Regionalization of four storylines for the decarbonization of the European power system including flexibilities

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Abstract:

In this paper, we investigate the impacts of different types of electricity demand with potential flexibiliy, such as heat pumps, battery electric vehicles, and photovoltaic battery storage systems on the balance of electricity generation and demand on a European scale. In order to evaluate this impact of flexibilities, first, we perform a regionalization to allocate generation capacities and flexible demands to the distribution grid level. Secondly, a stochastic dynamic programming model is applied to consider the impact of household batteries on the electricity generation and demand on a single node and national level. In order to consider uncertain future developments of generation capacities and demand, we apply the methodology to four storylines that have been defined within the ENSURE project. The results show that a high share of decentralized photovoltaic battery systems can contribute in a beneficial way in situations with a high positive or negative residual load. However, the uncoordinated dispatch of these storage units can also lead to some avoidable curtailments of renewable energies.

Keywords: Regionalization, Flexibilities, PV-BESS, Energy System Modeling, Stochastic Dynamic Programming

1 Introduction

The electricity system is undergoing substantial change due to the increasing efforts of countries to reduce their greenhouse gas emissions to minimize the global temperature increase. Recently, the EU Green Deal showed the growing ambitions of the European Union to accelerate the decarbonization of the energy system. With regard to electricity generation, replacing fossil fuel-based power plants with renewable energy sources (RES) reduces greenhouse gas emissions. Throughout Europe, high generation capacities of renewables, mainly wind and photovoltaic (PV), are being installed. On the demand side, sector coupling technologies connecting the electricity sector and the heat and mobility sector are being

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installed. Such technologies include battery electric vehicles (BEV) and heat pumps (HP). In recent years, they show increasing market shares due to their potential to decrease emissions when using electricity from renewables. Their respective shares are expected to increase in the future further.

Due to the volatile character of the two most relevant renewable electricity generation technologies, wind and PV, and their spatially depending potential, flexibility will play a crucial role in future electricity systems. Flexibility can be either provided by a storage technology, such as batteries, or demand flexibility [1]. BEVs, HPs, and battery storage systems (BSS) can provide such flexibility. Especially in Germany, a significant increase in home PV systems with integrated battery storage (PV-BESS) can be observed in recent years [2]. If used in a controlled or optimized way, these flexibilities present potentials to balance further the generation and demand side of the electrical system. However, when considering that a coordinated operation of PV-BESS is difficult due to the necessary participation of the owners the question arises whether the unsupervised control is beneficial from the system operator´s point of view or if it could even increase consumption peaks.

Therefore, it is crucial to investigate the integration of renewables and flexibilities in the future´s energy system. The project “New ENergy grid StructURes for the German Energiewende” (ENSURE)[2] focuses on how today´s energy system, especially the electricity grid, will have to change to ensure the security of supply in case of high shares of RES. Germany is the focus region of this project but also the other European countries are modeled in order to consider to the possible interactions of the energy systems. When investigating the effects of high shares of RES on the electrical grid, information about electricity generation and demand at each node is needed for all of the European countries. Since most political targets are defined at national level, e.g. additional generation capacity of wind and PV, these targets have to be disaggregated to electrical bus level.

In the literature, there are different approaches of how to model the development of generation and demand on a European scope. In [3] the RES expansion and futures demands are modeled. However, other European countries are aggregated to the national level and no regionalization of flexibilities is performed. Nobis et al. perform a regionalization based on publicly and commercially available data. The database includes information about electrical and thermal demand of different sectors (households; commerce, trade and service; industry), existing power plants, and spatial restrictions. Parameterizing this data basis different scenarios of future developments can be considered [4]. A bottom-up modeling for the European countries is performed in [5]. The regionalization of RES and demands in different sectors, including flexible demands, is done with high special resolution. The demands are later aggregated to the NUTS3 level. But for an analysis of the electrical grid, the highly resolved data should be aggregated to nodes of the electrical grid. In order to perform a regionalization of RES, demands and flexibilities with a high special resolution for all European countries on the level of nodes of the electrical grid, we adapt the approach of Slednev et al. [6], Slednev et al. [7], and Ruppert et al. [1].

[2] ENSURE project - https://www.kopernikus-projekte.de/en/projects/ensure

Considering the operation of flexible demands, there are comprehensive overviews of the different flexibility options, e.g. PV-BESS [8], HP [9], and BEV [10]. However, most of studies focus on either single households, or micro grids [11, 12]. Since our focus are not single units, the flexible demands have to be aggregated. In the literature there are different methods regarding this kind of aggregation. One method is to simulate or optimize a single unit by predefined rules and scaling up the results [13, 14, 15].

Another approach is Stochastic Dynamic Programming (SDP). By using SDP Groß et al. [16] showed an improved system operation by considering forecasting uncertainties of PV generation. In [17] the optimal operation of a PV generation unit including an electricity storage is determined using SDP in order to supply power to BEVs. Wu et al. [18] model a smart home energy management including BEV applying a SDP incorporating multiple variables. This improves the accuracy of the prediction of household demand and electricity generation from rooftop PV.

Thirdly, Stochastic Dual Dynamic Programming (SDDP) can be used to model PV system including batteries. In [19] the charge and discharge of batteries minimize the electricity costs of a household. Hafiz et al. develop an SDDP based method to optimize the operation of battery systems under real time conditions applying also a rule-based controller to improve the optimization efficiency [20]. However, none of these approaches applies the methodologies to the higher levels of the distribution grids or to the transmission grid, which is where this work fills a missing gap in the literature.

In this paper, we present the methodology of regionalization of flexible demands in the European countries and the stochastic optimization of PV-BESS in section 2. In section 3, we describe the case study the methodology is applied to. The use case includes four storylines depicting different possible future developments of generation capacities and electricity demands, including flexibilities. These storylines have been developed within the project ENSURE. Furthermore, the parametrization of the SDP approach is explained. The results we receive from applying the methodology to the use cases are presented in section 4. Finally, we draw conclusions and summarize our findings in section 5.

2 Methodology

2.1 Existing modelling framework

The computation of spatial and temporal highly resolved demand and renewable generation profiles for a given storyline follows the approach described in Slednev et al. [6] and Slednev et al. 2018 [7]. In a first step, voronoi-shapes are calculated depending on the Open Street Map [21] distribution grid nodes. Then generation and demand are allocated to the nodes in yearly steps. On the one hand, generation capacities of different types of RES are allocated to distribution grid nodes considering spatial restrictions, e.g. no use of restricted areas like military or nature conservation areas and minimum distances between wind turbines. The RES capacities are newly build or repowered depending on their levelized costs of electricity until a desired target of capacity or minimum energy production is met. On the other hand, electricity demand is distributed depending on socio-economic factors and known electricity demands on NUTS3 level and overlapped onto the distribution grid nodes.

