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Karlsruher Institut für Technologie (KIT)
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Band 12

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Decentralized Energy Systems, Market Integration, Optimization

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Executive Summary

The increasing electricity generation from renewable energy sources (RES) as a result of the German "Energiewende" leads to the expansion of distributed generation capacities of various technologies. This trend is expected to continue and causes major challenges for the traditional electricity sector, which originally was designed for large generation units and low fluctuation.

In this study we develop a flexible modeling toolbox for decentralized electricity systems with an agent-based simulation approach at its core. Two RES-E generation models for wind and PV each with a high temporal and spatial resolution are presented and approaches to model specific aspects of the demand side in detail are introduced. The implementation of an AC load flow algorithm is described and the concept of a market-based congestion management mechanism based on market price signals is outlined. Our main findings briefly summarize as the following:

- In order to decide if an available time series of renewable supply is useful for the analysis of decentralized energy systems, the gradients, maximum amplitudes and the spatial volatility of the input data is key. We develop three corresponding indicators measuring future input data: MARS; MGRS and spatial volatility.
- We present a methodology to simulate spatially and temporally correlated renewable supply time series. Our copula-based approach simulates irradiation at nine locations and reveals substantial differences to an approach simulating only one stochastic process.
- We evaluate the increasing stress on the electricity grid infrastructure through decentralization of renewable generation and a more flexible demand. Dynamic electricity prices down to the household level can lead to more or less congestion with the tariff setup being crucial to the results. In different systems, we find an increase in critical grid situations when RES-

E feed-in as well as demand flexibility is increased and the price signals are only based on wholesale market prices for electrical energy.

- When analyzing decentralized systems, the complexity strongly increases through the heterogeneity of stakeholders and the higher resolution of data. This challenges the application of optimization models, common in energy systems analysis and makes simulation approaches, as the agent-based simulation presented in this work, more and more promising.

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1 Challenges in decentralized electricity systems

With a share of 30 % of 2015's gross electricity production (Statistisches Bundesamt (DESTATIS) 2016) and targets of 40-45 % until 2025 and 55-60 % until 2035 (Bundesregierung 2015), respectively, Germany's electricity system is becoming more and more shaped by electricity produced from renewable energy sources (RES-E). While there are undeniable benefits, particularly in terms of greenhouse gas emissions, sustainability and dependency on fossil fuel imports, a visionary electricity system that makes extensive use of RES-E has to overcome several key challenges.

Electricity production from wind and solar energy is intermittent, thus changing the paradigm of an electricity system where, traditionally, demand had been considered as the main fluctuating factor and raising, for instance, the system's ramping requirements. Likewise, the installation of RES-E power plants drastically increases the degree of decentralization of electricity generation. While in the past, large conventional power plants dominated the electricity system, distributed generation means that electricity feed-in on lower voltage levels is rising. As a consequence, congestion in distribution grids and reversions of the power flow direction[1] become more frequent stressing the existing system. There are also some trends of an increasing spatial divergence between production and consumption in Germany. Moreover, together with the stronger involvement of the demand side in electricity markets, the system is getting more heterogeneous in terms of generators' and consumers' objectives, responsibilities and experiences. These developments are accompanied by a growing penetration and an improvement of automated smart systems.

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[1] In this context. "reversed" flow means electricity flowing from lower voltage levels of the grid to higher levels, opposed to the classical flow direction from power plants at high voltage levels to customers.

These trends will require considerable efforts, in order to operate and design future electricity systems in a reliable, economic and sustainable way. While a large body of literature focuses on the level of wholesale markets and high voltage electricity transmission, respectively, the analysis of challenges created in the operation of distribution networks and the design of decentralized solutions for an optimal integration of RES-E are less focused in current research. However, a comprehensive and system-wide approach considering the interactions between decentralized electricity systems and centralized markets is needed to provide valid analyses and decision support for shaping flexible and smart electricity systems with a high RES-E feed-in.

Within the scope of this research project, we study in the context of the German "Energiewende" the impact of different developments on the operation and design of future electricity systems, thereby, focusing on decentralized electricity systems. Given the underlying complexity, we focus on the following research issues in the domain of energy systems analysis. In the course of an increasing RES-E generation, it is essential to describe its temporal and spatial fluctuations as well as to explore how a rising volatile feed-in can affect the load flow in distribution networks and increase grid-related curtailment. On the other hand, demand-side flexibility is seen as a decentralized approach to support the integration of RES-E. However, the way demand flexibility, retail tariffs and corresponding price signals might alter the load flow in distribution networks is yet another novel factor in operating electricity systems. These developments are expected to increase the need for congestion management and to change its requirements. A decentralized organization of flexibility might prove as one potential solution to maintain a secure and economically efficient electricity supply. Relevant interactions between centralized and decentralized system layers are to be addressed as the analysis and design of electricity systems need to be based on comprehensive approaches.

Against this background, several specific objectives are formulated. Firstly, from a methodological point of view, the project aims at developing an appropriate model framework for studying distribution networks in the form of a flexible toolbox. At the core, an existing agent-based simulation model is extended. For the mentioned key factors (e.g. fluctuating RES-E feed-in, demand flexibility), specific methods are to be developed and implemented in the context of the agent-based model framework. Secondly, we need to collect and process necessary data on the level of decentralized electricity systems. Within the project, one illustrative decentralized system in Germany, namely "Schleswig-Holstein", and its integration in the corresponding wholesale market is simulated. Thirdly, we apply the model framework within several specific case studies focusing on the research issues addressed above in order to give new insights into the operation and design of future electricity systems. Finally, the model development process and in particular the case studies are used to derive recommendations for stakeholders and future research issues.

This report is structured in the following way (Figure 1): After briefly discussing general approaches to model electricity systems in Section 2, the modeling toolbox for decentralized electricity systems with an agent-based simulation approach at its core is proposed in Section 3. Major model developments are described in detail. Section 4 presents the data requirements in general and the data collection process for the illustrative decentralized electricity system in Germany. The results from several case studies using the developed simulation model or parts of it are highlighted in Section 5. The report concludes with recommendations for stakeholders and future research issues.

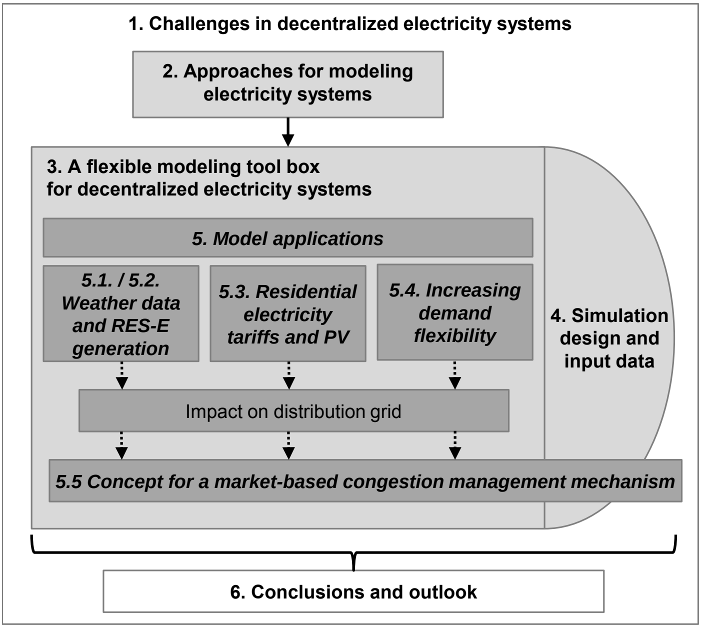


Figure 1: Overview of the project report structure

2 Approaches for modeling electricity systems

In order to analyze the research issues put forward in Section 1 an appropriate modeling approach is required. Electricity systems comprise all technologies and institutional arrangements which are necessary and implemented in reality in order to supply consumers with electrical energy. In general, such systems are considered to be very complex, due to the different techno-economic parameters, the diversity of stakeholders, the high societal value of electricity supply and interactions within the electricity system itself as well as with other systems (e.g. fuel or heat markets). Given this project's focus on potential interactions within liberalized electricity spot markets and decentralized systems, the research design needs to consider relevant market operations, the behavior of certain players and physical constraints of the distribution grid.

2.1 Energy systems analysis

Energy systems analysis is a comprehensive discipline which considers restrictions, dependencies and developments of complex energy systems in a structured, methodological way. Objectives of energy systems analysis can include describing a system, explaining the effects of different frameworks, identifying optimal pathways and, ultimately, providing structured support for decision making in the energy system. As such, energy systems analysis is an essential tool in the field of energy economics. At the center of energy systems analysis, there are the development, implementation and application of a mathematical-computational model representing the relevant features of the energy system under consideration.

In the last decades, different approaches to model electricity systems have been developed. A general distinction between optimization and simulation models can be made (see e.g. Ventosa et al. (2005), Foley et al. (2010), Möst und Keles (2010) and Pfenninger et al. (2014) for more detailed reviews). Traditionally, electricity systems have been strongly centralized and regulated, which is why optimization models have been in use for many decades for modeling electricity systems. The transition to a liberalized and more decentralized system is profoundly changing the operation of electricity systems. For instance, the increasing fragmentation of electricity generation raises the relative importance of smaller players with heterogeneous motivations. Consequently, given the ever-changing environments in electricity systems, innovative and adapted methods for studying electricity systems are required in order to provide adequate decision support.

In response to these developments, agent-based modeling and simulation (ABMS) as a suitable modeling approach for complex, socio-technical problems in general (e.g. Bonabeau 2002) has frequently been applied in the past years to study electricity systems and markets in particular (e.g. Ventosa et al. 2005). ABMS is generally able to represent interactions and dependencies in an economic, technical and social context (e.g. Tesfatsion 2002). So far, the main focus of ABMS techniques in the field of electricity systems has been on wholesale electricity markets (e.g. Sensfuß et al. 2007; Weidlich und Veit 2008; Guerci et al. 2010). This includes the PowerACE model, an agent-based simulation for electricity wholesale spot markets (e.g. Sensfuß et al. 2008), which is applied and extended in this research project. Nevertheless, there is a growing body of literature using ABMS for analyzing decentralized electricity systems as well. These studies tackle issues related to demand response, distributed generation and distribution grid modeling as well as local markets and their integration in centralized markets (e.g. Zhou et al. 2011; Dave et al. 2013; Chassin et al. 2014). A detailed literature review on ABMS of smart electricity grids and markets is given in Ringler et al. (2016).

