DER INTEGRATION STUDY FOR THE GERMAN STATE OF HESSE – METHODOLOGY AND KEY RESULTS

Alexander SCHEIDLER Roman BOLGARYN Jan ULFFERS Johannes DASENBROCK
Daniel HORST Philip GAUGLITZ Carsten PAPE Holger BECKER
Fraunhofer IEE – Germany
alexander.scheidler@iee.fraunhofer.de

Ilja KRYBUS
Bearing Point GmbH – Germany
ilja.krybus@bearingpoint.com

Martin BRAUN
University of Kassel and Fraunhofer IEE – Germany
martin.braun@uni-kassel.de

ABSTRACT

This paper presents results of a DER integration study for the German federal state of Hesse. The objective of the study was to determine the costs of grid reinforcement and expansion in the state's region for different DER scenarios, to assess possible measures for an advanced DER integration and to identify the needs for action in the regulatory framework.

INTRODUCTION

This paper outlines the methodology and present key results of a DER integration study conducted for the geographic region of the German state of Hesse (the full report in German is available at [1]). The state of Hesse is a federal state of Germany which covers nearly 6% of Germany's area and comprises just over 6 Mio. of Germany's residents. Objective of the study is the estimation of integration costs of future DER and new customers, the identification of effective measures for an advanced integration and the identification of needs for action in the regulatory framework. The study investigates three future DER and consumer scenarios for two target years.

As part of this study, various new methodological approaches were used. Instead of the usual spatial resolution at the municipal level, the state of Hesse is divided into around 3,000 geographical patches based on settlements. Both the regionalization of the future scenarios as well as the extrapolation of the grid simulation results to the entire state of Hesse are based on this spatial resolution. Analysis and calculation are done solely with models of real grids in large numbers at all voltage levels. Repeated probabilistic grid calculations are used to deal with the uncertainty of possible future positions and sizes of generators. The extrapolation of the grid simulation results to areas where grid data are not available is achieved by validated regression models. Detailed cost models based on annuities allow a meaningful comparison of conventional and innovative reinforcement measures.

In the following, some of the used methods are presented and the main results of the study are sketched and interpreted.

CONSIDERED SCENARIOS

The study predicts the expansion of renewable energy generation as well as increased usage of electric mobility and electric heat pumps. In order to consider different possible futures, a lower, medium and upper scenario for 2024 and 2034 are developed. The lower scenario models a delayed development of renewable energy production and new consumers. The medium scenario is based on the national energy policy and roadmap. The upper scenario reflects currently ambitious development goals (details in Figure 1) of Hesse.