For decentral flexibilities, we follow the modeling and regionalization described in Ruppert et al. [1]. Household HP are regionalized similarly to the electricity demand, however, distributed by known heat instead of electricity demands. The district heating HP are distributed based on the combined heat and power generation units within a country. For Germany, also data from the German District Heating Association (AGFW) could be used to further increase the accuracy of the modeling. For the demand of BEV, the distribution depends on the household electricity demand for all countries but Germany. In the latter case the vehicle registration numbers at NUTS 3 level are the distribution key. For PV-BESS the regionalization depends on the installed capacities of PV rooftop generation. Additionally to the work in [1], the demand of BEV from fast charging on the route is distributed according to Slednev et al. [22]. The modeling framework is depicted in Figure 1. The output that is delivered by this modeling are electricity generation profiles of different types of RES, demand profiles from conventional demand, and operation profiles from different flexibilities on the high voltage node level.

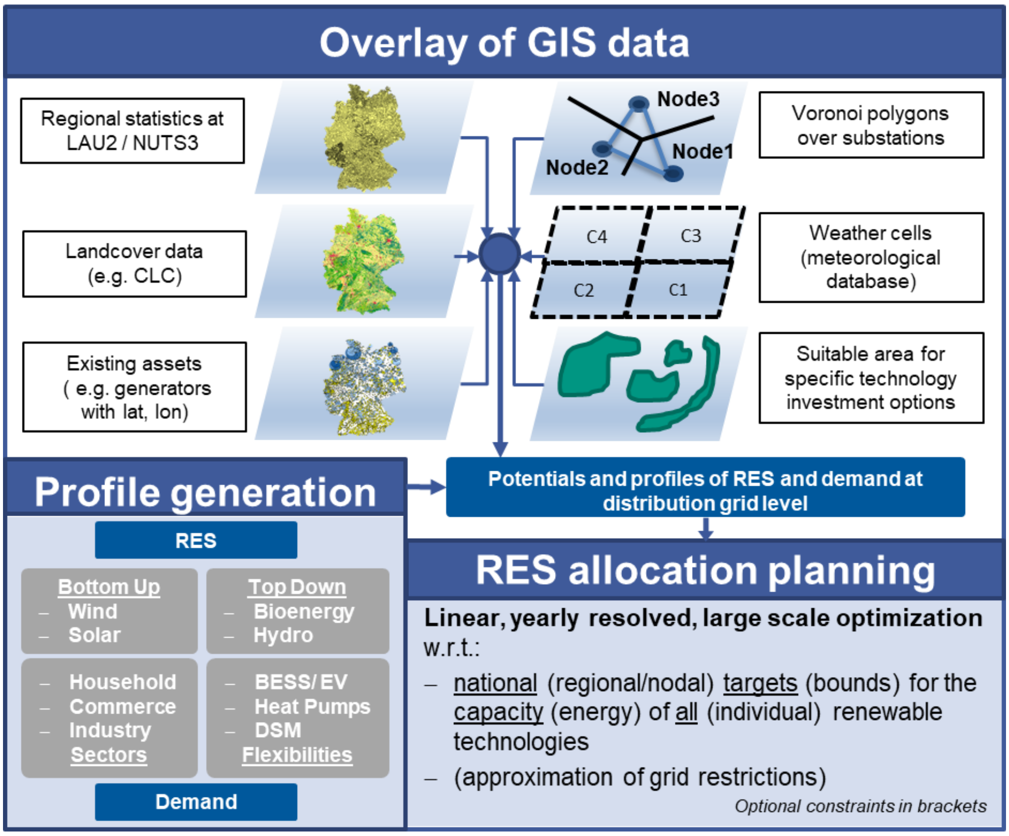

Figure 1: Description of the modeling of high-resolution RES generation and electricity demand

2.2 Stochastic dynamic programming of PV-BESS

Due to the large number of units, the modelling of the actual dispatch decision for decentral flexibilities remains a challenge. In the literature, this problem is often solved either by applying predefined dispatch strategies for the single units [14, 15], such as a peak shaving or valley filling policy or by optimizing representative units and upscaling the results [23, 13]. Slednev et al. [22] demonstrated a central dispatch optimization of all flexibilities aggregated to the distribution grid level in the context of an optimal power flow (OPF) problem for Germany and its neighbouring countries considering grid restrictions for the transmission and distribution grid based on the direct current (DC-OPF) approach [24]. Due to the computational challenge of extending this approach for a more realistic stochastic optimization or in the context of the complex altering current (AC-OPF), in the following an approach for a scalable individual stochastic optimization of decentral flexibilities, aggregated on distribution grid level, is presented. With a focus on deriving an individual optimal dispatch strategy for numerous flexible units, we chose a discretization of the solution space and a basic SDP approach. Furthermore, we focus on the optimization of a single flexibility in the first step and demonstrate the suitability of SDP for the efficient solution of such a problem based on dispatch optimization of PV-BESS on distribution grid level.

For simplicity we assume that the uncertainty about the maximum photovoltaic generation $X_{k,t}^{g.pv}$ and household demand $X_{k,t}^{d.hh}$ in hour t might be expressed through a stage-wise independent random vector ξ with K realizations per stage. For a given realization $k \in K$ of these parameters and a certain level of the battery volume V_t in stage t, we aim to minimize the cost $f_{t,k}(V_t, X_{k,t}^{d.hh}, X_{k,t}^{g.pv})$ for covering the demand of a household, which comprises the expenses for withdrawing $x_{k,t}^{d,g}$ or injecting $x_{k,t}^{g,g}$ electricity from or into the grid in the current stage and the probability weighted cost for the following stages. For a better readability all variable and parameter superscripts follow the convention that we first denote whether electricity is generated (g), demanded (d) or curtailed (c) and then by whom (household (hh), PV (pv), battery (b) or grid (g)).

$$f_{t,k}(V_t, X_{k,t}^{d.hh}, X_{k,t}^{g.pv}) := \min x_{k,t}^{d,g} c_t^{d,g} + x_{k,t}^{g,g} c_t^{g,g} + \sum_{k=1}^{K} p_k \, f_{k,t+1}(V_t, X_{k,t+1}^{d,hh}, X_{k,t+1}^{g,pv}) \tag{1}$$

$$v_{t+1} = V_t + x_t^{d,b}\mu - x_t^{g,b} \tag{2}$$

$$X_{k,t}^{d,hh} - X_{k,t}^{g,pv} + x_t^{d,b} - x_t^{g,b} + x_{k,t}^{c,pv} = x_{k,t}^{d,g} - x_{k,t}^{g,g} \tag{3}$$

$$x_{k,t}^{c,pv} \leq X_{k,t}^{g,pv} \tag{4}$$

$$x_{k,t}^{g,g} \leq \hat{X}^{g,pv}\alpha \tag{5}$$

$$v_{t+1} \leq V_{t+1}^{max} \tag{6}$$

$$x_t^{d,b} \leq \hat{X}^{d,b} \tag{7}$$

$$x_t^{g,b} \leq \hat{X}^{g,b} \tag{8}$$

$$x_t, v_t \geq 0 \tag{9}$$

The first constraint (eq. 2) links the transition of the state variable v_{t+1}, which defines the storage level at the beginning of an hour, to the charging ($x_{k,t}^{d,b}$) and discharging ($x_{k,t}^{g,b}$) action variables and its previous state V_t, which enters the equation as a parameter. The next inequation defines that the residual load of demand minus realized PV generation, which is the curtailment adjusted PV generation, is either balanced by the storage or the grid. The variable bounds in Eq 4-Eq. 9 restrict the valid range between a lower and upper bound. In detail, the battery charging (Eq.7), discharging (Eq.8) and volume (Eq.6) is limited to the available capacity. Furthermore, all variables are set to be positive (Eq. 8) and the curtailment variable

$x_{k,t}^{c,pv}$ is limited by the available PV generation (Eq 4) and the maximum feed-in into the grid to a share of the PV capacity (Eq 5).