In the context of this project, ABMS is understood as a flexible and efficient tool to simulate and analyze realistic electricity systems subject to various techno-economic restrictions in detail. The focus of the proposed methodology is on decentralized structures in electricity systems (e.g. distributed generation, distribution networks).

2.2 Agent-based simulation in PowerACE

The PowerACE model, an agent-based, bottom-up simulation model for wholesale electricity markets, forms the core of the modeling toolbox used in this project. Originally, the model was developed in order to simulate and study novel developments in the German electricity market mainly on the level of wholesale markets. For instance, the effects of electricity generated from RES-E on spot market prices (Sensfuß et al. 2008), the impact of introducing the EU Emissions Trading System on investment decisions (Genoese et al. 2007) as well as the existence of market power (Möst und Genoese 2009) were analyzed. More recent model extensions include the integration of uncertain parameters (Bublitz et al. 2014), the analysis of generation adequacy in interconnected electricity markets (Ringler et al. 2014) and the evaluation of different wholesale market design options (Keles et al. in press).

Within the model, major generation companies are represented by individual software agents thereby emulating the industry structure in the market area under consideration. Given their practical relevance, the model's focus is on the simulation of spot markets for electricity and in particular on the conventional power generation side. The simulated spot market is also the main interface between the existing PowerACE model and the extensions developed in this project. In each time step of the simulation, a spot market, which is set up as an auction with hourly delivery contracts, is cleared based on the agents' bids. Conventional power plants are offered on the spot market on a plant-by-plant basis by considering marginal costs including start-up costs as well as a potential scarcity mark-up; the other determinants of supply and demand are pooled for the respective market area (e.g. end-user demand, RES-E feed-in). Subsequently, the spot market operator clears the market by intersecting the aggregated demand and supply curves. At the end of each simulation year, investment options with regard to conventional power plants are evaluated based on the net present value criterion.

The main endogenous results of the PowerACE model include hourly spot market prices, the evolution of the power plant fleet and the development of carbon emissions in the electricity sector. Provided that input data is available, the simulation can be performed up to the year 2050 by repeating the simulation of the spot market and the investment planning. The model is implemented in Java and linked to a MySQL database.

The PowerACE model for wholesale electricity markets represents the starting point for this project. The existing model version is able to simulate the centralized clearing of energy markets with a high temporal resolution and thus provides the basis to dispatch generation and demand units. An established database for the German electricity system connected to the model facilitates approaching the research objectives. The implementation in Java of PowerACE offers a high technical flexibility.

3 A flexible modeling toolbox for decentralized electricity systems

In order to address the project's research issues the PowerACE model is extended in several ways. The key development is the integration of decentralized electricity systems into PowerACE in order to analyze the load flow in distribution grids and potential interactions with centralized markets. The model extensions have been designed in a way which allows using them within the market simulation or on a stand-alone basis. Furthermore, additional models for specific applications are developed outside the agent-based framework which could be integrated into PowerACE in future projects. Together, the existing PowerACE model and the extensions presented in this report form a flexible toolbox for analyzing distribution systems of different scales. In this section, we present key aspects of the overall simulation framework as well as of the individual extensions.

3.1 Overview of modeled decentralized electricity systems

The modeled decentralized systems are always considered as a subsystem of the high-level market area simulated in the centralized PowerACE model. Consequently, there is an overlap from a geographical and also from an institutional point of view, e.g. local electricity demand needs to be satisfied by buying electrical energy on centralized markets.

The key for analyzing decentralized systems is their representation in the most detailed way possible. Particularly, we consider electricity generation from RES-E (Section 3.2) and electricity demand (Section 3.3). Within the decentralized systems a load flow calculation for the distribution grid on the considered voltage level is performed in each time step as part of a congestion management (Section 3.4).

The decentralized systems are described on different layers. While the physical layer comprises all data on generation and demand as well as the considered grid elements, the market layer represents institutional arrangements for trading electricity. Different software agents link the layers by considering technical aspects of the system and by taking part in electricity markets.

With regard to the considered agents, there is a general distinction between market and basic agents. While the latter are merely operators of the represented physical units (e.g. demand unit, conventional power plant), market agents take part in electricity markets by buying or selling electricity. Different agent constellations are possible. For instance, conventional generators are both a basic agent and a market agent. In the case of households, it is assumed that specific aggregator agents, typically utilities, carry out the market operations.

The decentralized electricity systems and the centralized simulation environment are linked first and foremost via the spot market. Decentralized market agents take part in the spot market simulation by submitting respective bids. For the market clearing, the bids from the considered decentralized systems as well as from the remaining market area are relevant. Based on the results, the units in the decentralized systems are dispatched (Figure 2). From a programming perspective, using the existing Java interfaces and classes for the spot market implementation ensures the consistent coupling of the systems and modules, respectively.

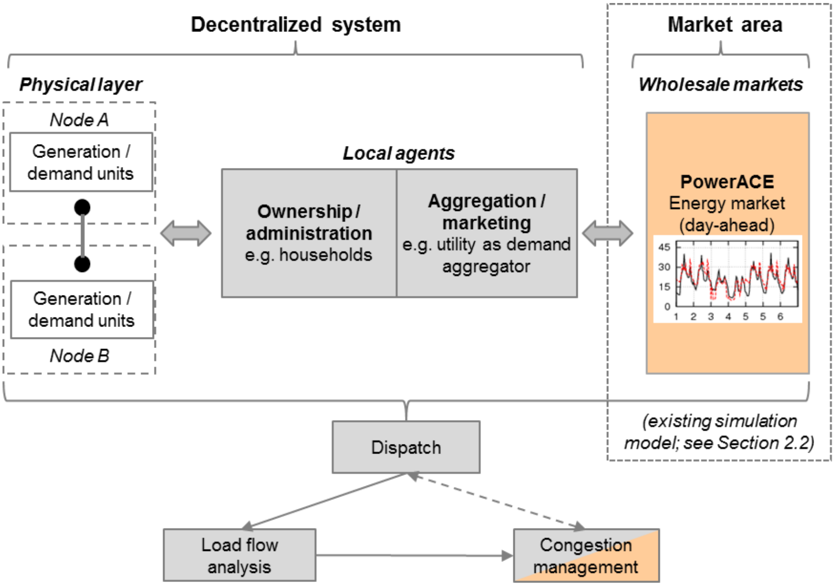


Figure 2: Overview of the extended PowerACE simulation framework

The integrated simulation follows in each hour several steps in order to determine the state of the decentralized system (see also Section 5.5):

- Basic agents determine their instantaneous electricity demand or supply. Necessary time series data may be given exogenously or determined endogenously depending on the simulation settings (see e.g. Section 3.2 for a time series generator of RES-E feed-in). Alternatively, agents express their willingness to buy and sell electricity, respectively, through market operations. For instance, conventional generators formulate market bids to sell electricity based on the available generation capacity and marginal costs.
- On this basis, market agents submit corresponding bids to the centralized spot market after being called by the market operator. This step is performed by all market agents in the decentralized system as well as by any remaining centralized agents.

- After the market clearing, the dispatch of all physical units in the respective decentralized system is determined. The responsible balancing group managers inform the distribution system operator (DSO) about the planned operations of the units.
- Subsequently, the DSO uses this information to calculate the expected load flow within the analyzed distribution grid and performs an evaluation with respect to potential congestion events in the system.
- If necessary, different types of congestion management methods can be activated and compared. The difference of the management approaches can lie in the spatial resolution of the DSO's actions regarding the regulation of generation and demand units or in the range of flexibility options available (e.g. exclusively RES-E curtailment or additional demand-side management).
- The developed simulation model can be applied in order to study the effects of different developments in decentralized electricity systems as well as in the market area on agent behavior, on the dispatch of units and on the load flow results in the represented decentralized systems. In the following subsections, several major developments, namely the simulation of RES-E electricity generation profiles, the representation of electricity demand and a module for load flow analysis, are presented in more detail.

3.2 Electricity generation from wind and PV

When modeling electricity systems subject to transmission and distribution restrictions, it is relevant to determine where RES-E is generated within the grid infrastructure. This section deals with the challenges to generate RES-E feed-in profiles with a high temporal and spatial resolution. General input data for the implemented approaches includes power plant information on the one hand and weather data on the other hand (see also Section 4):

- Technology-specific plant data
  - Wind: hub height, installed turbine, installation date
  - Photovoltaics (PV): net capacity, technology, module inclination, azimuth, installation date

- Weather time series data regarding wind speeds (m/s), solar irradiation (W/m²) and temperature (K), each on a 20 km x 20 km raster with a 10-minute resolution

The modeling of electricity generation basically consists of two steps:

- Preprocessing of the weather data
- Application to the generation model

3.2.1 Preprocessing of weather data

Typically, available weather data has to be transformed before using it as input for a generation model. The required input data depends on the specific generation technology (wind or PV) currently simulated.

Wind speed

The preprocessing for the wind generation model applies to the wind speed and the air density (derived from air temperature and pressure). In this study, wind speed data is available for heights of 70 m and 120 m above ground level while hub heights of actual wind power plants range from 30 m (e.g. Vestas V27, installed in 1994) to 123 m (e.g. Senvion 3.2 M114, installed in 2012). Since the power curve which transforms wind speeds to power output refers to wind speeds at hub heights, we adjust the given wind speed data for the height difference applying a logarithmic height correction (Hau 2012):

$$v_{hub} = v_{data} \cdot \frac{ln\left(\frac{h_{hub}}{z_0}\right)}{ln\left(\frac{h_{data}}{z_0}\right)}$$

v	Wind speed at hub height (hub) and at height above ground level available in the dataset ($data$) [m/s]
h	Hub height (hub) and height above ground level available in the dataset ($data$) [m]
z_0	Roughness length [m]

Air density

Wind power plants convert kinetic energy from air in motion. Therefore, the air density plays an important role for the amount of energy that can be converted to electricity. Furthermore, the relation between wind speed and power output of a specific wind power plant model is mostly given at standard atmosphere conditions. Therefore, it is necessary to account for a difference in air density between the input weather data and standard conditions. To calculate the air density at a given time step we apply the following formula (Molly 1990):

$$\rho_L = \rho_0 \cdot \frac{T_0}{t} \cdot \frac{p}{p_0}$$

p	Pressure [Pa]
t	Temperature [°K]
ρ_0	Density at standard conditions ($\rho_0 = 1.225\ kg/m^3$)
T_0	Temperature at standard conditions ($T_0 = 288.15°K$)
p_0	Air pressure at standard conditions ($p_0 = 1013.3\ hPa$)

The temperature is available at the two heights 70 m and 120 m mentioned above and interpolated or extrapolated to hub height. Since we have no information on air pressure, we hold the atmospheric pressure constant at standard conditions.