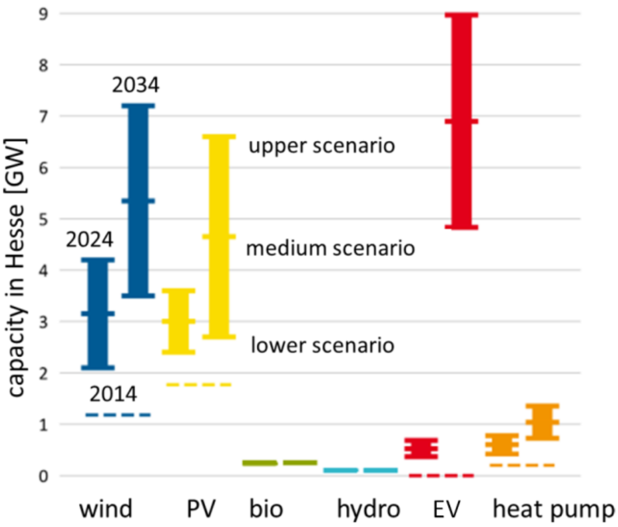


Figure 1: Predicted installed capacities for DER and new consumers

Based on these scenarios, future spatial distributions for each individual type of DER and new consumers are derived for the state of Hesse. Regarding wind energy, in a first step the probability of the installation of additional plants in predefined areas is determined. The suitability of an area is determined by the wind potential, the population density within a radius of 2 km, the presence of forest and the number of wind turbines that can be erected at each site. Given this probability, additional wind turbines are installed randomly until the overall capacity reaches the value assumed in the respective scenario. For the regionalization of future roof-mounted photovoltaic (PV) systems, a two-step process is used. In the first step, the overall target capacity specified in the considered scenario is distributed among the sites in Hesse. The approach takes the historical development of PV within the sites and the available roof areas into account. In the second step, the power is distributed among the buildings within each site based on a technological and economic evaluation of the inherent suitability of the individual building. Ground-mounted PV systems are placed in a 110 m edge strip along motorways and railways. The spatial distribution of electric heat pumps and electric vehicles (EVs) is also determined in two stages. In the first step, the overall predicted capacity is distributed to the communities of Hesse. In the second step, the heat pumps and EVs within the communities are distributed to individual buildings. The regionalization of EVs at the municipal level is done for different classes of charging opportunities: residential, workplace, public and along highways, according to individual criteria. The above described probabilistic procedures for regionalization are used to generate 50 different spatial distributions of DER and new consumers for each combination of year, scenario and technology.

GRID DATA AND GENERAL APPROACH

The basis of the study is a large number of models of real distribution grids. Nine DSOs provided grid models in different formats of commercial software, i.e. Sincal, PowerFactory, Neplan. These models were converted to the pandapower format [2] ensuring that all grid models follow the same principles of modelling (e.g. naming conventions) and use the same geographic projection. This allows to treat all grid models in the same way and to conduct fully automated simulations.

The general approach for all voltage levels is based on a method that can automatically reinforce a grid model using conventional measures only. Depending on the voltage level, different types of measures and algorithmic approaches are used. The reinforcement is done with respect to two load cases - a high load case and a high feed-in case. This method is then used to determine the necessary grid reinforcement cost for each combination of a given year, scenario and probabilistic distribution of DER and new consumers. The result is a distribution of expected costs. To analyse the impact of an innovative technology on the reinforcement costs, it is implemented in the grid model to the possible extent and then the costs for remaining conventional reinforcement measures are determined. The resulting distribution of cost can be compared to the base case of conventional grid reinforcement. In the following, most result figures will show these kinds of comparisons.

HIGH-VOLTAGE LEVEL

The analysis of the high-voltage (HV) level is based on a single integrated grid model including six 110 kV grids and a partial model of the overlying transmission grid. Methodology and results of the HV analyses are described in more detail in [3]. In order to estimate the expected reinforcement costs for a given scenario, an automated grid reinforcement approach is used. It iteratively determines all violations in all considered load cases and applies measures to remove them accordingly. More precisely, the maximal loading per line among all possible n-1 cases in the HV grid is determined at first. All lines identified as overloaded in any of the n-1 cases of any load case are then reinforced. The applied reinforcement measures depend on the extent of overloading. For lines with loading below 160% of their rated power, reserve measures like dynamic line rating and temperature resistant aluminum are used. However, if the loading of a line is higher than 160%, it must be replaced by conductors with a higher diameter. This also requires that the power poles are replaced due to the increase in weight and is therefore much more expensive. The n-1 analysis and the reinforcement step are repeated until no overloaded lines are left. Afterwards, a heuristic algorithm, as described in [4], is used to remove the remaining voltage violations.

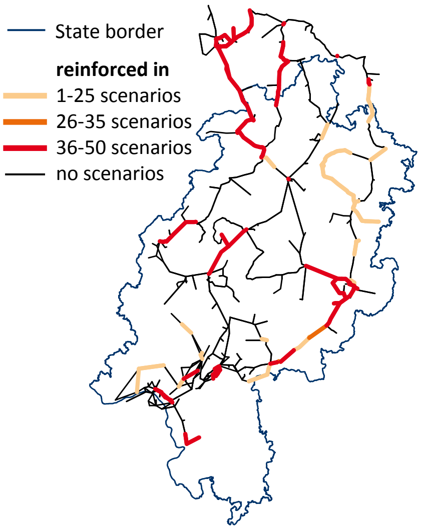


Figure 2: Conventional reinforcement (2034, medium scenario):

Calculating the 50 distributions allows an analysis of the likelihood of reinforcement of lines (Figure 2). As can be seen, some lines are sufficient for all future distributions of DER and new consumers. By 2034, 31% of all circuits require reinforcement.