In order to keep the problem traceable, the storage state variable is discretized with a step size of Δv and the problem is solved directly through a back-propagation procedure, starting in the last step and evaluating all possible actions in each state. Given a certain storage level $V_{s,t}$ in state $s \in S$ the action space for the storage charging and discharging decision is defined as follows:

$$x_t^{g,b} \in \{0: \Delta v: \min\{V_{s,t}, \lfloor X_t^{g,b}/\Delta v \rfloor \Delta v\}\} \quad (10)$$

$$x_t^{d,b} \in \{0: \Delta v/\mu: \min\{V_{t+1}^{max} - V_{s,t}, \lfloor X_t^{d,b}\mu/\Delta v \rfloor \Delta v/\mu\}\} \quad (11)$$

The full action space is then defined by the adjoint charging and discharging decisions of the battery, excluding an intersection besides of the zero value. By setting the cost for the grid exchange to infinite for an invalid grid feed-in, the corresponding constraint might be neglected, and the remaining variables are directly derived from Eq. 2.

Concerning the stochastic process, the definition of the recombining tree is based on the assumption that the forecast error for the demand and the PV generation is a fixed percentage of the deterministic value and follows a normal distributed with a mean of zero and fixed variance, independent of the forecast horizon and parameter level. After discretizing the probability space of the parameters into N bins, we derive the discrete value and probability for each bin based on probability density function and cumulative distribution function and end up with a recombining tree of $N^{pv}N^{hh} = K$ realizations per stage. In the last step the discrete realizations for the photovoltaic generation and household demand are adjusted such that the final parameters are restricted to technical limits.

3 Case Study

3.1 ENSURE Storylines

There are many possible future developments of the electricity system regarding the electricity generation mix and the future demands from either conventional consumers or new flexible consumers. The outcome of these possible developments cannot be known beforehand, especially considering time horizons up until 2050. Since not all different developments can be considered due to the sheer amount, four storylines developed in the ENSURE project are considered to address these uncertainties in the transition path [25].

Storyline A describes the reference scenario in which the reduction of greenhouse gas emissions in Europe until 2050 is expected to be ~80% compared to 1990. Germany, in particular, is predicted to reduce its emission by 55% and 85% in 2030 and 2050, respectively.

Storyline B is the most ambitioned regarding fulfilling the climate protection targets. In this storyline, climate neutrality is to be reached latest in 2050.

Storyline C has a focus on the European level and international exchange. Therefore, increased international transmission capacities are expected. The target is climate neutrality in 2050.

Lastly, in Storyline D a decentral future energy system is envisioned, including increased decentral flexibilities like PV-BESS. Climate neutrality is expected to be reached in 2050.

In all storylines, the generation capacities of 2040 of the Ten-Year Network Development Plan (TYNDP) 2020 are lower limits for the electricity generation mix in 2050. The generation capacities of the four storylines for 2030 and 2050 are presented in Figure 2 and Figure 3, respectively. For better representation, only the generation capacities of Germany and neighboring countries are included in the figures.