Solar irradiation

The preprocessing of weather data for the PV generation model applies to the solar irradiation data that is available as global irradiation on a horizontal plane (I_{glob}). Two steps are required to determine the irradiation on an inclined module (I_{module}). Firstly, the global incoming irradiation is divided into direct ($I_{dir,hor}$) and diffuse ($I_{diff,hor}$) irradiation on the horizontal plane and, secondly, these irradiation components are transformed to the incoming direct irradiation (I_{dir}), diffuse irradiation (I_{diff}) and reflectance (I_{refl}) on the inclined plane of the PV module.

Both the calculation of the irradiation at the horizontal plane and the translation to the irradiation at the inclined PV module require a formulation of the position of the sun relative to the module's location. The sun's position can be described fully deterministically by the solar altitude angle γ_S and the solar azimuth α_s. It is a function of time, both within the year and within the day, and also of the latitude and longitude of the PV module's location. The necessary calculations on the sun's position were adopted from Spencer (1971), Duffie und Beckman (2013) and Quaschning (2015) and will not be described in detail here. Applying the solar altitude and the clearness index, the diffuse irradiation on the horizontal plane $I_{diff,hor}$ can be estimated according to Reindl et al. (1990) as follows:

$I_{diff,hor}$ **Diffuse horizontal irradiation**, diffuse irradiation on a horizontal plane that was deflected before and is not arriving directly from the sun (Reindl et al. 1990):

$$I_{diff,hor} = \begin{cases} I_{glob} \cdot (1.020 - 0.254 \cdot k_T + 0.0123 \cdot sin\,\gamma_S) \mid k_T \leq 0.3 \\ I_{glob} \cdot (1.400 - 1.749 \cdot k_T + 0.177 \cdot sin\,\gamma_S) \mid 0.3 < k_T < 0.78 \\ I_{glob} \cdot (0.486 \cdot k_T - 0.182 \cdot sin\,\gamma_S) \mid k_T \geq 0.78 \end{cases}$$

I_{glob}	Global irradiation on a horizontal plane [W/m²]
γ_S	Solar altitude angle [°]

k_T Clearness index, proportion of total terrestrial and extraterrestrial irradiation on a horizontal plane [-] (calculated as in Quaschning 2015)

Since there is no reflection from the earth's surface to a horizontally orientated plane, the direct irradiation can simply be calculated as the remaining difference to the global irradiation:

$$I_{dir,hor} = I_{glob} - I_{diff,hor}$$

Having calculated both direct and diffuse irradiation on the horizontal plane, we derive the irradiation shares on an inclined module as follows:

I_{dir} **Direct irradiation**, beam irradiation on an inclined plane, incoming directly from the sun without deflection (Quaschning 2015):

$$I_{dir} = I_{dir,hor} \cdot \frac{cos\,\theta_m}{sin\,\gamma_S}$$

θ_m Irradiation incidence, the angle between incoming direct irradiation on a surface and the surface's normal vector [°]

$$\theta_m = \arccos(-\cos\gamma_S \cdot \sin\gamma_m \cdot \cos(\alpha_s - \alpha_m) + \sin\gamma_S \cdot \cos\gamma_m)$$

α_m Module azimuth, the direction of the module surface in horizontal direction (South=0°, West=90°, North=180°, East=270°)

I_{diff} **Diffuse irradiation**, diffuse irradiation on an inclined plane (Klucher 1979):

$$I_{diff} = I_{diff,hor} \cdot \frac{1}{2} \cdot (1 + cos\,\gamma_m) \cdot \left(1 + F \cdot sin^3 \frac{\gamma_m}{2}\right) \\ \cdot (1 + F \cdot cos^2\,\theta_m \cdot cos^3\,\gamma_S)$$

F Parameter comparing diffuse and total irradiation on horizontal plane

$$F = 1 - \left(\frac{I_{diff,hor}}{I_{glob}}\right)^2$$

I_{refl} **Reflected irradiation**, irradiation reflected from the earth surface and incoming at the module plane (Quaschning 2015):

$$I_{refl} = I_{glob} \cdot A \cdot \frac{1}{2} \cdot (1 - \cos(\gamma_m))$$

Finally, the incoming irradiation at module level amounts to the sum of these irradiation shares:

$$I_{module} = I_{dir} + I_{diff} + I_{refl}$$

The irradiation at module level is the most important input factor to a PV generation model, because it determines the fluctuating character of the generation time series of a PV plant. The next section will summarize how to calculate generation profiles applying the irradiation time series at module level.

3.2.2 Electricity generation models

Wind power generation model

Having calculated the wind speed at an arbitrary hub height and corrected it for changes in density, the wind speed time series can be transformed to a time series of wind power generation applying the wind turbine's power curve. The power curve is a function of the wind speed at hub height and represents the relationship between the power generation of a wind turbine and the prevailing wind situation.

PV power generation model

The detailed preprocessing of irradiation data allows the representation of quite individual PV plant configurations. Our approach to calculate the power output of a PV plant features several additional modeling stages considering multiple aspects of PV plant configurations. In the following, we summarize these steps for calculating the generation profiles and give literature references for a more detailed representation.

The power generation of a PV plant P_{PV} is modeled as a function of the following parameters:

$$P_{PV} = \eta_{inverter} \cdot P_{module} \cdot corr \cdot deg$$

$P_{module}(P_{rated}, I_{module}, I_{STC}, \eta_{module}, T_{module})$: Electricity output of a PV module [W]

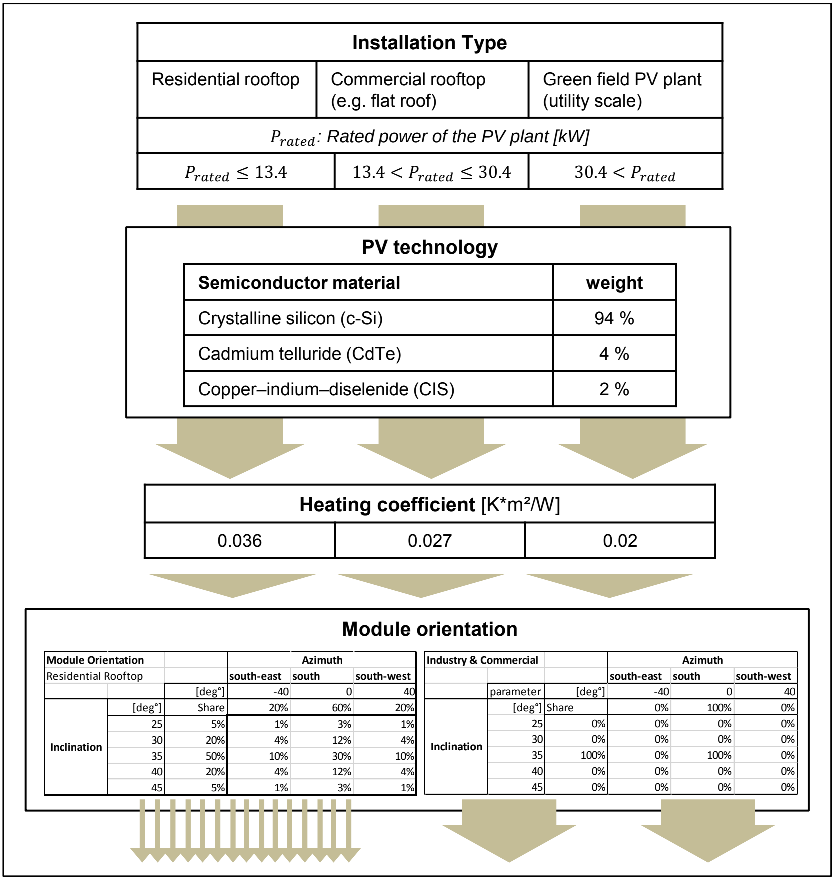
P_{rated}	Rated generation capacity of the PV module [W]
I_{module}	Irradiation on module level [W/m²]
I_{STC}	Irradiation at standard test conditions (1000 W/m²)
η_{module}	Relative module efficiency [-]
T_{module}	PV module temperature [K]

$\eta_{inverter}(P_{rated}, P_{lossInv}, P_{module})$: Inverter efficiency [-]

$corr$ Correction parameter to include losses from:
Mismatching (variation of module capacity in serial connection): $m = 5\ \%$

Reflection from module surface: $r = 2.5\ \%$
Dirt: $d = 2\ \%$
Losses prior to inverter: $c = 0.2\ \%$
$corr = (1 - d - r) * (1 - m) * (1 - c) = 0.905$

deg Degradation (0.5 % per year) lowering the maximum power output over time
$deg = 1 - (0.005 * age[in\ years])$



Installation Type		
Residential rooftop	Commercial rooftop (e.g. flat roof)	Green field PV plant (utility scale)
P_{rated}: *Rated power of the PV plant [kW]*		
$P_{rated} \leq 13.4$	$13.4 < P_{rated} \leq 30.4$	$30.4 < P_{rated}$

PV technology

Semiconductor material	weight
Crystalline silicon (c-Si)	94 %
Cadmium telluride (CdTe)	4 %
Copper–indium–diselenide (CIS)	2 %

Heating coefficient [K*m²/W]		
0.036	0.027	0.02

Module orientation

Module Orientation			Azimuth		
Residential Rooftop			south-east	south	south-west
		[deg°]	-40	0	40
Inclination	[deg°]	Share	20%	60%	20%
	25	5%	1%	3%	1%
	30	20%	4%	12%	4%
	35	50%	10%	30%	10%
	40	20%	4%	12%	4%
	45	5%	1%	3%	1%

Industry & Commercial			Azimuth		
			south-east	south	south-west
	parameter	[deg°]	-40	0	40
Inclination	[deg°]	Share	0%	100%	0%
	25	0%	0%	0%	0%
	30	0%	0%	0%	0%
	35	100%	0%	100%	0%
	40	0%	0%	0%	0%
	45	0%	0%	0%	0%

Figure 3: Overview of the assumptions with regard to the considered options for PV module configuration resulting in 17 different module configurations

The parameterization of the losses is adopted from Schubert (2012) and shall reflect effects that reduce the electricity generation of a PV module not yet covered in our physical modeling approach described above. The function on how to aggregate the loss parameters to determine the correction parameter $corr$ is based on our own assumptions. These correction parameters are neither constant over time nor equal for different modules but should reflect the average losses quite well. The degradation parameter deg covers the decreasing performance of PV modules when aging. We apply a linearly degradation which decreases the module efficiency by 0.5 % per year based on Osterwald et al. (2006).

