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Techno-economic modelling of low-voltage networks – a concept to determine the grid investment required in Germany and the implications for grid utilisation fees

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Summary

The increasing deployment of decentralised rooftop photovoltaic systems (PV systems) and the expected future diffusion of plug-in electric vehicles (PEVs) can have a major influence on the need to expand low-voltage networks in the near future. The associated grid investments are refinanced via grid utilisation fees (GUF). Some of the GUF are passed on from higher to lower voltage levels. At the same time, decentralised electricity generation from PV systems is currently exempt from paying GUF in Germany. This study determines the grid investment required based on the example of a low-voltage network in a suburb and the underlying change in electricity demand used to refinance the grid investment. A newly developed modelling concept is introduced to do so. The analysis focuses on the German household sector for the year 2030. Key findings from the analysis are that the future penetration of PV systems and the charging capacity of PEVs will have a considerable influence on maximum grid loads and the associated investment requirements. The required grid investment mainly concerns additional lines or (adjustable) local grid transformers. Furthermore, the analysis shows a direct correlation between the self-consumption of decentrally generated power, the increased electricity demand due to PEVs and the required grid investment. This shows that additional grid investment is required from an average penetration rate of 0.5 kW PEV inverter power output per person and 1 kWp installed PV capacity per person in the local network area. At the same time, GUF can be reduced due to the increase in electricity demand by PEVs. Correspondingly, PV systems reduce the amount of power withdrawn from the grid, which means the specific GUF could increase by up to 2.1 eurocent per kWh by 2030 under the current surcharge mechanism. Households with an electric vehicle but without a photovoltaic system contribute roughly four times as much to refinancing the electric grids as comparable households without an electric vehicle but with a photovoltaic system do.

Key words: Electric vehicle (PEV), rooftop photovoltaic system (PV system), low-voltage networks, household sector, grid utilisation fees (GUF)

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1 Background and objective

The characteristics of electricity demand in German households are set to change significantly in the coming years due to the increasing operation of decentralised rooftop photovoltaic systems (PV systems) and the greater use of plug-in electric vehicles (PEVs) [*Boßmann and Staffell*, 2015; *Klingler*, 2017]. Moreover, this technological change will influence the refinancing of electrical low-voltage networks via grid utilisation fees (GUF) [*Marwitz et al.*, 2016]. Studies show that, in the future, especially suburban low-voltage networks will be penetrated by PV systems and PEVs. This is due to the fact that PEVs are economical for drivers with a high annual mileage covering short distances – something that more frequently applies to commuter passenger cars in suburban networks [*Plötz et al.*, 2014]. In addition, landlord-tenant relationships are less common in suburban networks, which means that a higher level of self-consumption is achieved by PV systems in these networks. Due to the resulting increased economic efficiency, suburban networks are also more strongly penetrated by PV systems than rural or urban ones [*Lödl et al.*, 2010]. The high penetration of the networks by these technologies can in turn lead to thermal overload of grid equipment and/or voltage deviations [*Dallmer-Zerbe et al.*, 2014; *Ueda et al.*, 2008]. While decentralised feed-in can lead to voltage increases, an increase in power demand can reduce grid voltage [*O'Gorman and Redfern*, 2004]. High electrical loads can overload the electricity networks. Grid overloads are the main cause of investment demand in the affected networks [*Ackermann et al.*, 2014; *Agricola et al.*, 2014; *Tröster et al.*, 2014]. These framework conditions also have direct implications for the refinancing cycles of grid operating equipment.

According to current estimations, Germany will need to invest up to 4.2 billion euros by 2030 in its low-voltage networks alone [*Agricola et al.*, 2014]. This is approximately 10 % of the total investment required for grid expansion of the distribution networks [*Agricola et al.*, 2014]. The investment required for grid expansion in Germany is refinanced using grid utilisation fees (GUF), which are paid at the low-voltage level by private households, among others [Bundesministerium der Justiz und für Verbraucherschutz (BMJV), 2015]. While wholesale electricity prices have fallen sharply in recent years due to the merit-order effect, the electricity prices for final consumers, on the other hand, have risen steeply to an average level of approx. 29 ct/kWh in the household sector in 2017 [Bundesverband der Energie- und Wasserwirtschaft e.V. (BDEW), 2017]. This strong increase in household electricity prices has resulted in approx.

350,000 households in Germany not being able to pay their electricity bill each year [Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen (BNetzA), 2016]. The electricity price increase in recent years was mainly due to the increased EEG surcharge (EEG is the German Renewable Energies Act) and increased GUF [Bundesverband der Energie- und Wasserwirtschaft e.V. (BDEW), 2017; *Matallana-Tost et al.*, 2014]. In the last few years, GUF were about 7 ct/kWh on average in Germany and thus accounted for approx. 20 % of the electricity price in the household sector [Bundesverband der Energie- und Wasserwirtschaft e.V. (BDEW), 2017; *Friedrichsen et al.*, 2016; *Hinz et al.*, 2014; *Jahn and Graichen*, 2016].