Figure 3 and Figure 4 present the influence of the investigated innovative technologies on the expected reinforcement cost at the HV and HV/MV transformer level. Using conventional measures only, the costs in the HV level reach 314 Million EUR (median, present value) and 216 million EUR for the HV/MV substations.

High Temperature Low Sag conductors (HLTS) are lighter and have lower sag than conventional conductors. HLTS conductors can be continuously operated at temperatures up to 210 °C. As a result, the reinforced overhead lines can be operated with about twice as high currents as before. Utilization of HLTS conductors in combination with local Q(V) control of wind parks and PV power plants that are connected to the HV or HV/MV voltage level can contribute to cost savings of about 10%. Active power curtailment of PV generators in the low-voltage (LV) level would increase the cost savings in the

HV level to about 15%. The combination of HLTS, local Q(V) control and active power curtailment in the LV grids has the highest cost-saving effect.

Reactive power control with the power factor of 0.95 has a positive effect on the HV level, while having a negative effect on the costs of HV/MV substations because it causes higher loading of transformers. The overall cost effect in the HV and the HV/MV level is beneficial. The power factor of 0.9 leads to higher HV reinforcement costs, because more lines are overloaded.

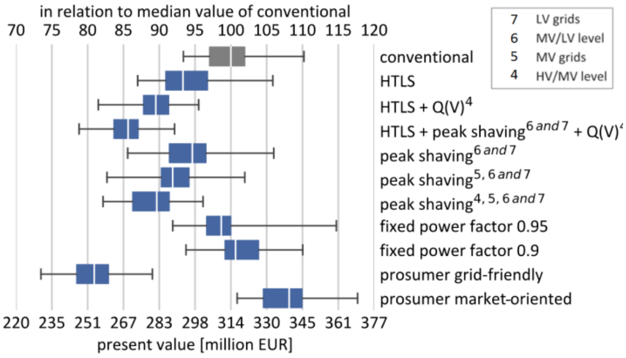


Figure 3: Impact of innovative technologies on the reinforcement costs of the HV grids

Curtailment in the LV grids has a cost reduction potential of about 5% for HV/MV substations and HV grids. If applied in all voltage levels, it can reduce substation costs by about 9% and HV grid costs by about 10%. However, curtailment in voltage levels other than LV would require additional costs due to remuneration.

Prosumer applications have the highest effect on the costs in the HV grids, while also having the highest uncertainty because their market potential and the costs of additional ICT infrastructure are yet unknown.

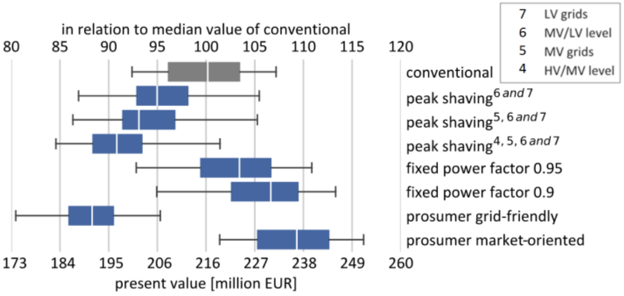


Figure 4: Impact of the innovative technologies on the reinforcement costs of the HV/MV substations

LV AND MV SCENARIO INTEGRATION

The scenario predictions consist of forecasts for roof-mounted PV systems, EV charging stations, heat pumps, wind farms and large PV farms forecasted as geographic points with an associated power value. As a pre-calculation step, all buildings are assigned to the nearest LV grid connection points. Predicted PV plants, heat pumps and EV charging stations within a real estate can then be assigned to the corresponding grid connection point. As for MV grids, the shortest distance is used for the forecast allocation to the substations (see Figure 5). Medium-voltage energy sources, i.e. ground-mounted PV power plants and wind farms, are not implemented directly into the grid models. Instead, a single bus with a static generator is added to the grid model. Eventually, the automatic grid reinforcement decides how this bus is connected to the grid. More details on the automated grid planning can be found in [4] and [5].