The calculation of the module's power output before losses and correction parameters P_{module} is calculated following Huld et al. (2010). The inverter efficiency $\eta_{inverter}$ is derived from Schubert (2012) and Macêdo und Zilles (2007). The assumptions with regard to configuration details of the PV plant form essential parts of the generation model. The ability of a PV plant to generate power is a function of numerous parameters of which we cover the following ( ):

- PV technology: A major factor for a PV module's efficiency is the implemented technology which can be characterized by the chosen semiconductor material (see Huld et al. 2010). We take three different technologies, namely crystalline silicon, cadmium telluride, copper-indium-diselenide, into account and calculate the module's efficiency after Huld et al. (2010). The market shares of the technologies are adopted from Schubert (2012).
- Heating coefficient: The way how a PV module is mounted determines the heat exchange of the module with its environment. Following Drews et al. (2007), we differentiate three installation types that heat up differently when exposed to irradiation.
- Module orientation: We assume that there are no tracking PV modules, which means that the orientation of all modeled PV plants is fixed. Each module's orientation influences the incoming irradiation to a large extent. Based on calculations by Suri et al. (2007) with regard to optimal module orientation, we assume a module orientation of 0° azimuth (south facing) and 35° inclination as optimal. PV modules of the installation types "commercial rooftop" and "green field PV" are modeled with this optimal orientation. For the installation type "residential rooftop" we apply a Gaussian-like distribution around this optimum resulting in 15 different module orientations.

The above described wind and PV electricity generation models are implemented in a way which allows the user to select a temporal and spatial resolution appropriate for the respective analysis, only bound by the actual model input (Section 4). Most of the analysis in this work is done at a temporal resolution of 15 minutes using 10-minute raw weather data as input. The spatial resolution of the wind and PV generation is partly based on exact locations of the plants and partly aggregated on the level of municipalities (see also Section 4.2).

3.3 Demand-side modeling

In current electricity systems, demand flexibility is considered to be low, i.e. most consumers have little incentives and possibilities, respectively, to change their common consumption behavior. However, there is long-ongoing research that a higher flexibility of demand could help to reduce the need for peak-load generation capacities, to limit investments in transmission and distribution networks as well as to support the overall integration of RES-E in electricity systems (e.g. Strbac 2008). One way to increase demand flexibility is through demand response programs, of which dynamic end-user electricity prices are one option. These prices would be aligned to wholesale electricity prices and, therefore, implicitly also to the RES-E feed-in. The price elasticity of electricity demand is one way to express the sensitivity of electricity consumers to prices (e.g. Lijesen 2007). In this context, methods to analyze the potential and the effects of demand flexibility need to be developed (e.g. for business development, in the context of energy systems analysis).

Analogous to the electricity generation from RES-E in decentralized systems, modeling electricity demand requires a similar temporal and spatial resolution. For that purpose, several approaches are carried out in this research project in order to generate adequate input data on the one hand and to simulate an appropriate (market) behavior considering price elasticities as well as different tariffs on the other hand. In this context, the following paragraphs describe two selected aspects: firstly, a newly developed bottom-up load model for residential electricity demand (Section 3.3.1) and, secondly, an approach how to consider price elasticity of demand in the spot market simulation (Section 3.3.2). Additionally, Section 4.2 of this report specifies briefly how demand data for different consumer groups is estimated from statistical figures. Following the general model setup, the different modules can be activated and combined in a flexible manner.

3.3.1 Bottom-up load model for residential electricity demand

Standard load profiles, frequently used by utilities and modelers today, do not explicitly consider potential impacts caused by different tariffs and by the heterogeneity of consumers. Therefore, a new bottom-up load model for residential electricity demand is developed. The approach intends to generate weekly load profiles with a 15-minute resolution for a portfolio of heterogeneous households. Repeated model applications allow the creation of profiles for longer horizons, e.g. for one year (Hayn et al. 2014a).

The comprehensive model framework offers several features. Firstly, load profiles for different household types varying by size and by their equipment with electrical appliances can be generated. In total, the model integrates around 15 different types of appliances and offers additionally the opportunity to include residential PV systems for self-consumption. Secondly, appliances are differentiated according to whether and how they are available for load shifting by the user. In general, only appliances with a thermal storage (e.g. fridges, heating and hot water systems) or with flexible starting times (e.g. washing machines, dish washers) provide demand flexibility. Furthermore, a distinction is made between automatic price reaction by "smart" appliances and manual shifting. Each appliance is characterized by a simplified load profile, a household-specific peak load and an average utilization rate. Thirdly, the model reflects the reaction of households to external signals in the form of either variable energy prices or variable capacity prices indicating shortage situations in the electricity system. Both types of signals are determined externally by the electricity supplier.

From a methodological point of view, the model combines simulating and optimizing methods. Initially, the utilization of all installed appliances is simulated for the specific week and each household using the respective input data. In case of variable energy prices being provided to the household, a minimization of energy costs is intended by adapting the utilization of appliances according to the received price signals. Under variable capacity prices, the optimization should guarantee that a pre-defined capacity limit is not breached. A combination of both tariff designs, variable energy and variable capacity prices, is possible. The corresponding mixed integer linear optimization problems are formulated in Hayn et al. (submitted).

The overall modeling process consists of several steps (Figure 4). After reading input data and initializing the set of households, the initial load profile is simulated. By aggregating the power consumption of each appliance in every time step of a week, each household's total load profile can be constructed which reflects the behavior under a tariff with a fixed energy price. A more detailed description of this submodule can be found in Hayn et al. (2014b). Subsequently, the optimization problems with respect to the appliances’ utilizations according to the owned tariff, potential PV system and share of manual load shifting are solved. In case of variable energy prices the optimization is done for each appliance over the respective week; in case of variable capacity prices only selected situations with expected shortages announced by the supplier are considered and optimized as a whole. Eventually, solving the optimization problems will typically lead to an update of the previously simulated load profiles.

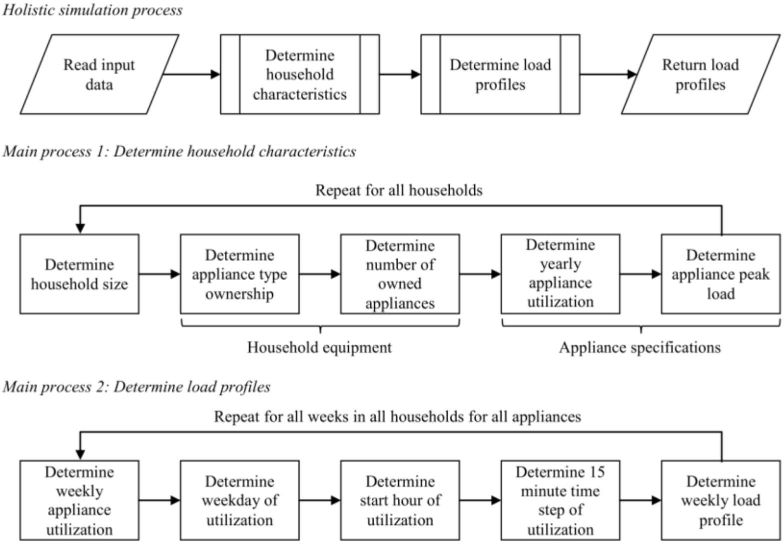


Figure 4: Simplified flow diagram of the developed bottom-up load model (Hayn et al. 2014b)

The modeling approach requires different types of input data. Amongst others, the distribution of household sizes and appliance types as well as the distribution of appliance utilization are prerequisites for the initial simulation. The optimization relies, in particular, on various detailed technical characteristics of the appliances and the externally determined price or control signals. For calibration and validation purposes, standard load profiles and empirical data on manual demand flexibility from a field trial (Hillemacher 2014) are used.

Originally, the model was developed on a stand-alone basis in order to analyze the impact of different designs of residential end-user tariffs. In a future step, a coupling with the PowerACE framework is envisaged. This combination would allow using the detailed data for residential electricity demand as an input for the simulation of a decentralized system. In return, simulated spot market prices could be used in order to test the reaction of households depending on the tariff design.

3.3.2 Market behavior with price-elastic demand

In order to consider price elasticity of demand in the spot market simulation, one possible approach has been implemented in the PowerACE model. In general, there are dedicated demand trader agents in the simulated wholesale market responsible for purchasing the expected volumes. These demand traders are to be understood as intermediaries aggregating the demand of many consumers under contract. In the simplest model version, there is one demand trader for each decentralized system and one additional demand trader representing the remaining market area.