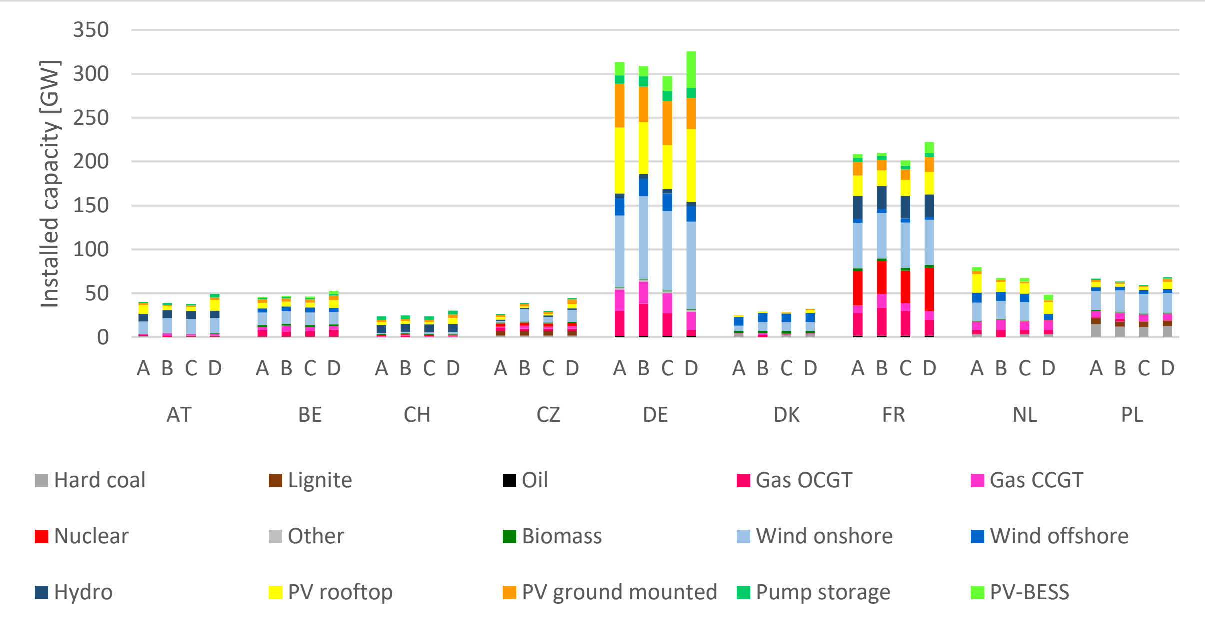

Figure 2: Generation capacities in the four storylines in 2030

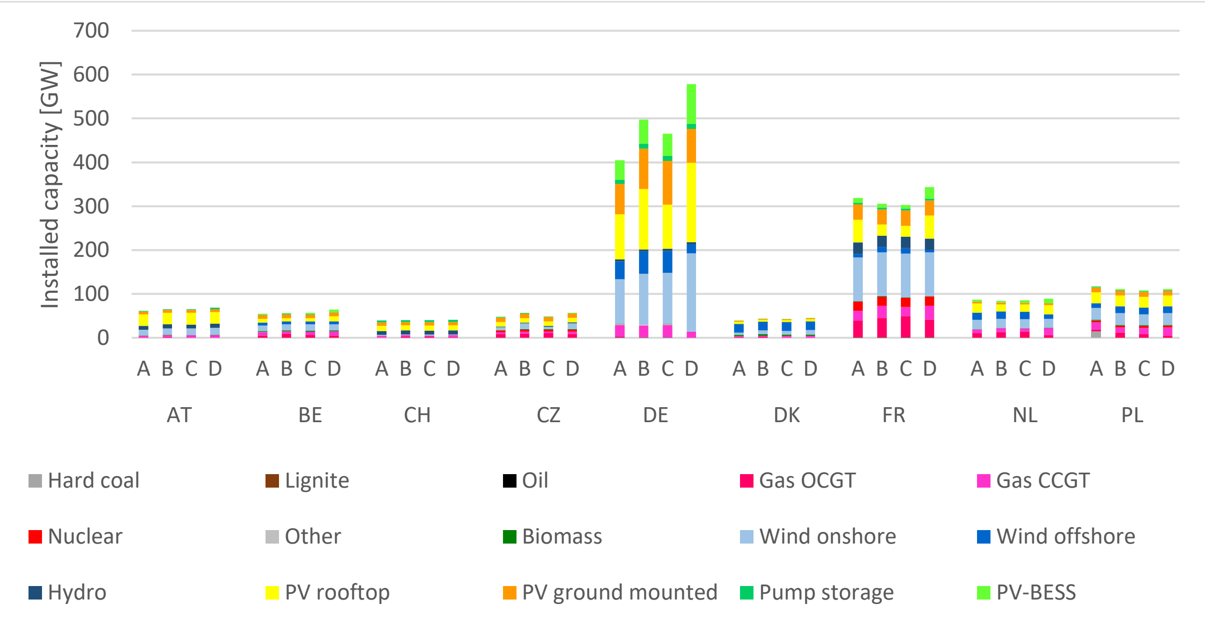

Figure 3: Generation capacities in the four storylines in 2050

As shown, already in 2030, the generation capacities of coal power plants are drastically reduced. In Germany, the coal phase-out already took place before 2030 in all storylines. This implies a drastic acceleration compared to the current plans of the government to terminate the coal phase-out until 2038. The generation capacities of these storylines have been allocated to the distribution grid level [7].

Regarding the flexibilities installed in each of the four storylines, Figure 4 presents the annual electricity demand on a national level in 2030 and 2050. Note that the conventional electricity demand is not included here due to the focus on flexible demands.

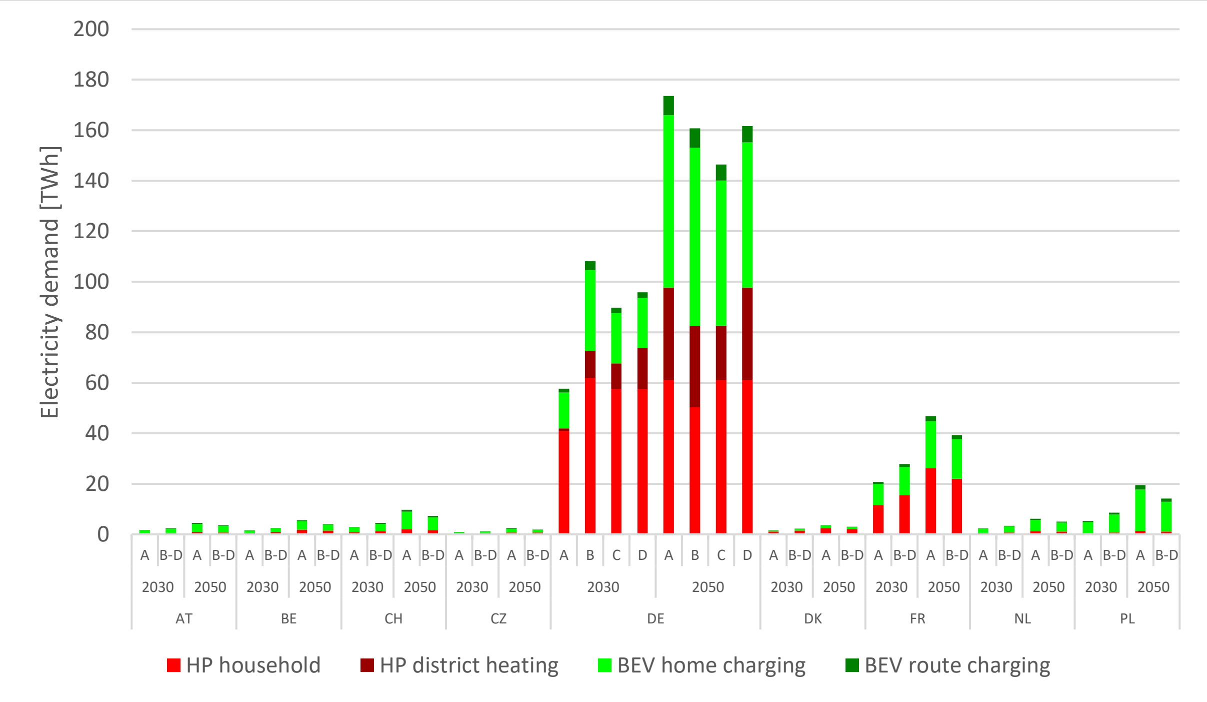

Figure 4: Electricity demand of flexible consumers in the four storylines in 2030 and 2050

As shown, the differences between the storylines are apparent, especially in 2050. Since ENSURE focuses on the German energy system, the electricity demand in storylines B, C, and D differs only in Germany. Furthermore, the electricity demand for district heating is only considered in Germany.

3.2 Stochastic optimization of the PV-BESS

After regionalizing the household demand, PV generation capacity, and PV-BESS capacity to the distribution grid level, a normalization and discretization of the input values has to be performed in order to derive the stochastic optimized PV-BESS profiles for the central European distribution grid based on the proposed SDP approach. In the first step we choose the battery discharge capacity of each distribution grid node as the reference basis by dividing all other values though this value. Afterwards we rescaled the parameters by multiplying with 1000. Finally, we choose a step size of 10 for discretizing the storage level state space.

Concerning the stochastic process, we assumed a stagewise independent normal distribution of the forecast error, defined as a percentage of the deterministic value, with a zero mean and a standard deviation of 0.15 for the household demand and of 0.05 for the available PV generation. After dividing the probability space into 3 bins, to cover a low and a high positive and a negative deviation we end up with 9 discrete realizations of the two random parameters per stage and in total with 9^{8760} scenarios for the whole year. This is depicted in Figure 5.

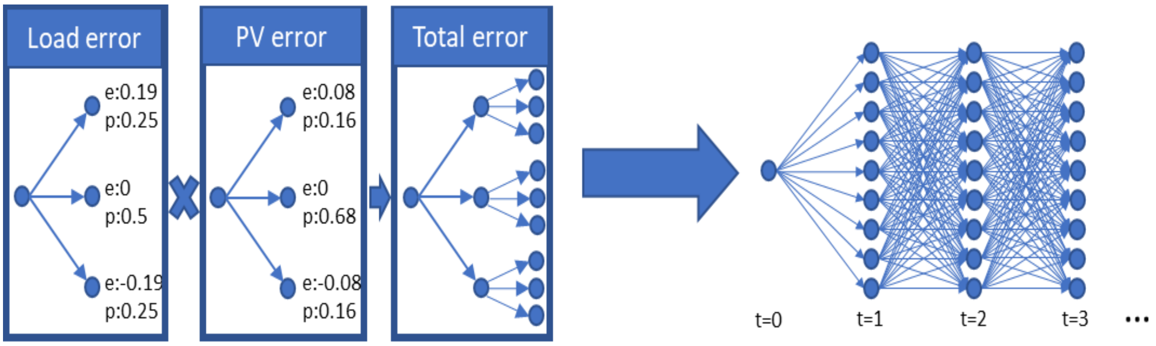

Figure 5: Description of the resulting 9^{8760} stochastic scenarios for the whole year

Finally, we defined the start and end conditions of the storage such that we assumed a zero cost-to-go function value in T+1 and choose a random initial storage level between 0 and 0.5 of the available capacity in the first stage.