The legal foundation in Germany for financing electricity grids using GUF is based on the German Energy Industry Act (EnWG), the Electricity Network Tariff Regulation (StromNEV), the Ordinance on Electricity Network Access (StromNZV) and the Ordinance on Incentive Regulation (ARegV) [*Friedrichsen et al.*, 2016]. GUF are paid by grid users to network operators for the use, maintenance and expansion of the network and are used to cover the grid costs of the operators. The grid costs are determined for each network level of a network operator. Furthermore, a share of the costs are passed on from higher network levels to the underlying lower ones [*Friedrichsen et al.*, 2016]. The payments are always made up of a service price and a kilowatt hour rate (cost per kWh). The low-voltage level is an exception to this. Users connected to networks at this voltage level whose power is not measured can be asked to pay a basic price instead of a service price (§ 17 para. 2 StromNEV) [Bundesministerium der Justiz und für Verbraucherschutz (BMJV), 2015].

The operators of decentralised PV systems receive a payment for operating the systems because decentralised generation reduces the amount of electricity that has to be supplied from higher network levels (avoided grid utilisation fees) (§ 18 StromNEV) [Bundesministerium der Justiz und für Verbraucherschutz (BMJV), 2015]. At the same time, those operating PV systems in the household sector reduce the electricity demand from the grid and pay lower GUF as a result. This has the effect of spreading the network costs of network operators across a smaller electricity demand. Consequently, the specific GUF increase. In particular, those network participants with high electricity demand then have to pay higher fees. These include network participants using PEVs, among others [*Marwitz et al.*, 2016]. On the other hand, PEV users may be accorded reduced GUF. However, to be entitled to this, the vehicle users must allow network operators the possibility to intervene and control the charging of their PEVs (§ 14a EnWG) [Bundestag, 2005].

Households supplying and consuming their own electricity reduce the amount of power they need from the grid and therefore reduce the electricity demand used as the basis for allocating GUF via the kilowatt-hour rate. The sinking electricity generation costs of PV systems and rising GUF thus lead to self-consumed (PV) power becoming ever more attractive. At the same time, households with PEVs can improve the capacity utilisation of these networks due to additional power demand from the grid and lower GUF. Since especially PV systems and PEVs will have a marked influence on household electricity demand in the future, it is essential to determine how strongly these technologies affect the financing of the grid and to what extent households with PV systems decouple themselves from financing the grid.

The aim of this study is to determine a model-based concept for the techno-economic analysis of grid expansion, electricity demand and decentralised self-generation and the resulting levy on final customers in German households. The concept is then applied to a case study of a suburban low-voltage network for 2030.

To start with, we outline the current status of the discussion by providing an overview of existing techno-economic models of low-voltage networks (Chapter 2). This is followed by a description of the developed modelling concept. This concept comprises a module for projecting electricity demand and a grid model (Chapter 3). The model is applied to a case study of a low-voltage network. This analyses the penetration of PV systems and PEVs in the year 2030. The scenario analysis is supplemented by a sensitivity analysis, which varies the output of the installed PV systems and the charging capacity of the PEVs in order to draw conclusions about the monetary implications of expanding low-voltage networks with higher and lower PV penetration and high and low charging capacities of PEVs (Chapter 4). The study finishes with conclusions and an outlook (Chapter 5).

2 Existing studies on the influence of PV systems and electric vehicles on grid utilisation fees

The need for investment in low-voltage electricity networks is indicated by overloads occurring in the networks. Grid overloads occur if the load for which the network was originally designed is exceeded. The operation of PV systems and PEVs can have a strong influence on the maximum loads in low-voltage electricity networks in the future. If networks are overloaded, grid operators react by investing in their networks. These network investments are refinanced using GUF. In addition, GUF are also affected by the electricity demand of households in a network area. Increased household demand for power leads to higher network utilisation, while self-generated power lowers the amount of electricity needed from the grid and leads to reduced network utilisation. Since the network costs are allocated based partially on the electricity demand from the networks, increased utilisation leads to falling specific grid utilisation fees and reduced utilisation to rising specific grid utilisation fees. In the future, household electricity demand from low-voltage networks can also be strongly influenced by the operation of PEVs and PV systems. To be able to depict the influence of PEVs and PV systems on GUF, an approach must be able to plot the load peaks due to decentralised generation and power demand in detail. In addition, it is necessary to show grid overloads and the resulting need for grid investment as well as the influence of these technologies on household electricity demand.

A large number of existing approaches plot either grid overloads due to PEVs and/or PV systems in detail, but do not go on to quantify the resulting investment required in low-voltage networks [*Barth*, 2013; *Dallinger*, 2012; *Dallinger et al.*, 2017; *Ying*, 2011]. Other studies determine the future network investment required across several voltage levels. However, they do not conduct detailed simulations of PEV electricity demand and the decentralised feed-in of power from PV systems. Consequently, there is no way to draw conclusions about the need for grid investment due to the operation of PEVs and PV systems [*Ackermann et al.*, 2014; *Agricola et al.*, 2014; Avacon AG/HSN Magdeburg GmbH et al., 2015]. There are approaches that illustrate the influence of PEVs on grid investment requirements, but they do not determine how these investments impact GUF. In addition, these approaches do not quantify how changes in the demand for power from electricity networks affect GUF [*Pieltain Fernandez et al.*, 2011; *Prüggler et al.*, 2008; *van Zoest et al.*, 2014; *Veldman and Verzijlbergh*, 2015; *Verzijlbergh*, 2013].