Demand traders take part in the spot market auction in the same way as other traders (e.g. plant operators). In case demand is fully inelastic, the demand trader creates one price-independent bid for each hour, i.e. the bid volume will always be satisfied irrespective of the market clearing price. Alternatively, demand flexibility can be considered by setting for each demand trader a value for the price elasticity of demand as well as for the share of total demand being considered as price-elastic. In the strict sense, these values express the expected spot market demand flexibility of the consumers aggregated by the corresponding trader. On this basis, the demand trader constructs for each spot market auction a bid curve consisting of one price-independent bid point for the inelastic share of the expected demand and several price-dependent bid points. The expected static demand and the average price forecast for the following day serve as a reference point around which the bid curve is determined. How the bid volumes in a specific hour h of the following day depend on the bid price is given by the following relation:

$$Q_h(P) = A_h * (P_h)^{\varepsilon}$$

$$\text{with } A_h = \frac{Q_h^0}{(P^0)^{\varepsilon}}$$

$Q_h(P)$	Demand as a function of electricity price [MWh]
Q_h^0	Reference demand (expected demand without flexibility) [MWh]
P_h	Expected electricity price [EUR/MWh]
P^0	Reference electricity price (mean expected electricity price on the following day of the simulation) [EUR/MWh]
ε	Price elasticity of demand [-]

Figure 5 shows several differently shaped bid curves by varying the value for price elasticity and for the share of elastic demand.

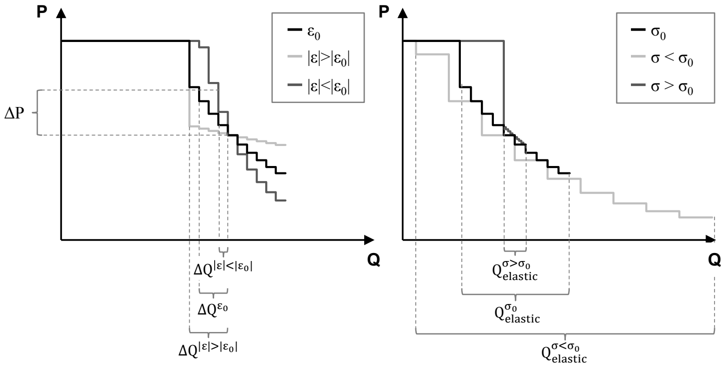


Figure 5: Illustration of bid curves with different values for price elasticity (left) and for the share of elastic demand (right)

With such step-wise bid curves submitted to the energy market, the market clearing will result in different market prices depending on the merit order and instantaneous RES-E feed-in.

3.4 Congestion management in distribution networks

The simulation framework to be developed in the course of this project is intended to replicate a wholesale spot market for one market area together with selected decentralized electricity systems as part of the total system in more detail. Thereby, the model features some simple forms of interdependencies between the centralized and decentralized system layers.

On the one hand, decentralized systems affect the total system. The demand and generation of all units in the decentralized systems are offered to the centralized energy market either via direct participation of market agents (e.g. generators with large conventional power plants) or indirectly via intermediaries (e.g. owners of RES-E units). Consequently, depending on the relative size of decentralized units, results for the whole market area are influenced to a greater or lesser extent by the behavior of the decentralized systems' agents.

On the other hand, (centralized) market results affect the behavior and operation of decentralized agents and units, respectively. Firstly, expected market prices are to some extent relevant for spot market bids. For instance, conventional generators and price-elastic demand bidders (Section 3.3.2) try to forecast spot market prices based on a merit order approach. In consequence, the price forecast determines the distribution of potential start-up costs and bid prices. Secondly, and more importantly, the results of the centralized spot market determine the dispatch of all units in the market area including those in the decentralized systems and in consequence also the load flow. This is a reflection of the current market design in Germany which does not consider any network constraints in the spot market. In systems with a low probability of grid bottlenecks, this is an efficient approach given the higher predictability of market results and liquidity of the marketplace. However, with an increasing spatial deviation between production and consumption as well as with a shift of feed-in and active load management along the voltage levels, a "copperplate" approach might be too short-sighted. Without any signals of the grid situation, there are no incentives for market participants to adjust their behavior neither on the short term nor in the long term accordingly.

3.4.1 Status Quo

In this project, we focus on congestions that arise in decentralized electricity systems, thus we limit our analysis to distribution grids with a voltage level of 110 kV or lower. In most European countries, the distribution grid has been expanded continuously to serve demand at all times without congestion. In Germany, there is virtually no congestion on the level of distribution grids with respect to serving demand. However, numerous German distribution system operators regularly face congestion caused by RES-E generation (Monitoringbericht 2015 2015). The strong expansion of renewable installations in Germany, which happened foremost within the distribution grid, leads to situations in which more RES-E is generated than the electricity grid can accommodate.

Figure 6 shows the development of renewable curtailment within Germany over the last years starting in 2009. The increasing trend is clearly recognizable.

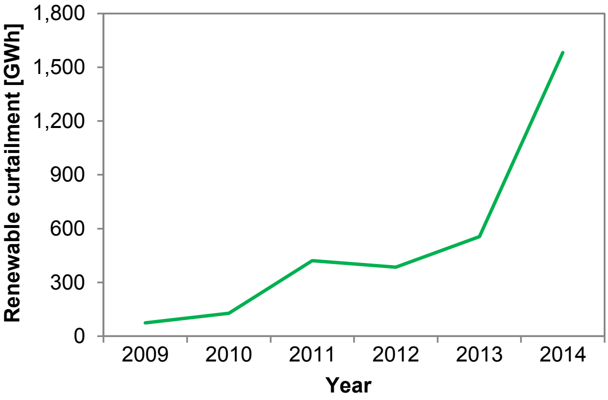


Figure 6: Curtailment of RES-E generation in Germany (own illustration; data from Monitoringbericht 2015 2015)

The current regulation with regard to congestion in distribution networks provides for the curtailment of planned electricity generation. Thereby, conventional (fossil) generation capacities are considered first, followed by the different RES-E technologies. Since most conventional generation capacity is connected to the transmission grid level (voltage level of 220 kV and 380 kV) congestion management in distribution networks can be simplified to curtailing renewables. Furthermore, we only consider the curtailment of PV and wind generation units, which account for more than 90 % of the curtailment (Monitoringbericht 2015 2015).

At the time of writing this report, there is no detailed regulation on how to execute the congestion management procedures. There is no guideline which provides an algorithm on how to choose which RES-E generator to curtail. However, it is prescribed by law, to carry out the congestion management in a way that enables as much feed-in from RES-E and from combined heat and power plants as possible (Bundesministerium für Wirtschaft und Energie (BMWi) 01.08.2014). It is not transparent how a DSO finally decides on curtailment and the success of minimizing RES-E curtailment is hardly verifiable. There is neither cooperation between different DSOs nor available research about congestion management approaches known to the authors. Improvements in congestion management algorithms by one DSO known to the authors do not seem to be transferred to others DSOs or to be discussed in a scientific, public manner. The approaches appear to be independent of one another and not to be reproducible.

3.4.2 Load flow analysis

In order to determine the electrical load on each grid element, we apply a load flow analysis for the decentralized electricity system. Grid congestion describes a situation in which the power generation and demand dispatch based on the results of the spot market for electricity would lead to a grid state that is unacceptable. A grid state is unacceptable if one or more of the following limitations are violated for one or more elements of the grid:

- Voltage (+/-)
- Power/thermal limit (+/-)

Extensive injection and consumption, respectively, of both real and reactive power may cause thermal flows in grid components, such as lines or transformers, to exceed the components rating. As the resulting congestions are a main driver for the development of decentralized markets due to the resulting inefficiencies, it is necessary to include the electricity grid into a modeling approach when investigating decentralized electricity systems. We determine congestions in the distribution grid by integrating a load flow analysis into the PowerACE simulation framework, as it was developed in Ruppert et al. (2016). In order to incorporate both voltage-related and current-related congestions, an AC formulation is used, performing the standard iterative Newton-Raphson approach in order to solve the numerical problem given by the nonlinear load flow equations. The approach mainly consists of solving the active and reactive power equations until the desired tolerance limit is reached:

$$P_i(V,\delta) = P_i^G - P_i^D$$

$$Q_i(V,\delta) = Q_i^G - Q_i^D$$

V	Voltage magnitude [-]
δ	Voltage angle [°]
P_i^G, Q_i^G	Active and reactive Power generation [MW, MVAr]
P_i^D, Q_i^D	Active and reactive power demand [MW, MVAr]

In each iteration step, the following power mismatch equations are solved using the Jacobian matrix:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}, \text{with:}$$

$$H = \frac{\partial \Delta P(V,\delta)}{\partial \delta}, \qquad M = \frac{\partial \Delta Q(V,\delta)}{\partial \delta}, \qquad N = \frac{\partial \Delta P(V,\delta)}{\partial V},$$

$$L = \frac{\partial \Delta Q(V,\delta)}{\partial V}$$

The load flow is performed on the distribution grid level, with each substation being represented by a unique busbar. All thermal and renewable generation units as well as consumers are assigned to individual busbars. We define the busbar in a substation connected to the transmission grid as slack bus whose active and reactive power supply offers a degree of freedom since it potentially provides large amounts of both positive and negative power, though, limited by the transformers installed in the substation. The resulting voltage magnitude and angle on each busbar for the static load situation allow the calculation of flows on the systems' lines. In case of current flows exceeding the rated thermal limit of the line, a congestion occurs which needs to be eliminated by congestion management measures. Countermeasures are also required if the voltage deviation from the rated voltage is higher than the accepted deviation.

4 Simulation design and input data for the case studies

4.1 General simulation setup

The structure of the extended agent-based simulation model requires different types of input data for at least one decentralized electricity system as well as for the high-level market area representing the centralized market. At the current stage of the model development and application, one illustrative decentralized electricity system has been defined, tested and evaluated in detail. This approach allows an in-depth representation of the selected system in a manageable setting. Thereby, it is imperative for the selected system to provide sufficient and relevant links for applying the model (e.g. high share of RES-E in the selected system). In future, several decentralized systems could be integrated in parallel while considering potential interactions between them.

In order to analyze the research topics outlined in the previous sections, the electricity system of Schleswig-Holstein, a state in Northern Germany, including a representation of its 110 kV distribution network is chosen for several reasons. The region of Schleswig-Holstein is already characterized by a very high penetration of distributed generation. In fact, the annually generated electricity from renewables amounts to 80 % of the consumed electricity, a share far above the German average. Furthermore, the wind power density[1] is the highest among all German Bundesländer (city states excluded; Bundesverband der Energie- und Wasserwirtschaft (BDEW) 2015a). Table 1 compares Schleswig-Holstein and Germany with respect to selected indicators. As such, the electricity system of Schleswig-Holstein exemplifies energy systems with a high share of RES-E feed-in and can serve as a show

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[1] Ratio of installed capacity of wind onshore to land surface area.

case for current and future challenges in designing and operating electricity systems. Even today, the distribution grid operator in Schleswig-Holstein is frequently forced to take action with respect to the curtailment of RES-E units due to potential grid congestion ("Einspeisemanagement" according to § 11 EEG and § 13 Sec. 2 EnWG). Recent studies have attempted to quantify the magnitude of these interventions and the associated costs (Ecofys 2012; Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein (MELUR) et al. 2014).