For the parametrization of the PV-BESS system and the cost function, we considered a case with a rate of the storage volume to the discharging capacity (c-rate) of one and an equal charging and discharging capacity. Furthermore, we restricted the maximum PV-grid injection in one hour to half of the installed capacity. With the goal of incentivizing a high self-consumption, we choose a constant cost coefficient, with a revenue from grid injection set ten times lower than the cost for withdrawing electricity from the grid.

4 Results

This chapter discusses the results of the regionalization of flexible demands and the stochastic optimization of PV-BESS and its impact on the local and national level.

4.1 Regionalization of flexible demand

The flexible demands of HP for district heating and households, BEV charging at home or on the route, as well as PV-BESS have been disaggregated to the distribution grid level as described in chapter 2.2. Figure 6 exemplarily presents the annual electricity demand of these flexibilities in 2030 and 2050 for Storyline B at the distribution grid level. The equivalent figures for the other storylines can be found in Annex A. The electricity demand of PV-BESS shown in the figures is the electricity that is temporarily stored in the batteries and results from the stochastic optimization. As shown, the electricity consumed by the PV-BESS is lower than HP and BEV's demand.

Especially regions with a high population show a high density of flexible demands, which is consistent with most of them usually being part of household systems. Electricity demand by heat pumps is notably lower in 2050 compared to 2030. This decrease is caused by the improvements in household insulations and the resulting lower demand for heating. On the contrary, the electricity demand from BEV increases significantly due to their increasing share in the further future.

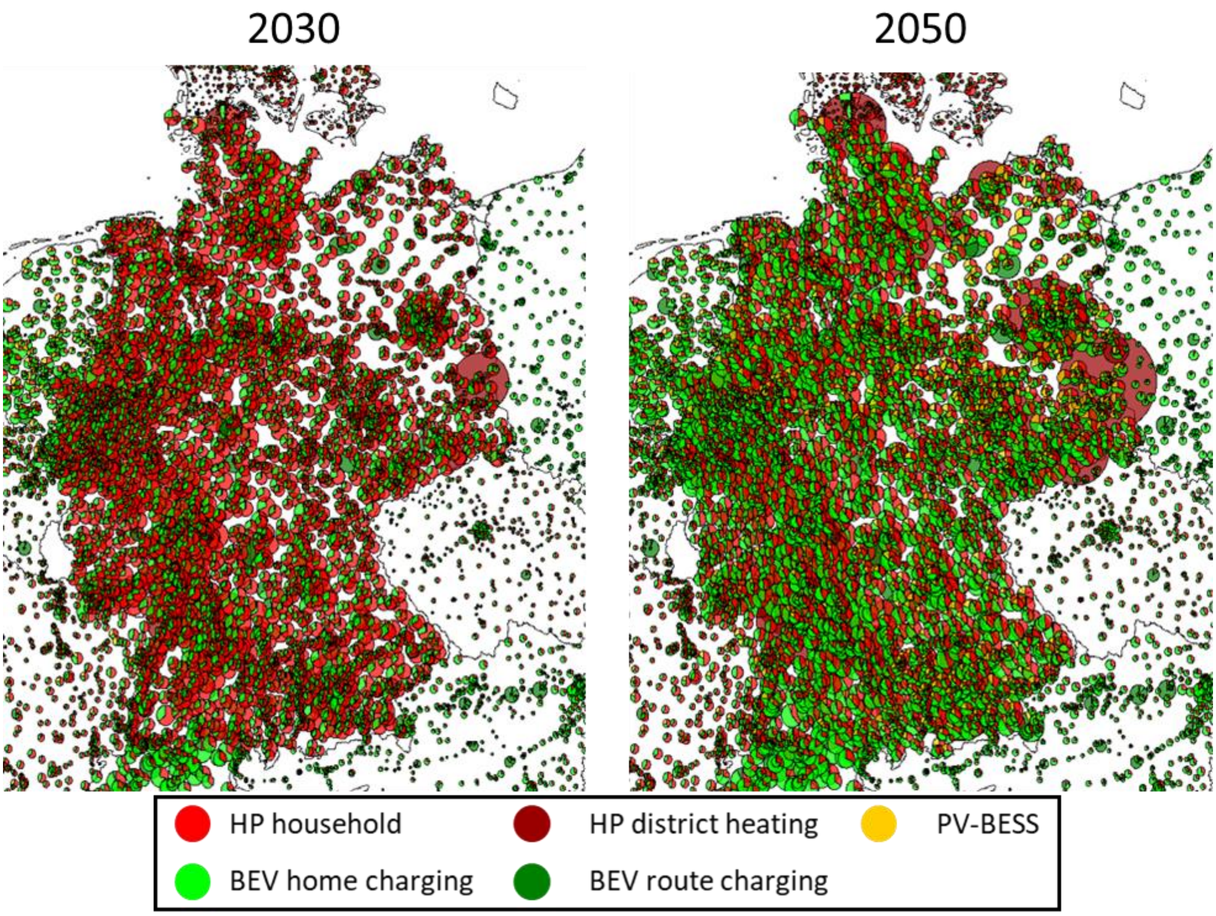

Figure 6: Regionalization of flexible demands of Storyline B in 2030 and 2050

4.2 Effects of the stochastic optimization of PV-BESS at distribution node level

The presentation of the effects of the stochastic optimization in the following focusses on the results of the year 2050 with higher PV-BESS capacities compared to 2030. In order to show the effect of PV-BESS operation at a single distribution grid node, we have identified one node with comparably high PV-BESS capacities. Figure 7 shows the respective generation of RES, demand from conventional and flexible consumers, and the generation and consumption of PV-BESS in one week of summer in 2050 for the four storylines. Additionally, residual load curves including and excluding the generation and consumption of PV-BESS are depicted to indicate the effects of PV-BESS.

As shown, the consumption of the PV-BESS in hours with high PV generation decreases the generation peaks, which could lead to lower curtailments that need to be done due to the high electricity generation from RES. Furthermore, the residual load gets closer to zero in the evening hours where PV-BESS are usually discharged, e.g., in storyline A in the hours 40 to 60. It can be seen that the generation of RES plus the generation of PV-BESS exceeds the electricity demand. Without the PV-BESS, the electricity demand was higher than the electricity generation from RES. This could potentially decrease the stress on the electrical system, depending on the rest of the system, of course.

However, in some hours, the generation from PV-BESS increases the excess of electricity generation from RES even further. See storyline D in Figure 7 at hours 100 to 120 as an example. The generation from PV-BESS increases the generation peak from wind energy even further. This might not be desired from a system point of view since other RES could have to be curtailed consequently. Nevertheless, whether or not electricity from RES has to be curtailed depends on the rest of the system as well. The increase in surplus electricity generation mainly occurs when there is a high generation from wind turbines in the evening hours when households preferably use the electricity in their storage.