An existing approach illustrates the economic burdens on households due to changes in GUF. It looks at which GUF exist for different regions in Germany and how these can be better aligned using a modified cost allocation mechanism [*Hinz et al.*, 2014]. However, this approach cannot be used to draw conclusions about the causes of network overloads and the associated need for network expansion [*Elsland*, 2016; *Hinz et al.*, 2014]. In particular, it is not possible to illustrate how the decentralised feed-in of power from PV systems and the additional electricity demand due to PEVs affect GUF. However, this is necessary to determine whether the network costs are allocated in a fair way to the households actually causing them. These approaches do not illustrate the influence of network investments and a change in network utilisation on GUF.

Consequently, the existing approaches do not consider the combined analysis of electricity demand due to PEVs and decentralised feed-in of PV systems on household electricity demand and the investment needed in electrical networks. In addition, it is unclear how the technologies affect grid utilisation and thus existing GUF. As GUF depend strongly on PV and PEV penetration rates and grid design, a new approach must be developed that maps grid investments in low-voltage networks for different penetration rates of household technologies. Table 1 summarises the main studies that determine the influence of changes in electricity demand due to the operation of PV systems and PEVs on grid overloads, grid investments and/or grid utilisation fees.

Approach	**Grid overloads**	**Grid investments**	**GUF**	**Sources**
TU-Cottbus	Yes	No	No	[*Ying*, 2011]
PowerACE	Yes	No	No	[*Dallinger*, 2012; *Dallinger et al.*, 2017]
Stuttgart-IER	Yes	No	No	[*Barth*, 2013]
Dena	No	Yes	Yes	[*Agricola et al.*, 2014]
Energynautics	No	Yes	No	[*Ackermann et al.*, 2014]
NAP	No	Yes	No	[Avacon AG/HSN Magdeburg GmbH et al., 2015]
IIT-Comillas	Yes	Yes	No	[*Pieltain Fernandez et al.*, 2011]
TU-Delft	Yes	Yes	No	[*van Zoest et al.*, 2014; *Veldman and Verzijlbergh*, 2015; *Verzijlbergh*, 2013]
TU-Wien	Yes	Yes	No	[*Prüggler et al.*, 2008]
NEP	No	Yes	Yes	[*Elsland et al.*, 2016]
RWTH-IAEW	No	Yes	Yes	[*Büchner et al.*, 2014]
TU-Dresden	No	Yes	Yes	[*Hinz et al.*, 2014]

Table 1: Approaches that depict the influence of electric vehicles and photovoltaic systems on grid overload, grid investments and/or grid utilisation fees.

3 Methodology

3.1 Modelling concept

An innovative modelling concept is used as a systems analysis approach, in which techno-economic analyses are linked by two models. First, the FORECAST model (FORecasting Energy Consumption Analysis and Simulation Tool) calculates the annual household electricity demand up to the year 2030

[Fraunhofer Institute for Systems and Innovation Research (ISI), 2017]. The electricity demand is broken down regionally and determined differentiated by administrative district (NUTS 3) and postcode area. These results with spatial resolution then form one input parameter to the subsequent grid model FLEX-GOLD (FLEXible Grid and stakehOLDers). FLEX-GOLD illustrates the technical network loads and overloads, the investment behaviour of distribution network operators and the resulting costs for households [*Marwitz et al.*, 2016]. Further key input parameters to the grid model include the driving and charging behaviour of electric vehicles (PEVs) and the installed capacity of PV systems, among others. Figure 1 shows the structure of the modelling concept.

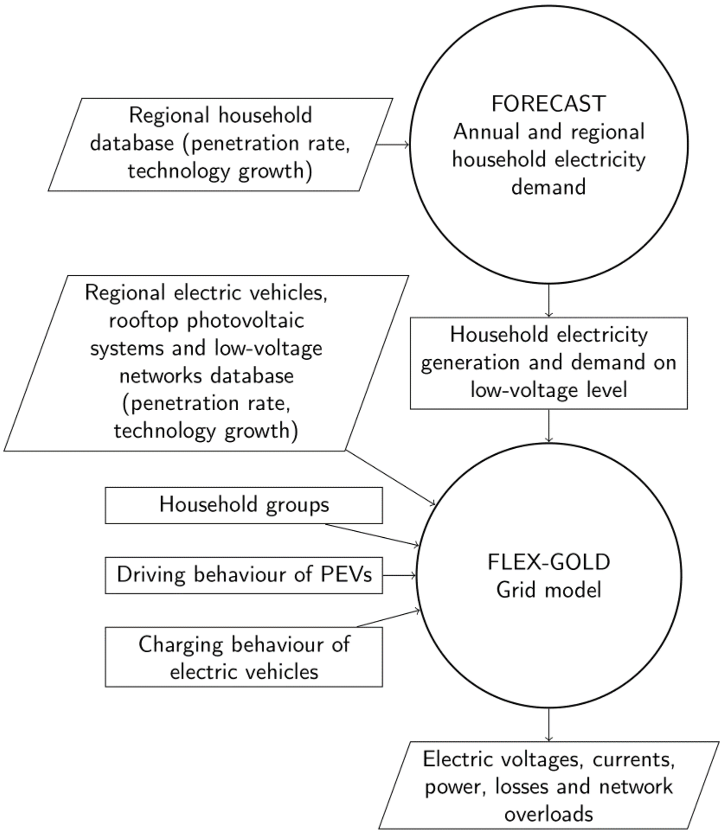


Figure 1: Structure of the model consisting of the electricity demand model FORECAST and the grid model FLEX-GOLD