The simulation setup also requires data for the centralized wholesale market of Germany to be considered in the model. A detailed description of comparable datasets for the German market area can be retrieved, for instance, from Genoese (2010) and Bublitz et al. (2014).

Table 1: Comparison between Schleswig-Holstein and Germany

	Unit	Year	Schleswig-Holstein	Germany	Share
Area	km²	2013	15,800.0	357,339.0	4.4 %
Population	Million	2014	2.82	80.77	3.5 %
Final energy consumption (electricity)	TWh	2013	12.00	523.22	2.3 %
RES-E generation	TWh	2013	10.42	125.80	8.3 %
of which: Biomass			2.47	36.26	6.8 %
Wind onshore			6.68	50.80	13.2 %
Solar			1.25	29.71	4.2 %
Installed capacity	GW	2013	5.54	77.65	7.1 %
of which: Biomass			0.36	6.10	5.9 %
Wind onshore			3.75	33.66	11.2 %
Solar			1.41	35.35	4.0 %

Sources: BDEW (2015a), BMWi (2015), Länderarbeitskreis Energiebilanzen (2015), MELUR and Statistisches Amt für Hamburg und Schleswig-Holstein (2015), Statistische Ämter des Bundes und der Länder (2015b)

4.2 Processing of selected input data types on regional level

The following paragraphs briefly describe how raw data is collected and processed on a regional level for selected input data types (grid, RES-E generation, conventional power plants and demand). The respective approaches are illustrated for Schleswig-Holstein but can also be applied to other systems.

General structure of the input data

Detailed technical properties of the relevant physical units (e.g. grid nodes, power plants) are necessary to configure the system. Furthermore, information on the units' geographic location is essential for determining the units' point of grid connection. The agent owning a physical unit and the agent operating it do not need to be identical. In particular, distributed generation units (e.g. PV) are typically owned by single households or other small-scale entities which usually lack interest, competence or other requirements to actively participate in electricity market operations. In these cases, aggregating agents take over the selling of the generated electricity. Certain agents can own and operate units at the same time (e.g. operator of large conventional power plants).

Moreover, hourly time series of electricity generation and demand are needed in order to analyze the load flow and congestion events within the electricity grid. In the model, time series are compiled in three different ways depending on the data type:

- Using exogenous "ready-to-use" time series (e.g. normalized demand for different consumer types)
- Simulation of time series within the model (e.g. generation from wind and PV; Section 3.2)

- Endogenous and indirect determination through agent behavior and market results (e.g. conventional power plants, price-elastic demand; Section 3.3.2)

Therefore, the hourly dispatch of the physical units is, in the end, set by their technical properties, their time series and their agent behavior model, respectively. Electricity generation and consumption are then aggregated on node level for each time step.

Electricity grid data

In order to consider grid constraints in the selected systems, it is essential to define all nodes of the respective grid. Nodes, i.e. locations within the grid where load can be injected or withdrawn, represent either a substation which connects two grids of different voltage levels (e.g. between 110 kV and 380 kV) or a connection between lines of the grid on the same voltage level. Often, multiple instances of the two types are interconnected in one place composing a bus, represented as one node within the model.

The assumed grid model of Schleswig-Holstein is composed of 131 nodes on the 110 kV voltage level, of which ten represent transformer stations connecting the 110 kV distribution grid to a higher voltage level. The nodes are interconnected by 253 lines. Geographic information concerning the location of nodes and routing of lines is taken from the website of the respective DSO, Schleswig-Holstein Netz AG[2], personal communication with the DSO and the OpenStreetMap project[3]. Figure 7 illustrates the identified grid nodes and lines, the locations of wind parks and the subdivision of the area to municipality level.

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[2] https://www.sh-netz.com

[3] https://www.openstreetmap.org

Figure 7: Representation of the model grid with 110kV substations (black dots), lines (black lines), connecting substations to the 220/380kV grid (red dots), wind power plants (blue triangle) and municipalities (polygons with white outline)[4]

The grid nodes define the considered electrical network and also form the basis for breaking the analyzed grid down to subareas. Given the lack of detailed data concerning the actual grid connection of all the system's physical units, the location where electricity is injected or withdrawn needs to be estimated in a systematic way. For that purpose, a Voronoi diagram of the area covered by the analyzed grid is created. The approach defines, for each grid node, a surrounding subarea in the form of a polygon as the set of all the points on the plane being closest to that specific grid node. In the end, the total plane is divided into as many subareas as there are grid nodes. Thus, each physical unit with known or approximated geographic coordinates can

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[4] Maps throughout this book (figure 7, 9, and 11) were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. For more information about Esri® software, please visit www.esri.com.

be assigned to a subarea and thus to a unique grid node. Figure 8 shows the separation of the considered grid area into Voronoi polygons.

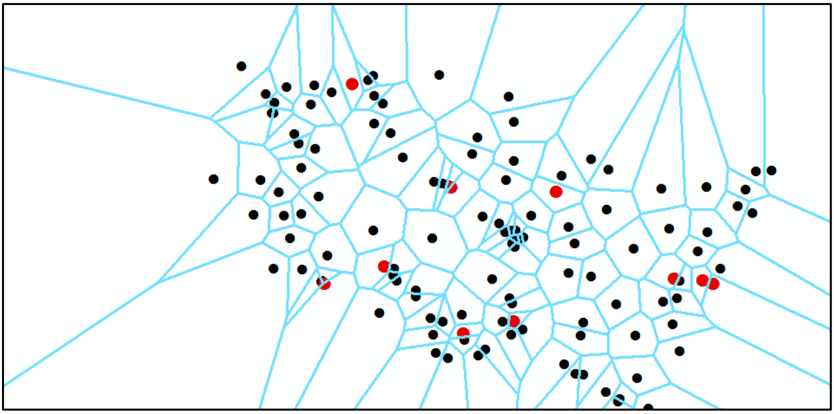

Figure 8: Voronoi diagram of the considered grid area

Weather data

For the analysis in this work, we apply a large weather dataset which covers large parts of Europe on a 20 km x 20 km resolution. Figure 9 gives an overview of the covered area and the structure of the data.

Each colored pixel corresponds to a "weather cell" with individual information on:

- Wind speed at 70 m and 140 m height [m/s]
- Wind direction [°]
- Temperature at 70 m and 140 m height [K]
- Global solar irradiation [W/m²]

With regard to the temporal resolution, the data is available on a 10-minute basis from 1990 to 2012. The model data was supplied by downscaling reanalysis data of solar global irradiance from the NASA program Modern-Era Retrospective Analysis For Research and Applications applying the mesoscale model MM5 (MM5 Community Model Homepage 2003).

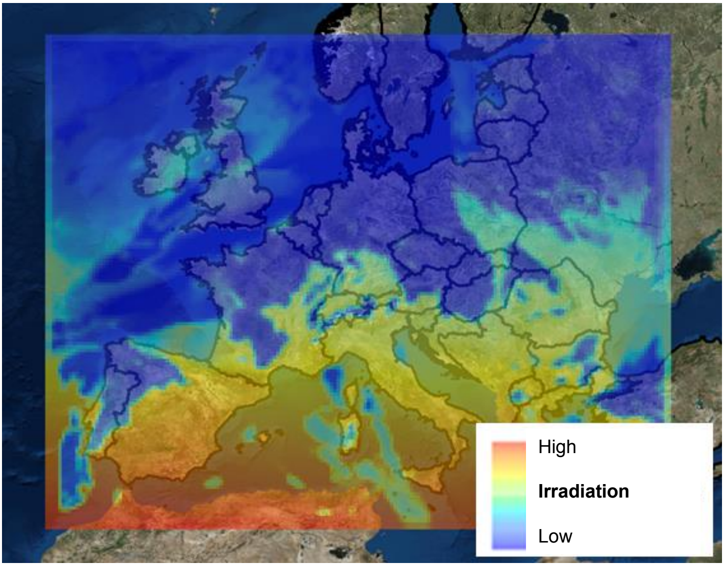

Figure 9: Solar irradiation at one time step within the utilized dataset

Renewable generation data

In order to generate RES-E feed-in profiles on a nodal basis, we collected information about the geographic location of RES-E plants. The main source is a public register of the German Federal Network Agency Bundesnetzagentur 2015b) which includes a full list of RES-E generation units in Germany that feed electricity into the grid and are entitled to feed-in tariffs. This publication comprises a list of more than one million generation units including information on:

- Generation technology: wind onshore/offshore, PV, biomass, biogas, water, sewage gas, geothermal
- Installation date
- Net capacity [kW]
- Energy yield per year [kWh]
- Feed-in tariff rate
- Geographic location of the generation unit or the municipality[5] it is located in

For the modeling of wind power generation, the information from above is complemented by a database providing more details on the wind technology implemented (The Wind Power 2015). From this database, the wind power model utilizes the following parameters:

- Turbine manufacturer and turbine type
- Net capacity [kW]
- Hub height [m]
- Rotor diameter [m]
- Geographic location of the generation unit or the wind park it belongs to [lat. / long.]

Conventional power plant data

With respect to conventional power plants, the reference list of power plants in Germany published by the Bundesnetzagentur (2015a) is filtered for those plants located in the covered system and on the considered voltage level. The

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[5] In Germany, municipalities are uniquely identified by an official key ("Amtlicher Gemeindeschlüssel"). The matching between municipalities and grid nodes is based on the approach described above using the "geographic center" of the municipality for determining the relevant Voronoi polygon.

dispatch of conventional power plants is simulated endogenously and ultimately depends on the bidding strategy of the generation agents and the results of the centralized wholesale spot market for electricity (Bublitz et al. 2015).