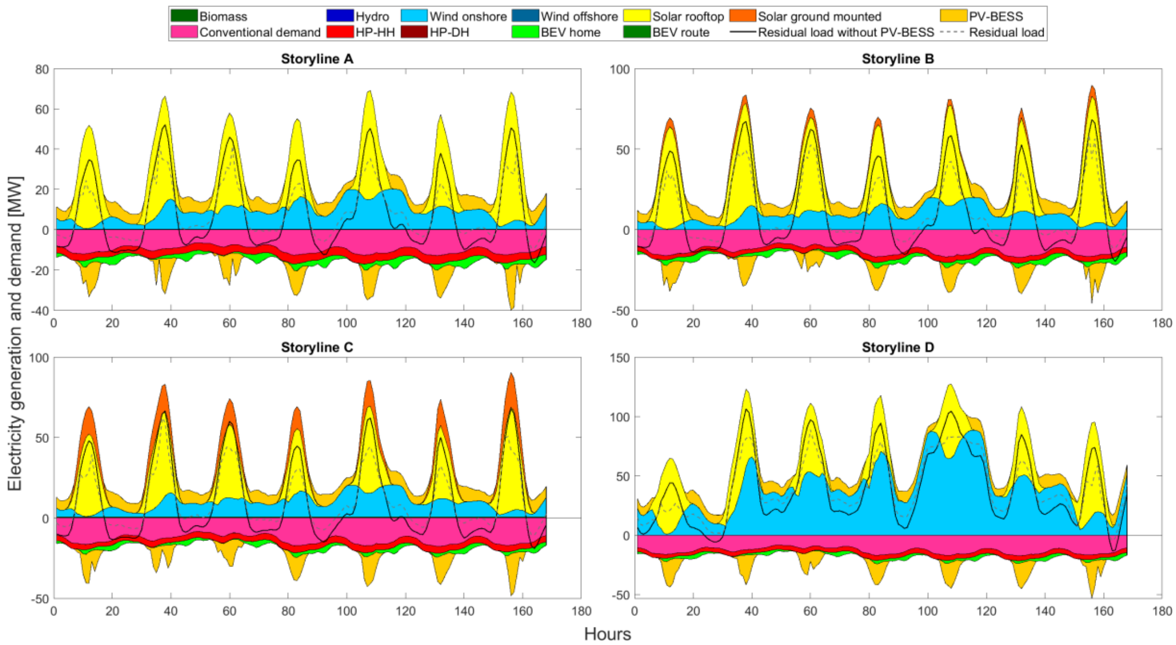

Figure 7: Renewable generation, demand, and residual load of one week in summer at one node in 2050

4.3 Impact on system level

In the last chapter, the question has been raised whether the increase in electricity surplus could result in higher curtailments of RES. In order to address this question, we show the generation and load profiles in the same week in 2050 in Figure 8 and Figure 9 for Germany and France, respectively. These countries were chosen due to their high share of PV-BESS compared to other countries.

As shown in Figure 8, in storyline D, in the hours 140 to 150, the generation of PV-BESS leads to a higher surplus of electricity compared to the case of no PV-BESS. From a system point of view, this can result in higher curtailments of RES in these hours if the electricity cannot be exported to other electrically connected countries. However, this effect is lower compared to the single distribution grid node. On the other hand, the operation of PV-BESS generation also lowers the peaks from PV generation, which can result in lower curtailments.

The amount of curtailed energy from RES is, of course, also dependent on the restrictions of the electrical grid. Therefore, it is not certain whether the operation of PV-BESS leads to additional curtailments in the hours of its generation.

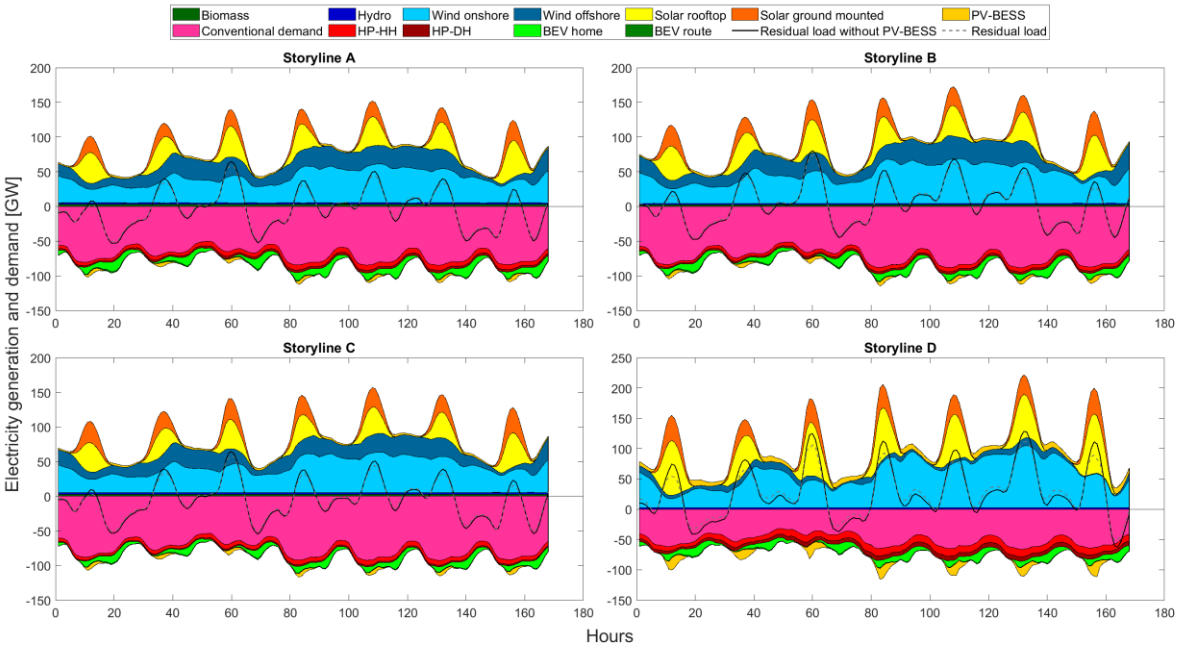

Figure 8: Renewable generation, demand, and residual load in the market area of Germany in 2050