3.2 Modelling electricity demand

In the demand model FORECAST, bottom-up analyses are made of the long-term trajectories of electricity demand development [Fraunhofer Institute for Systems and Innovation Research (ISI), 2017]. These consider the special structural and technological features of the household sector, the heterogeneity of decision behaviour on the part of different actors and the development of final consumer prices [*Elsland*, 2016]. Key structural influencing variables are the number of persons and the floor area per household. With regard to the technological composition, the electricity demand in FORECAST maps all the relevant consumers in the household sector, excluding the power demand due to electric mobility that is determined directly in the grid model. The big power consumers in the household sector are white goods, ICT applications, lighting and electricity-based heating technologies [*Elsland*, 2016]. Mapping the development of electricity demand in detail has the added benefit that its change over time – and the impacts on the load associated with this – are included in the analysis to determine the network loads.

The spatial breakdown of electricity demand by NUTS 3 regions and postcode area is done using consumer group-specific allocation keys (e. g. electrical power demand per household appliance). A detailed description of the methodological approach to the regional breakdown is given in [*Elsland et al.*, 2015b]. The underlying data used for regionalisation are based on spatially resolved studies and official statistics [*Schlömer et al.*, 2015; Statistisches Bundesamt (StBA), 2013]. The calculation results for the regional breakdown have already been analysed in past projects using historical network data and the resulting regional consumption patterns were found to be of high quality [*Elsland et al.*, 2015a; Statistisches Bundesamt (StBA), 2015].

3.3 Modelling the low-voltage networks

The electrical and economic simulation of a suburban low-voltage network is performed in the grid model FLEX-GOLD based on the power demand in specific postcode areas. The objective of this simulation is to determine network congestion and overloads and the resulting potential need for investment in network expansion. Electricity networks are designed for maximum loads. This is why the network simulation is carried out at times with the highest demand and the highest generation. For demand, this correlates with the volume of traffic due to electric vehicles. The driving behaviour of privately used passenger cars differs between different weekdays. Therefore, the simulation is conducted for the week (from Monday to Sunday) with the highest network load during spring period (month of March). The time resolution of the simulation is 15 minutes. Analogous to the remarks in [*Marwitz et al.*, 2016], the installed capacity of rooftop PV systems in low-voltage level is spread across different regions. It was deduced that the PV systems in individual regions have an average output of 6 kWp.

With regard to the development of electricity demand, it can be assumed that electric vehicles (PEVs) in particular will increase the electricity demand of households in the future [*Dallinger et al.*, 2017; *Wu et al.*, 2015]. Accordingly, in addition to the upstream analysis of conventional power applications (see chapter 3.2), a simulation of electric vehicles is carried out in FLEX-GOLD. Based on empirical driving data of electric vehicles and the underlying charging strategies, electricity demand profiles are derived with 15-minute resolution. This granular resolution of the load flow is necessary because the demand for power in low-voltage networks is strongly determined by the driving and charging behaviour of electric vehicles. The empirical driving data are based on past test runs, assuming that the users of the vehicles start charging after the last trip until a new trip begins or until the vehicle battery is fully charged [Dallinger et al., 2017; Wu et al., 2015].

PEVs and PV systems are assigned randomly to households in the network area and thus influence their power demand from the electricity grid. The FLEX-GOLD model maps how changing power demand affects existing GUF. In addition, it is calculated how much households with a PEV and PV system, those with only a PEV, those with only a PV system and those without these technologies contribute to the refinancing of networks via GUF.

In addition, the demand for household electricity or the feed-in from PV systems can also result in a need for grid expansion. Grid expansion is assumed to comply with the following logic that is based on the distribution network study by dena [*Agricola et al.*, 2014]. In the event of network overloads, a distribution system operator (DSO) reacts by installing additional lines to reinforce the network. Network overloads can occur due to too high demand for electrical power or too much power fed into the grid from photovoltaic (PV) systems. A distinction is made here between thermal and voltage-related network overloads. Thermal overloads occur if the electrical current exceeds the nominal value of network equipment. Voltage-related network overloads occur if the voltage at a network node deviates from the nominal value by more than 4 % [*Agricola et al.*, 2014; *Dallmer-Zerbe et al.*, 2014]. If a thermal overload occurs, the DSO installs a new line from the local network transformer to the halfway point of the overloaded network section. In the event of voltage-related overloads, a new line is added from the network transformer to the last third of the overloaded power line [*Agricola et al.*, 2014; *Marwitz et al.*, 2016].

4 Case study of a suburban low-voltage network

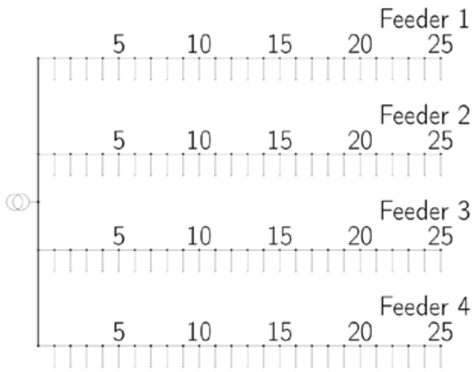
4.1 Definition and parameters

4.1.1 Starting situation of the electricity network and framework parameters of grid expansion

The case study is based on the example of a suburban low-voltage network in Germany in the target year 2030. The network is supplied by a 630 kVA local transformer and consists of four lines, each of which features 25 nodes. One household with an average of 2.5 persons is connected to each node. The nodes are interlinked by NAYY-J type cables, and the conductor cross-section of each cable is 150 mm^2 [*Agricola et al.*, 2014; *Dallmer-Zerbe et al.*, 2014]. On average, about 28 m of cable are laid for each low-voltage house connection in German postcode areas with average population density [*Marwitz et al.*, 2016]. This value was applied in the case study.