Electricity demand data

Along with generation data, the hourly electricity demand in each grid node needs to be simulated. Lacking detailed measurement data, a top-down approach was chosen for most analyses in order to derive electrical load curves with the required temporal and spatial resolution. For that purpose, the total yearly electricity consumption in the decentralized system is segmented by consumer type (residential, industry, services, agriculture and transport).

Table 2: Overview of the considered indicators for the temporal and spatial breakdown of demand data

Consumer type	Basis for temporal profile	Variables for spatial breakdown
Residential	Standard load profile	• Population
Industry	Residual system profile	• Number of businesses • Number of employees • Gross pay
Services	Standard load profile	• Gross value added (district level) • Number of employees
Agriculture	Standard load profile	• Number of farms (district level) • Number of employees (district level) • Agricultural land
Transport	Constant (base load)	• Population

The spatial breakdown of each segment's total consumption on the level of municipalities is based on a combination of different parameters derived from public statistics (Regionaldatenbank Deutschland[6]). For instance, the breakdown for residential consumption considers the population in each municipality. In order to derive hourly values for our analysis, the total consumption for each segment and municipality is distributed over all hours of the year applying standard load profiles for different consumer groups which are publicly available and often used by different stakeholders (e.g. electricity suppliers) in Germany (Bundesverband der Energie- und Wasserwirtschaft (BDEW) 2015c). We chose to use standard load profiles despite their weaknesses (see also Section 3.3.1) since we lack alternative endogenous approaches and data sources, which meet the requirements of the targeted application. Table 2 summarizes the considered indicators for the temporal and spatial breakdown of the demand. Figure 10 illustrates how the total yearly electricity consumption is distributed over consumer types and the grid nodes of the modeled distribution grid.

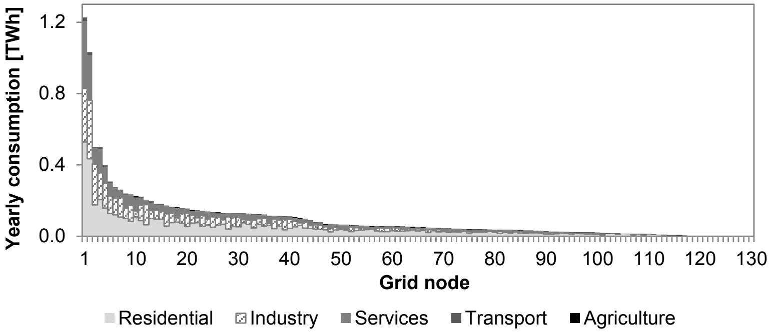

Figure 10: Cumulated yearly electricity consumption for each grid node and consumer type in the illustrative decentralized system

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[6] https://www.regionalstatistik.de

5 Analyzing current and future challenges in decentralized electricity systems

In the following subsections, the results from several case studies using the developed modeling toolbox (Section 1) as well as parts of the input data for the illustrative system (Section 1) are highlighted[1]. At first, we illustrate how RES-E profiles with a high temporal and spatial resolution can be assessed and simulated making use of an extensive weather dataset (Section 5.1 and Section 5.2). However, not only distributed generation from RES-E plays an ever increasing role, but also the potential impact of demand-side flexibility needs to be considered when analyzing decentralized systems. The increasing feed-in from RES-E and the availability of more flexible demand units make the adjustment of congestion management in distribution networks indispensable and put pressure on the overdue improvement of the corresponding processes. In this context, Section 5.3 and Section 5.4 show on different levels how retail tariffs and corresponding price signals can influence the load flow in distribution networks. In Section 5.5, we propose a concept of a market-based congestion management mechanism based on market price signals.

5.1 Developing assessment indicators for weather model data

In the course of this project, we carried out two separate analyses with regard to the RES-E supply in the context of decentralized electricity systems. In the first analysis, we compare the irradiation data from the extensive weather dataset, which was the output of a numerical weather model applied in

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[1] All presented case studies have been published separately and are summarized in the following subsections. The original sources are referenced for further details.

hindsight 1990-2012, with measurement data from weather stations distributed over Germany as shown in Figure 11 (Schermeyer et al. 2015a).

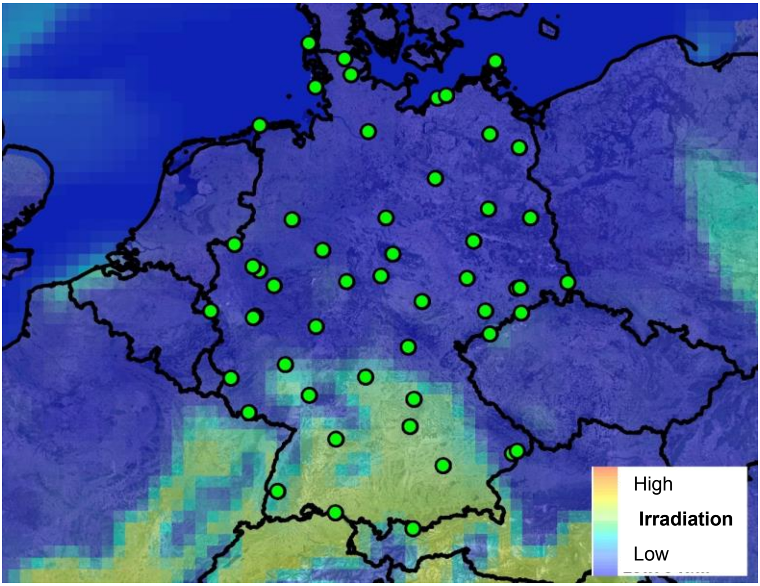

Figure 11: Illustration of the available irradiation model data on a 20 km x 20 km scale (colored by irradiation level) and the sites of 57 measurement stations (green dots) used for the analysis (Schermeyer et al. 2015a)

The objective of the comparison is to estimate the model's ability to reproduce realistic solar irradiation time series. This is relevant because synthetic weather data is gaining more and more importance as input for energy systems models. However, it is an open question to what extent modeled weather data captures the relevant characteristics of an irradiation supply time series in an appropriate way for energy systems analysis.

For that purpose, the authors develop three novel indicators which capture those characteristics of an irradiation supply time series that are particularly suited for the dimensioning of decentralized electricity systems:

- **Maximum gradient of radiation supply** (MGRS): The MGRS indicates the extent and occurrence of extreme changes in the irradiation supply over time, which affect the need for flexible generation and demand units.

$$MGRS_{\alpha,\Delta t} = \frac{1}{(N-t)} \sum_{t}^{N} \Delta P_{t,\Delta t}$$

$$|\left[\Delta P_{1,\Delta t} \leq \Delta P_{2,\Delta t} \leq \cdots \leq \Delta P_{t,\Delta t} \leq \cdots \leq \Delta P_{N,\Delta t}\right]; t = max\left\{k \in \mathbb{N} | k \leq \frac{\alpha}{100} N\right\}; \alpha < 100$$

ΔP	Gradient within the time series between two elements x_n
N	Number of elements within the time series
Δt	Temporal distance (resolution) between time series elements
α	Regarded quantile

- **Maximum amplitude of radiation supply** (MARS): The MARS is an indicator for the occurrence of very high values of a given time series. This is relevant since decentralized electricity systems and grids are exposed to PV feed-in and need to account for extreme situations even if they are rare.

$$MARS_{\alpha} = \frac{1}{(N-t_0)} \sum_{t=t_0}^{N} x_t$$

$$|\left[x_1 \leq x_2 \leq \cdots \leq x_t \leq \cdots \leq x_N\right]; t = max\left\{k \in \mathbb{N} | k \leq \frac{\alpha}{100} N\right\}; \alpha < 100$$

$x_1 \ldots x_N$	Time series elements at a site
N	Number of elements within the time series
α	Regarded quantile

- **Spatial volatility** quantifies the variation in renewable energy supply over space. Power systems constantly balance spatial differences in energy demand and supply. Thus, the spatial volatility of renewable energy supply is relevant for the system's dimensioning.

$$vola_t = \frac{\sigma_t}{\mu_t^S} = \frac{\sqrt{\frac{1}{S-1}\sum_{s=1}^{S}(x_t^s - \mu_t^S)^2}}{\mu_t^S}$$

x_t^s	Time series element at station s and time step t
μ_t	Arithmetic mean of the time series over the number of available stations S during time step t
σ_t	Standard deviation over the number of available stations S during time step t

The authors find that the weather dataset which is applied for the different analyses of this work shows significant differences compared to measurements with regard to the average irradiation level (measured as mean-bias-error). The spatial volatility of the model data is noticeably larger compared to measured data. However, large deviations are rather seldom. This is revealed by a quite low root mean square error between model and measurement data. The correlation between model and measurement data is also quite high reaching 90 % on average. Extreme high values, measured by the MARS, are captured by the model quite realistically, while the MGRS reveals different results depending on the analyzed time step size. All in all, the model data appears to simulate quite satisfactorily the average weather within a 20 km x 20 km zone.

5.2 Stochastic simulation of solar energy supply

In a second analysis, we develop an approach for the stochastic simulation of spatially correlated time series of solar irradiation supply (Schermeyer et al. 2015b). This is relevant, since irradiation data and other renewable supply data are rarely available on a high temporal and spatial resolution as needed when analyzing decentralized electricity systems. Stochastic simulation methods can be applied to characterize the available data and generate synthetic time series. Also, the stochastic model can be used for a Monte Carlo analysis generating numerous renewable supply scenarios and thus covering also rare and extreme values.

In their analysis, Schermeyer et al. (2015b) fit a stochastic model to selected locations of the above mentioned weather dataset. The authors opt for a copula-based approach and generate uniformly distributed random numbers. The random numbers are drawn with a Gaussian copula and are correlated in accordance to the measured correlation of the irradiation processes that shall be modeled. Applying the empirical cumulative distribution function of each location's historical time series, the authors transform the uniformly distributed data into the original domain.

The simulation approach is applied to an illustrative modeling of PV power generation. The case study compares the PV generation time series simulated in two ways: firstly, it is assumed that all PV plants are exposed to the same irradiation, representing a simulation approach with low spatial resolution, not capturing the differences in irradiation supply over space. Secondly, the considered area is represented by 9 equally distributed locations, all with their own irradiation process but correlated to each other. The findings about the difference in aggregated power production are shown in Figure 12.

