Framework*, Procedia Computer Science Volume 19, 2013, Pages 854-859, https://doi.org/10.1016/j.procs.2013.06.114

[20] DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik in DIN und VDE. DIN EN 50160:2020-11—Voltage, Characteristics of Electricity Supplied by Public Electricity Networks; German Version EN 50160:2010 + Cor.:2010 + A1:2015 + A2:2019,+ A3:2019; Beuth Verlag GmbH: Berlin, Germany, 2020.

# Presenter Biography

Lukasz Brodecki is a research assistant at the Institute of Energy Economics and Rational Energy Use (IER), University of Stuttgart in Stuttgart since 2014. He graduated in 2012 from the Tsinghua University in Beijing in Automotive Engineering (M.Sc.) and received his Masters degree in Industrial Engineering in 2013 from the RWTH Aachen University with a focus on renewable energies. His research field includes the modelling of the energy and heat market, the study of impacts of energy-autarky ambitions in municipalities and development of energy system models, in particular TIMES Local.