If network overloads occur, a DSO invests in the congested network section by adding more cable. It is assumed that the DSO uses NAYY-J type cables with a conductor cross-section of 300 mm^2. The cost to the DSO is 130 euros per metre. 80 % of this is for installation (earthworks, cable laying and finishing) and 20 % for the cost of materials [*Fraunholz*, 2014; *Marwitz et al.*, 2016]. A composite interest rate[1] of 4.3 % is applied to depict the costs of capital. The composite interest rate comprises the interest rate of 2.5 % for borrowed capital and the 6.9 % rate of return on equity from the third regulatory period before taxes. In addition, the maximum equity ratio of 40 % is applied here [*Noothout et al.*, 2016]. A depreciation period of 40 years is assumed for the investments [Bundesministerium der Justiz und für Verbraucherschutz (BMJV), 2015]. Figure 2 illustrates the network topology of the output network and lists the main network parameters.

1 Also referred to as the Weighted Average Cost of Capital (WACC).



Network parameter	Value	Unit
Transformer capacity	630	kVA
Total cable length	2820	m
Conductor cross-section	150	mm^2
Cable length per house	28	m/HH
Lines	4	-
Network nodes	100	-
Households	100	-

Figure 2: Topology of the suburban network and network parameters for 2030

4.1.2 Technological parameters of rooftop photovoltaic systems and electric vehicles

The main technological parameters are the installed PV capacity and the degree of PEV diffusion. Regarding the installed PV capacity, it is assumed that there are ten PV systems each with 6 kWp installed in the analysed network area by 2030 [*Marwitz et al.*, 2016]. This development is derived from trends in the expansion corridors across Germany. The installed system capacity corresponds to the average rooftop system capacity in German suburban low-voltage networks [*Lödl et al.*, 2010; *Ruppert et al.*, 2016]. The PV systems are assumed to have an average lifespan of 23 years in 2030. Regarding PEV diffusion, existing studies presume that electric vehicles will diffuse in suburban regions to start with [*Plötz et al.*, 2014]. This study assumes an ambitious market acceleration of electric vehicles, which triples the average diffusion of PEVs in Germany for the analysed suburban network [*Gnann*, 2015]. This translates into 46 vehicles (in 100 households) in 2030 in the analysed network area. A charging capacity of 10.8 kW is assumed for the PEVs [Nationale Plattform Elektromobilität (NPE), 2010]. The PEVs and PV systems are assigned stochastically to the 100 households.

A sensitivity analysis is carried out in chapters 4.2.2 and 4.2.3 to explore the implications of PEVs and PV systems on grid design and potential grid expansion in more detail. The sensitivity analysis varies the installed capacity of each PV system and the PEV charging capacity to examine a wider range of power demand that has a critical influence on the load situation in the network. In total, five further variants of installed PV capacity are calculated (multiples of ½, 2, 4, 6 and 8 compared to the output power of 6 kWp) and two further variants of PEV charging capacity (3.6 kW and 22 kW). The range of installed PV capacity is oriented on real-life regional conditions found in Germany [*Marwitz et al.*, 2016]. Typical charging capacities of PEVs are used to vary the charging capacity [Nationale Plattform Elektromobilität (NPE), 2010]. In addition, variants are analysed with no PV systems and no PEVs connected to the network. The remaining parameters are constant within the sensitivity analysis.

Parameter	Value	Unit
No. PV systems	10	-
Installed capacity of each PV system	0; 3; 6; 12; 24; 36; 48	kWp/syste
Lifespan of each PV system	23	a
No. PEVs	46	
Charging capacity of each PEV	0; 3,6; 10,8; 22	kW

Table 2: Technological parameters of rooftop photovoltaic systems and electric vehicles

4.2 Results

4.2.1 Network loads if charging capacity of electric vehicles and installed capacity of photovoltaic systems remain constant

Box plots are used to analyse the network loads or voltage deviations (Figure 3), and are interpreted as follows: The suburban low-voltage network consists of four lines, each with 25 network nodes (see section 3.1). The network voltage changes over the simulation period and is evaluated separately for each node. The lower whisker indicates the biggest voltage dip over the simulation period. The upper whisker shows the highest network voltage for each node. In addition, the network voltages at each node are allocated to individual quartiles. The lower quartile represents the 25 % smallest network voltages. The 25 % highest voltage values form the upper quartile. The middle of each box plot shows the median network voltage at the respective node. This representation was chosen because power grids are designed for the maximum load condition. The box plots also indicate that strong voltage fluctuations occur, but that these are rare.

In the analysed network area, voltage deviations occur that are caused exclusively by the demand for power from the network. In this case, there are no network overloads due to the power fed in to the network from PV systems. Figure 3 also shows that the four lines of the suburban low-voltage network are unevenly loaded. In line 1, the network voltage only drops below the limit of 4 % of the nominal value at node 17 to 25. In contrast, the biggest voltage dips occur in line 3 from node 8 to 25. Here, the voltage drops by up to 8.2 % below its nominal value. Lines 2 and 4 show roughly equal loads (see Figure 3).