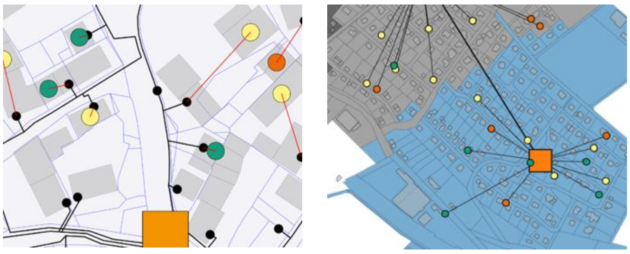


Figure 5: Exemplary assignment of scenario predictions; (grid lines and connection points (black); real estates (blue lines); houses (gray); forecast for PV plants (yellow), heat pumps (orange circle) and EV charging stations (green); MV/LV transformers (orange))

MEDIUM-VOLTAGE LEVEL RESULTS

The influence of innovative technologies on expected reinforcement cost of the MV grids is given in Figure 6. Reactive power control methods can reduce the necessary grid reinforcement. Note that due to missing LV grid data, the behaviour of roof-top mounted plants using Q(V) cannot be modelled. The Q(V) characteristic in medium-voltage grids is exclusively used by plants directly connected to the MV level. In contrast, fixed power factor control is used by all plants. This difference in modelling causes the cost savings when applying fixed power factor (12%) to be about twice as high compared to Q(V) (6%).

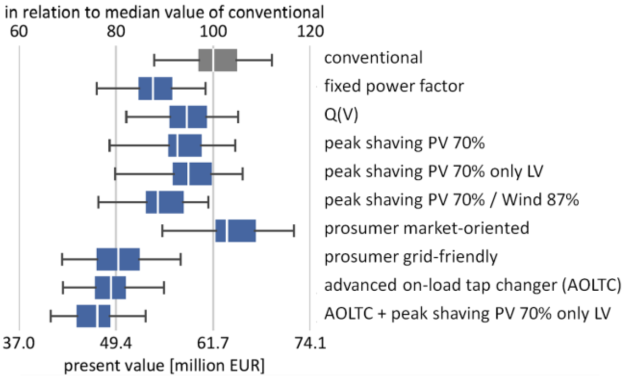


Figure 6: Impact of the innovative technologies on the reinforcement costs of the MV grids

Peak shaving of low-voltage PV plants reduces costs by around 5%. The additional effect of PV peak shaving both at the LV and the MV level accounts for another 2%. The most effective variant with 11% cost savings is peak shaving of PV plants to 70% as well as limiting wind plants to 87%. In none of the presented alternatives

cost for curtailed energy is included. The impact of remuneration for curtailed energy is further analysed in [1].
The advanced OLTC (AOLTC) control of the HV/MV transformer allows for an adapted setting of the OLTC voltage set point depending on the active power flow at the HV/MV transformer. As can be seen, AOLTC is the single technology with the largest cost savings of about 21% compared to conventional grid reinforcement and expansion based on the median. When combined with PV peak shaving in LV grids, the investment costs can be further reduced. Additional reactive power control technologies add no relevant effect because the AOLTC usually mitigates all voltage violations.
The grid-friendly operation of prosumer assets, such as controllable PV storage systems or EVs, also has the potential of reducing the investment cost by around 20%. It is important to note that the realisation of this potential depends on future implementation of smart grid communication infrastructure as well as regulatory changes. Market-oriented prosumer behaviour, however, only slightly increases costs by about 3%.