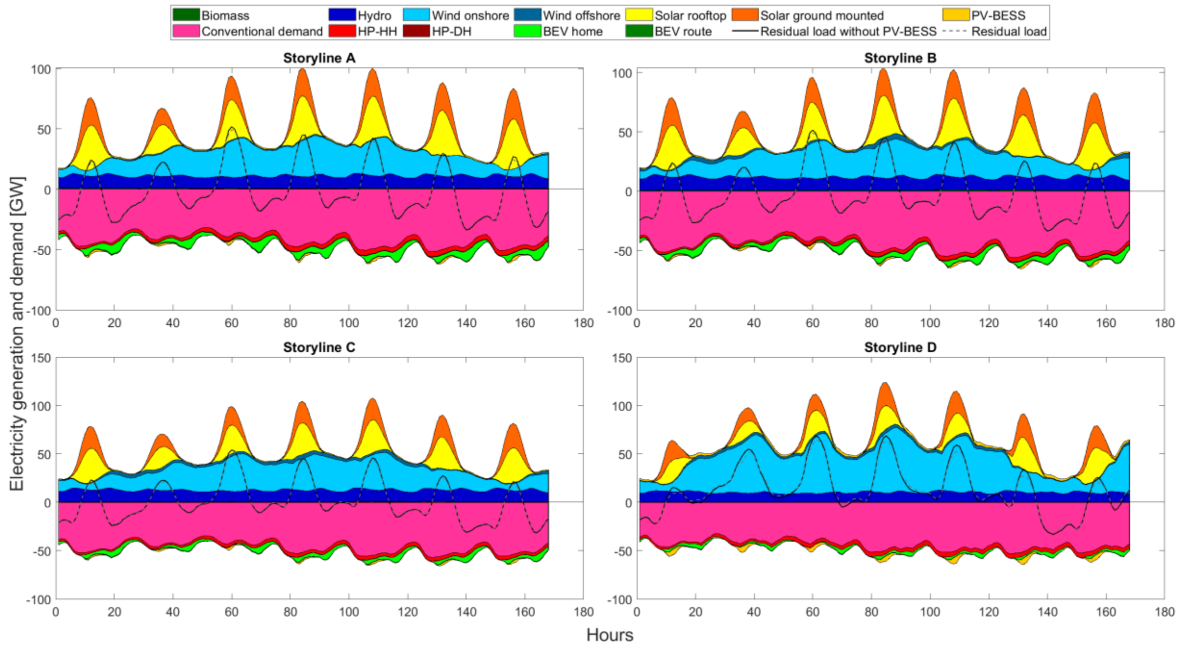

Figure 9: Renewable generation, demand, and residual load in the market area of France in 2050

To see the effects of PV-BESS on the whole year, we calculate the residual load of each hour and sort them in descending order. Figure 10 presents the resulting duration curves in 2050. In 2050, a shift in the duration curves can be observed. If we look e.g. at storyline D, the highest residual load decreases, as does the maximum negative residual load, i.e., the surplus of electricity from RES. Both of these observations imply an overall system improvement. However, the number of hours with a positive residual load decreases only slightly in all storylines.

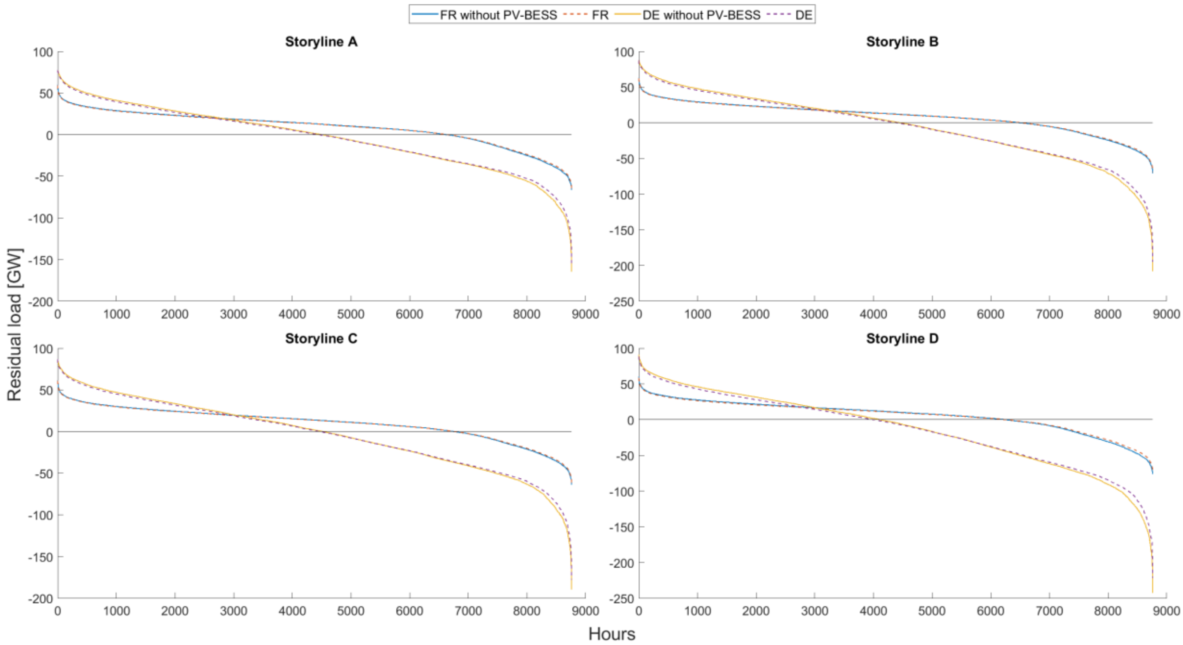

Figure 10: Sorted residual load duration curves of Germany and France in 2050

5 Conclusions and outlook

In this paper, we presented a two-step approach for the regionalization of flexible demands and the stochastic optimization of PV-BESS on the European level within a modelling framework for decentralized demand, flexibilities and renewables. Considering four storylines in the years 2030 and 2050, the impacts of PV-BESS is shown to improve the system behavior in a large number of hours. However, it is not always optimal from a system point of view. This is mainly because the PV-BESS often discharge in the evening hours when the demand of households is comparably high. This means that there might be additional surplus energy in hours with high production from other renewables, mainly wind turbines. However, it cannot be stated whether the surplus energy can be used or has to be curtailed. Other flexible options like Power-to-Gas might be able to make use of the electricity surplus. From the system point of view, PV-BESS can reduce the peak residual load while also decreasing the peak negative residual load. However, the PV-BESS affects the number of hours with either positive or negative residual load only slightly.

Since the demand from BEV and HP was not considered flexible in the evaluation, there is still the question of whether or not their flexibility and the flexibility of the PV-BESS could improve the balance of generation and demand. Especially in the 2050, the demand of BEV and HP is expected to be very high in all four storylines. Therefore, the potential benefit is high and should be investigated in future works.

Lastly, a sensitivity analysis of the storage volume of the PV-BESS could lead to further conclusions. Since the volume of the storage highly influences the generation and demand time spans of the batteries, it should be considered to re-evaluate the impact of PV-BESS considering different scenarios of average storage volumes and comparing the results.