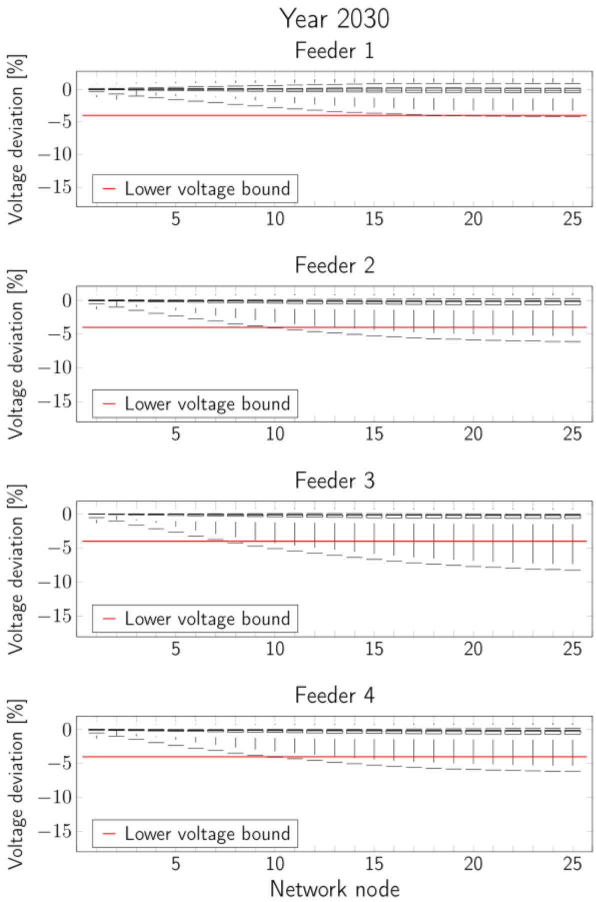


Figure 3: Voltage deviation from the nominal value of the network voltage in the analysed suburban area (charging capacity per electric vehicle: 10.8 kW, installed PV capacity per system: 6 kWp).

4.2.2 Network loads if the charging capacities of electric vehicles and installed capacities of photovoltaic systems are varied

This chapter discusses the results of the sensitivity analysis. As shown in Figure 4, the maximum deviation from the network voltage is plotted here for each variant combination over the simulation period. Due to the network topology, the maximum voltage deviation always occurs at node 25 on one of the four lines. The red dashed line in Figure 4 indicates where power supply and demand can balance. However, because neither the charging behaviour of PEVs nor other conventional power consumers in the network model are aligned to the amount of electricity fed in by PV systems, power demand and supply do not necessarily balance.

The analysis shows that voltage deviations occur in the analysed network area before thermal overloads take place (Figure 4). In the analysed week in March 2030, the network voltage deviates from the nominal value by between +7.7 % (top left) and -9.7 % (bottom right). The highest network voltage occurs if the installed capacity of all PV systems is increased from 6 kWp to 48 kWp and electric vehicles with low charging capacities of 3.6 kW draw power from the grid or if no PEVs are connected to the network. The biggest voltage dip occurs if all electric vehicles draw 22 kW of power from the network and there is no power fed in from PV systems.

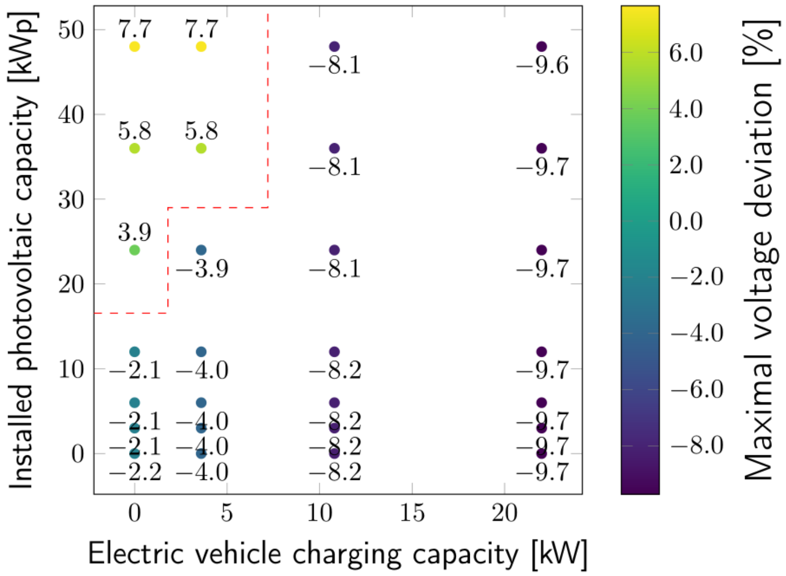


Figure 4: Maximum deviations of the nominal voltage in the suburban low-voltage network for the four lines in the area analysed (charging capacity per electric vehicle: 0 to 22 kW; installed PV capacity per system: 0 to 48 kWp).

The network can operate normally if electric vehicles take 3.6 kW or only low amounts of electric power from the network and if PV systems smaller than 24 kWp are operated in the network at the same time.