LOW-VOLTAGE LEVEL RESULTS

The study expects that no line overloading, transformer overloading or voltage band violation will appear in 30% of the analysed LV grids. There is a chance that problems occur in 40% of the grids, depending on the specific distribution of new DER. As for the remaining 30% of the LV grids, violations are very likely regardless of the distribution of new DER.

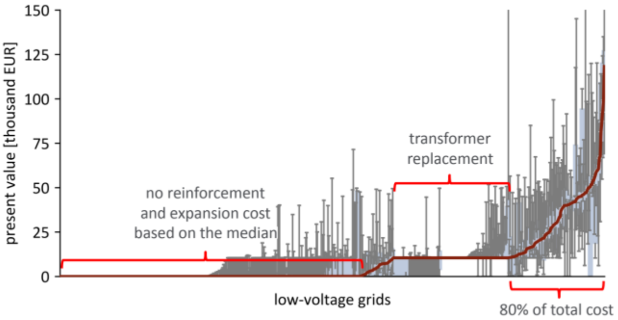
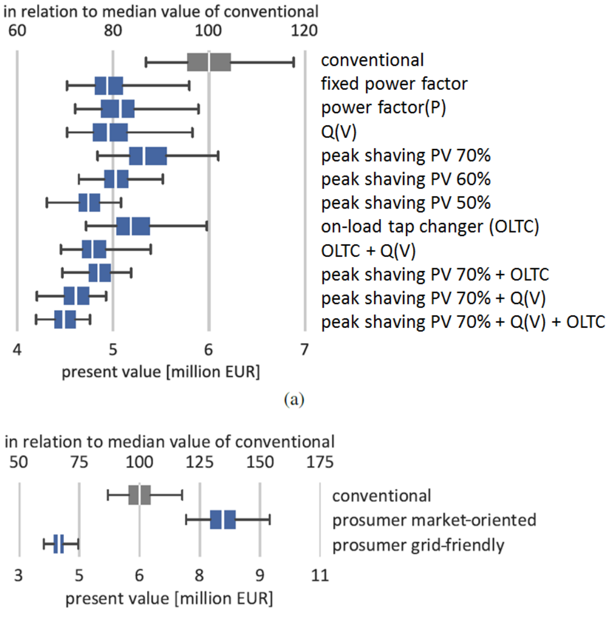


Figure 7: Distribution of the expected grid reinforcement cost for all LV grids

Whereas mostly voltage violations are observed in 2024, transformer overloading is the most common violation in 2034, occurring in over 60% of the problematic cases. In general, line overloading plays only a marginal role.
Figure 7 depicts 670 boxplots sorted by median values. Each boxplot represents the distribution of the expected grid reinforcement cost of a single LV grid. The figure can be divided into three sections. The first section contains grids where grid reinforcement is unlikely. The second section contains grids that have only the existing transformer replaced by a transformer with higher rated power in most cases. The last section contains grids that have to be reinforced in most of the 50 distributions. Although this section only contains 25% of the grids, they contribute to 80% of the overall reinforcement and expansion costs. Two-thirds of the costs in 2034 are due to new transformers or new substations and only one-third is due to new or replaced lines.



(a)

(b)

Figure 8: Impact of the innovative technologies on the reinforcement costs of the LV grids

Figure 8 reports the effects of the investigated innovative technologies on the expected costs. All technologies potentially lower the necessary grid reinforcement costs. Reactive power control technologies are able to decrease costs by around 20%. The three different peak shaving levels (limiting maximum feed-in power to 70%, 60% or 50%) save from 17% to 23%. MV/LV transformers with OLTC lead to savings of 18%. In this case however, due to the additional investment cost of OLTC, this technology is only applied when it leads to net savings, which is the case in about 18% of the LV grids if used solely and net savings in about 6% of the LV grids, when combined with peak shaving and Q(V). OLTC is especially effective in grids with severe voltage band violations in both load cases. The types of occurring violations in the LV grids are very diverse. Consequently, the combination of voltage controlling technologies with peak shaving leads to the highest overall savings.
Different operation modes of prosumer assets have significantly higher effects than in the MV level. A grid-friendly operation of prosumers has the potential to reduce investment cost by 35%. In contrast, a market-oriented behaviour has the opposite effect by increasing cost by 35%.