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Annex A: Regionalization results of Storylines A, C, and D

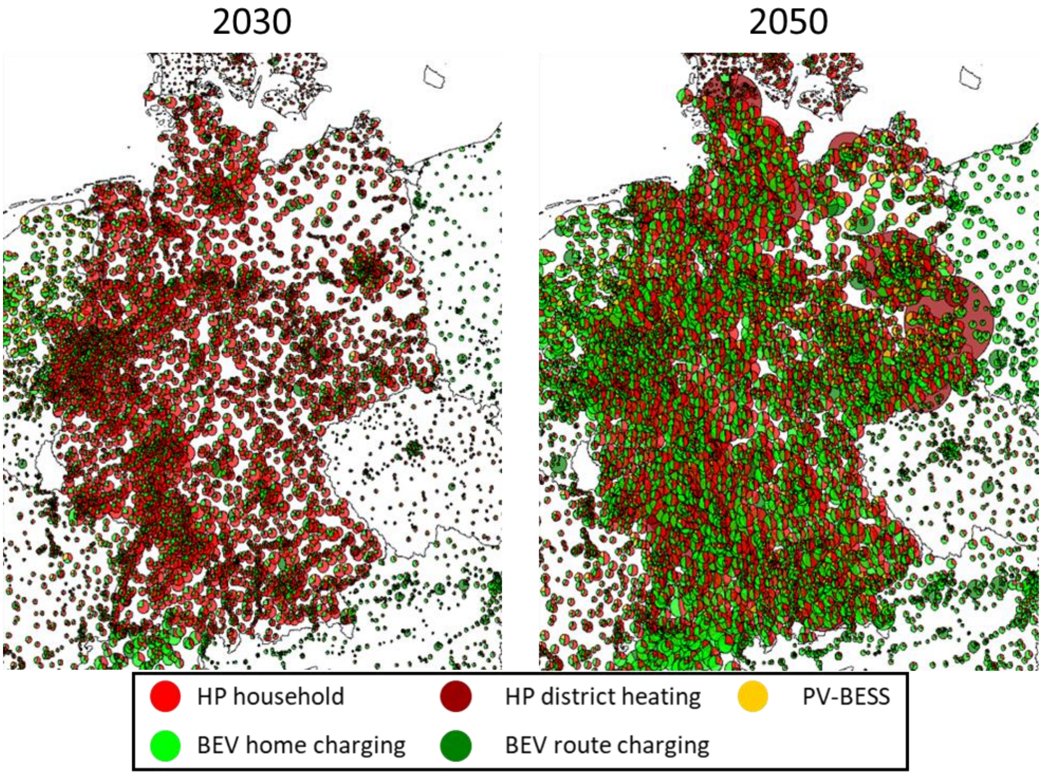

Figure 11: Regionalization of flexible demands of Storyline A in 2030 and 2050

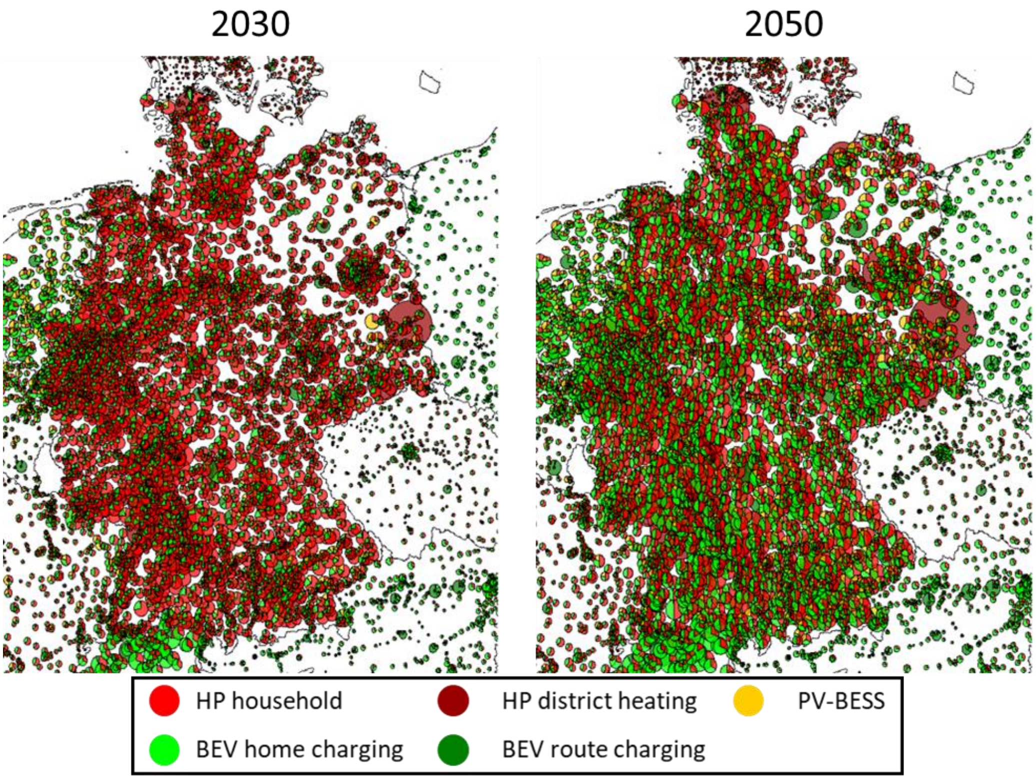

Figure 12: Regionalization of flexible demands of Storyline C in 2030 and 2050

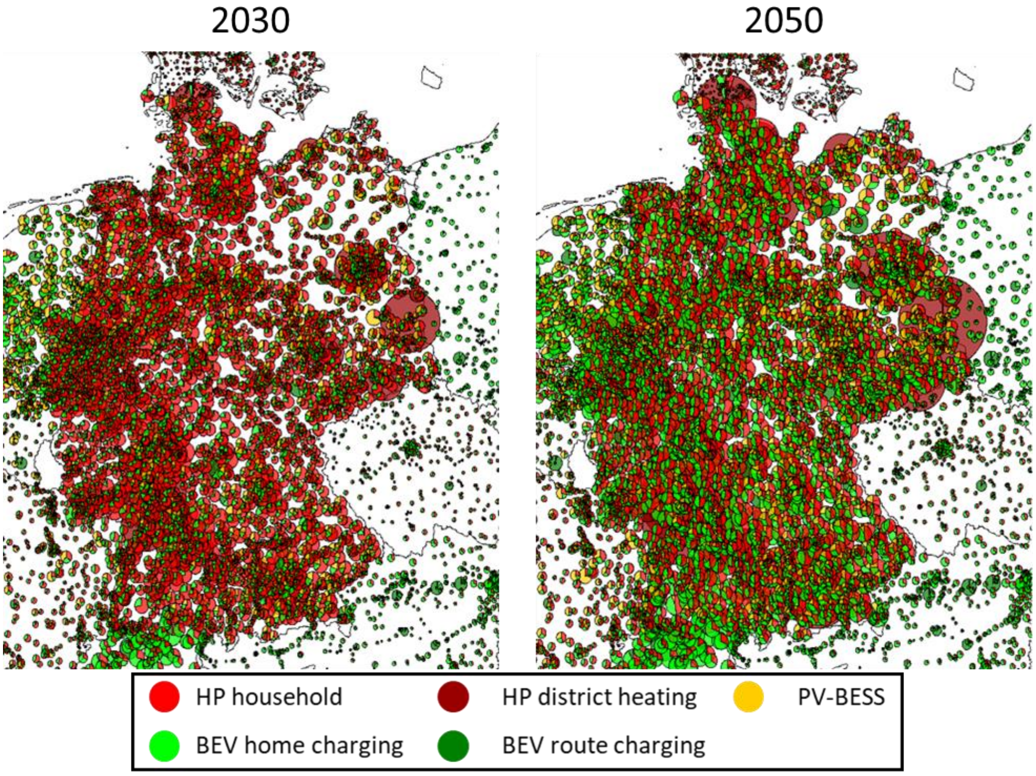

Figure 13: Regionalization of flexible demands of Storyline D in 2030