4.2.3 Network investments and grid utilisation fees

The distribution system operators (DSO) in Germany are responsible for secure and stable grid operation in low-voltage networks. In addition, DSO are obligated to reinforce and expand their networks in line with demand [Bundestag, 2005]. Up to 2030, the responsible DSO would reinforce the analysed suburban low-voltage network at least along the overloaded line. The voltage drops could also be eliminated by an adjustable local transformer, although this would then control the voltage along all four lines [*Rohde et al.*, 2013]. Alternatively, the DSO could lay additional cables or wires to reduce the network voltage.

Investment in the analysed network is required from an average penetration rate of 0.5 kW inverter output per person and 1 kWp of installed PV capacity per person. At very high capacities, the investment required can amount to 365,000 euros. These network investments in turn lead to additional grid utilisation fees of up to 2.1 eurocent per kWh in 2030 solely due to the required grid expansion at the low-voltage level. These are heavily influenced by the installed capacity of each PV system as well as the charging capacity of PEVs. Higher charging capacity leads to higher network loads and overloads that may result in an increased need for network investment. At high installed capacities, PV systems also result in load peaks. The model reacts to these by expanding the network. In addition, higher PV system capacities lead to a higher amount of self-consumed power and accordingly a reduction in the power supplied from the network. Since network investments are spread over the electricity demand in the network area, increased self-consumption of power leads to rising grid utilisation fees (see Figure 5).

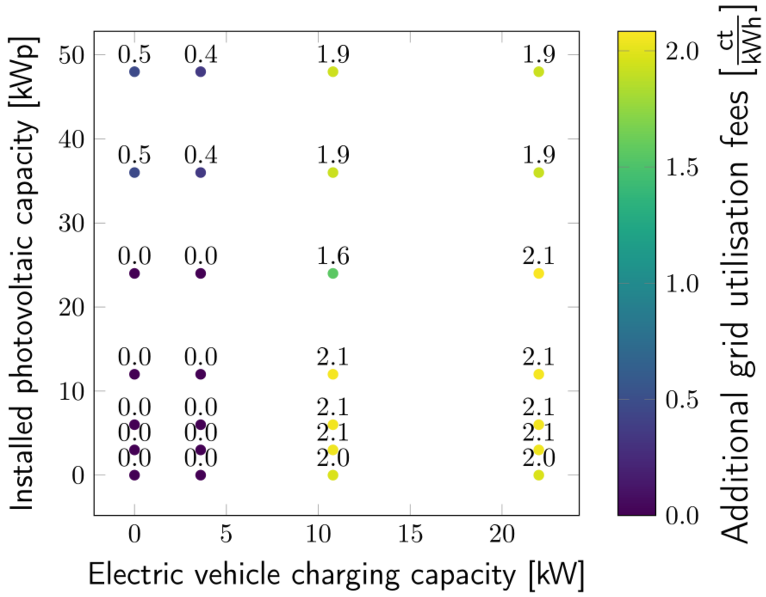


Figure 5: Additional grid utilisation fees (GUF) due to installing new lines in the analysed suburban area for different capacities of photovoltaic systems and electric vehicles (charging capacity per electric vehicle: 0 to 22 kW; installed PV capacity per system: 0 to 48 kWp).

4.2.4 Cost implications for households

The following section illustrates how much different households have to pay additional grid utilisation fees (GUF) based on their electricity demand from the network due to the network investments determined in section 4.2.3. The mean values of all households are shown that either have a PEV and no PV system or a PV system but no PEV. In addition, the average values are shown for households that have either both technologies or neither technology.

The results are illustrated for the case in which PEVs are charged with 10.8 kW and the installed capacity of all PV systems is 6 kWp. In this case, due to their low demand for electricity, households with a PV system but without a PEV shoulder the lowest network investments with approx. 1,500 euros. In contrast to this, the highest economic burdens are borne by those households with a PEV and without PV. Up to 2030, these households have to bear costs of 4,800 euros, three times the network investment required from a household with PV but without a PEV. The second highest cost burden of approx. 3,500 euros up to 2030 is borne by households operating a PV system and a PEV at home. Households without these technologies pay approx. 2,900 euros on average (see Figure 6).

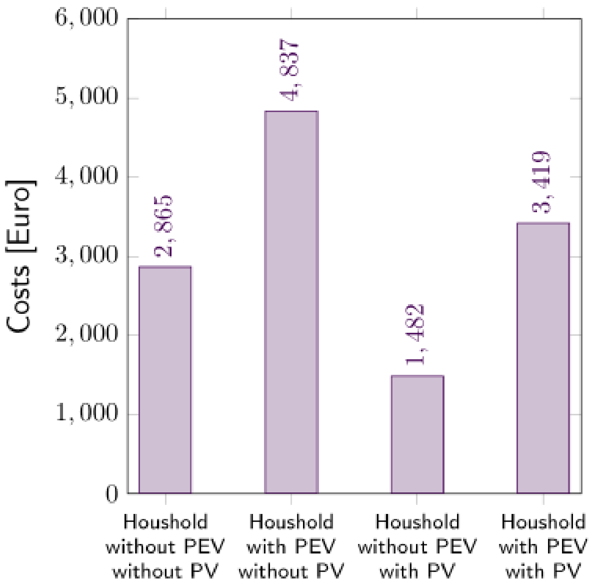


Figure 6: Investments for an average household for different equipment alternatives with electric vehicle (PEV) or rooftop photovoltaic (PV) system (charging capacity for each electric vehicle: 10.8 kW; installed PV capacity per system: 6 kWp).