OVERALL RESULTS OF THE STUDY

Extrapolation of the results of the calculated grids to areas without grid data is a necessary step to estimate the expected costs for the state of Hesse. To this end, a regression model is used that relates properties of geographic areas (e.g., number of inhabitants, area, expected DER) with expected costs.

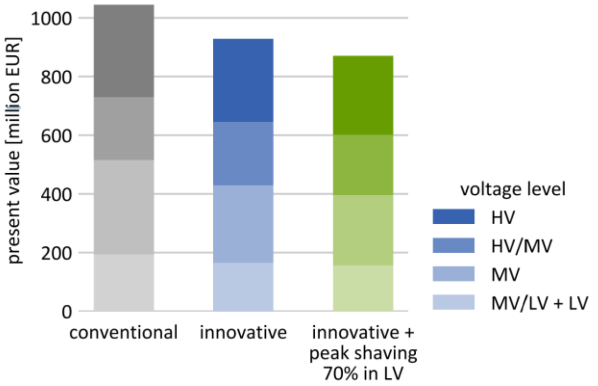


Figure 9: Expected DER integration and grid reinforcement cost for the state of Hesse 2034, medium scenario

Figure 9 shows the grid expansion costs (mean values) for the state of Hesse over all voltage levels for the medium scenario 2034. Grid expansion costs of around 1 billion EUR are expected in 2034 in total for the low-, medium- and high-voltage level, if grid expansion is limited to conventional technologies and planning approaches. All values contain reinforcement and expansion costs as well as connection costs. Innovative planning approaches and new technologies, that are nowadays already available, i.e. on-load tap changer (OLTC) for LV transformers, Q(V) control, advanced HV/MV transformer tap control (AOLTC) and high temperature low sag conductors (HTLS), can reduce grid investment costs by about 11% in 2034.

PV peak shaving in the LV level can reduce the overall investment costs at all voltage levels by additional 6% because the effect of LV peak shaving is cumulative over all voltage levels. Indeed, the power that is curtailed in the low-voltage level cannot affect other voltage levels.

SUMMARY

This paper presented the methodology and selected results from a grid study conducted for the German federal state of Hesse. The study analyses more than 900 real distribution grids at all voltage levels. The investigated grids show a considerable variation in their hosting capacity and consequently in the expected grid reinforcement and expansion costs. This emphasises the importance of the high sample sizes of real grids as used by the study in order to obtain the necessary significance.

Innovative technologies can lead to large possible savings in single grids. However, considered over many grids and all voltage levels, their cost saving potential is limited. In total, the possible savings due to innovative technologies (excluded peak shaving) compared to the conventional measures amount to 11%. This relatively low value can be explained as follows. Besides peak shaving, all other considered innovative technologies mainly target voltage problems. However, the main part of the expected grid reinforcement and expansion costs for the HV grids as well as HV/MV transformers are caused by overloaded equipment. Reactive power control technologies utilised in other voltage levels can even cause additional overloading and thus increase necessary investment cost for HV/MV substations. On the other hand, although on the MV level voltage violations are a main cause of grid reinforcement, two-thirds of the overall costs arise from connecting large DER plants. Potential savings regarding connection costs are minimal because they are determined by the geographic distance to the grid.

Depending on the operational behaviour (grid- friendly/ market oriented), prosumer assets can lead to a substantial cost saving potential or risks of additional costs. These scenarios, however, require a developed smart grid infrastructure as well as regulatory changes.

Acknowledgments

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