5 Conclusions

Due to the uncontrolled charging of PEVs, the decentralised feed-in of power from PV systems and the electricity demand by PEVs are not likely to coincide, because PEVs frequently need electricity from the network during the evening hours, while PV systems feed in power to the network over midday.

Under the regulatory conditions in place today, two effects of operating PV systems can lead to rising grid utilisation fees. First, operating PV can mean network investments are required due to network overloads that are refinanced using GUF. Second, PV systems can be used to meet part of a household's electricity demand. This reduces the amount of power taken from the network that forms the basis for allocating GUF. The networks are less utilised and the specific GUF rise as a result.

In contrast to this, PEVs can also cause network investments, but at the same time they represent an option for better utilisation of the networks. The specific GUF decline due to improved capacity utilisation. In this way, PEVs can counter the attractiveness of self-consumed PV power due to rising GUF. As a result, all those connected to the network stand to benefit from the additional power demand due to PEVs as long as their demand for electrical power from the grid does not result in the need for investments in the network.

Furthermore, the study shows that households with PV systems decouple themselves from the refinancing of electricity networks under current regulations, while households with PEV are strongly involved. In the case study examined, a household with a PV system pays roughly only half the amount that a household with no PV system does to refinancing the low-voltage network. Due to its increased power demand, a household with a PEV contributes about twice as much to refinancing the analysed network as a household without any of the technologies. In contrast to households with PV systems, those with PEVs therefore have an interest in avoiding grid investments because these households are strongly involved in their refinancing due to their high electricity demand. Especially in regions with high PV penetration, grid investment requirements can arise from the operation of these systems, which may only be refinanced to a limited extent by the plant operators. This is why incentives should be created in these areas in particular that encourage the operation of such systems in a way that benefits the network. Alternatively, the regulatory framework could be changed so that PV system operators pay higher GUFs if operating these systems means that grid investments are required.

6 Critical appraisal and outlook

The modelling approach described here plots PEVs, PV systems and households in electricity networks for one week. The load profile of household power demand and the load profile of PV systems is predefined at the beginning of the simulation for the week regarded depending on the weather and the weekday. However, household power demand over time is also dependent on the behaviour of those living in the respective home. The modelling approach could be further developed by including this behaviour over a longer period of time.

To distribute the network investments across different household groups, the necessary investments are extrapolated from the analysed week until the end of the service life of all the extra cables installed. At the same time, this does not illustrate any seasonal effects. The decentralised power generation from PV systems changes with the season as does household power demand and the driving behaviour of PEVs. These effects are not captured by the methodological approach selected. With regard to the driving behaviour of PEV, for example, longer holiday trips cannot be taken into account. The approach could be improved by including these aspects.

The analyses show that the decentralised power generation of PV systems and the power demand due to charging PEVs can result in strong congestion in networks. Using decentralised storage systems or charging strategies can help to balance local supply and demand and can also reduce power peaks in low-voltage networks. The latter only occurs, however, if the storage systems and charging are controlled in a way that benefits the grid, and there are no financial incentives to do this at present. It can therefore be inferred from this that the study analyses the extremes of grid loads, which is appropriate given the fact that electricity networks are always designed for the maximum load situation. Another way to reduce grid loads and a possible approach that requires further research is the curtailment of PV systems as well as the use of other, temporally more flexible loads which should be taken into account in the modelling approach.

As soon as changes are made to the system used for distributing GUF, the results have to be reinterpreted or these changes included in the model. The study is made for 2030 and applies the regulatory framework of 2017. At the same time, it is probable that the economic burdens resulting from grid operation will be distributed differently by 2030. For instance, variable GUF could be introduced at the low-voltage level and/or decentralised power generation incorporated into the refinancing of low-voltage electricity networks. It should also be pointed out that the modelling concept does not consider reduced GUF, which can be granted to PEV users in line with § 14a of the German Energy Industry Act if vehicle charging is controlled to benefit the grid [Bundestag, 2005]. This would alter the maximum loads and also the resulting grid investment requirements, GUF and the economic burdens for households.

This study concentrates on a suburban low-voltage network based on the median lengths of cables and lines in the German low-voltage grid. In this context, one criticism is that electricity networks with long extensions or longer cables and lines react more sensitively to electrical loads. Furthermore, it is also the case that networks in rural regions are more frequently affected by this than those in regions with a higher population density [*Marwitz et al.*, 2016]. Concerning the diffusion of PEVs and PV systems, it should also be pointed out that this will affect the different regions in Germany to a strongly differing extent in the future, which has direct implications for network loads (cf. [*Marwitz et al.*, 2016]).

In addition to the technical consequences of network overloads, the heterogeneity of electrical low-voltage networks could potentially lead to very different regional investment requirements for grid expansion. Grid expansion is financed via grid utilisation fees that are borne at the low-voltage level by private households, among others. This means that, in the future, if there is high penetration of electric vehicles and PV systems, grid users in regions with sensitive networks will be more strongly affected by higher grid utilisation fees than households in other regions will. This is also a topic that needs researching, because it enables us to explore the extent to which the future development of electricity demand and the decentralised generation of electricity place an additional burden on households under the current mechanism for allocating grid utilisation fees.

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