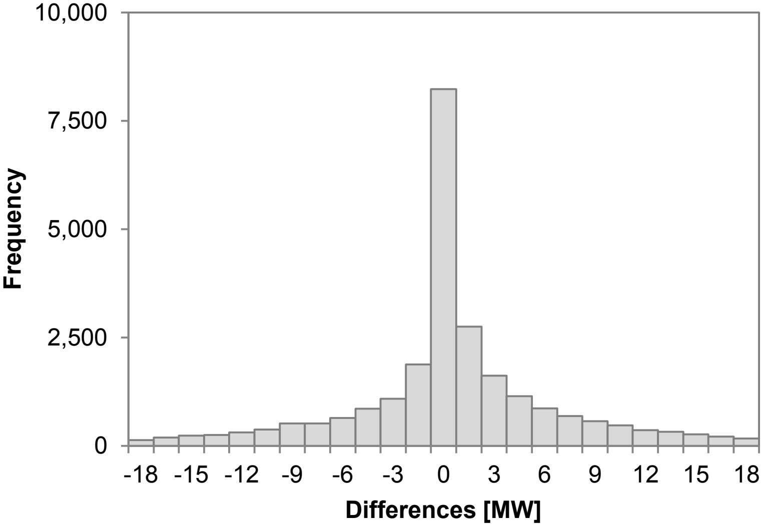

Figure 12: Histogram of differences in power generation between the case of all generation at a single location and the case of equal distribution of generation capacity over all locations (irradiation values equal to zero excluded; simulation of 52,560 10-minute time steps of one year)

In their work, the authors develop a methodology which explicitly fits the analysis of decentralized electricity systems where spatial differences in supply are especially relevant.

5.3 Impact of residential electricity tariffs with variable energy prices on low voltage grids with PV generation

Increasing the flexibility of demand is considered as a key instrument for the introduction of decentralized market structures in order to reduce congestions in the distribution grid.

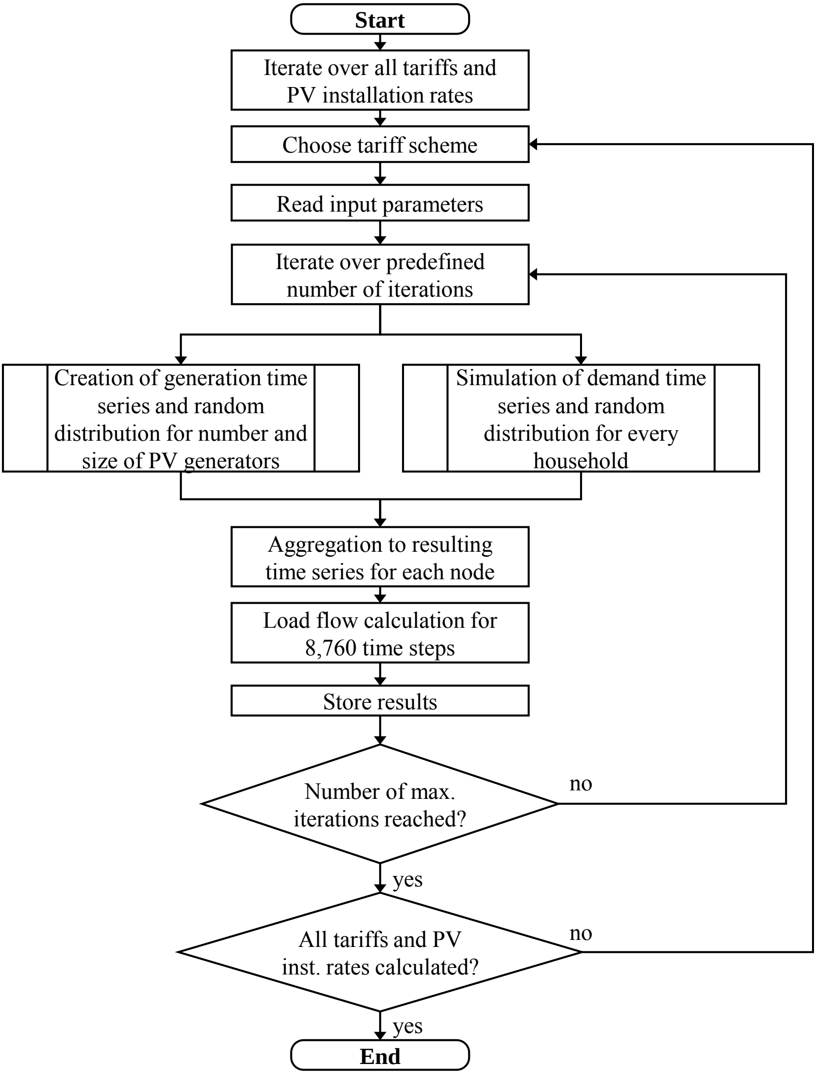

Figure 13: Flow chart of Monte Carlo approach (Ruppert et al. 2016)

In the household sector, variable energy pricing for customers can create the required incentives for the desired change in consumption behavior. However, the incentives given to the customers vary strongly when taking a grid perspective in comparison to a market perspective, which follows the directive of minimizing energy costs at the wholesale market. As most existing approaches, which are utilizing variable energy prices, use the market perspective, Ruppert et al. (2016) investigate the consequences of two tariff structures using dynamic energy pricing on the utilization of an illustrative low voltage grid under consideration of PV generation. Figure 13 shows the different steps of the simulation process.

The developed approach consists of three main elements: firstly, a residential demand model in order to investigate the response of households to price changes by using price elasticities, secondly, a model generating profiles of PV generation and, thirdly, a probabilistic load flow simulation model using a Monte Carlo approach.

The elasticities used in the residential demand model were obtained from the large-scale field test MeRegio, which included up to 1,100 participants in Southern Germany (Hillemacher et al. 2013; Hirsch et al. 2010). The test group subject to dynamic pricing consisting of three price levels was compared to a reference group subject to a traditional, flat tariff. As a single, unified price elasticity does not properly reflect all customers' behavior, price elasticities for 72 classes were clustered, accounting for the most significant effects on elasticity (season of the year, day of the week, hour of the day, tariff level continuance etc.). In addition to household demand, PV generation was considered in the model. For that purpose, four installation sizes ranging from 3 to 12 kWp were randomly distributed based on the given installation rate in the grid. Both models provide input for the Monte Carlo simulation, where individual time series of demand and generation were created for each iteration step.

The authors show that in several hours the power flow direction is revered and the limit for voltage deviation is exceeded due to the increasing PV generation. Although, dynamic residential electricity tariffs can generally support grid stability, it is vital to design the tariff carefully in order to avoid aggravating grid situations during demand peaks.

5.4 Increasing demand flexibility and its potential effects on decentralized electricity systems

Demand response programs are expected to increase demand flexibility and ultimately to support the adaptation of the electricity system to current challenges (see also Section 3.3). However, research has shown that such programs could also cause some detrimental effects. New demand peaks can occur which might not be met by supply in the energy market or render transmission and distribution infeasible (“avalanche effects”; e.g. Ramchurn et al. 2011; Boait et al. 2013). Therefore, an analysis is undertaken in Ringler et al. (2015) regarding the effects of an increasing demand flexibility on local electricity systems and the role of the current market design in Germany. For the analysis, necessary data is processed and different adjustments to the PowerACE model are made. On this basis, several simulation runs with the PowerACE model are applied to study potential impacts on the modeled electricity system as defined in Section 1.

Since price elasticity of demand is generally not known, an approach is formulated to determine corresponding values from empirical bid curves of day-ahead markets (see also Figure 15). Based on these bid curves, which are published by electricity exchanges on an hourly basis, electricity demand as a function of bid prices is estimated using a polynomial regression. Together with market clearing results, numerical values for the so-called point price elasticity of demand can be calculated. Additionally, the bid curves allow deducing the share of total demand which is bid in a price-dependent way after all. Both, the price elasticity and the overall share of elastic demand are indicators for the demand flexibility of the aggregated consumers. For the analysis, a dataset by the European Energy Exchange (EEX) for the German day-ahead market and the period between September 2015 and July 2015 is evaluated.

In order to consider a price-elastic electricity demand in the PowerACE model, the extension as presented in Section 3.3.2 is used. The demand traders in the model create bid curves to be submitted to the spot market. The overall simulation process follows the steps as described in Section 3.1. The load flow analysis allows identifying critical grid situations under different scenarios.

Based on the approach to determine empirically the day-ahead price elasticity of demand in Germany, an average value for each year of the available dataset is calculated (Table 3). Over the whole period the mean value is -0.062. Similarly, the share of inelastic electricity demand is calculated and found to be 0.85 on average.

Table 3: Average price elasticity of demand and share of inelastic electricity demand

Year	Average price elasticity of demand	Share of inelastic electricity demand
2010	-0.095	0.83
2011	-0.075	0.84
2012	-0.052	0.83
2013	-0.040	0.86
2014	-0.068	0.86
2015	-0.074	0.85

Subsequently, the impact of different levels of demand flexibility, which is operationalized by the elasticity and share of demand to be bid in a price-dependent way, is analyzed. Based on the PowerACE model and different scenarios, several situations have been identified where increasing demand flexibility leads to a higher maximum utilization of certain grid elements (lines, transformers) during a simulation run compared to the base case. These results indicate that higher demand flexibility can cause additional stress in distribution grids.

These first results indicate that in case of increasing demand flexibility in future electricity systems new critical situations in distribution grids may occur. This is particularly the case when price signals used by suppliers to influence demand behavior do not incorporate local conditions, e.g. with respect to RES-E feed-in and grid topology. However, suppliers have little economic incentives to do so given the current market design in Germany with wholesale electricity price being only based on marginal generation costs. Recently, there have been several tentative proposals in order to amend the market design in this respect. Amongst others, the German associations Regionale Flexibilitätsmärkte 2014 (2014), Bundesverband Neue Energiewirtschaft (bne) (2014) and Bundesverband der Energie- und Wasserwirtschaft (BDEW) (2015b) published concepts for regional marketplaces which should facilitate the market-based utilization of local flexibility options. Distribution grid operators could use these flexibility options in events of (expected) congestions. Other remedies in order to avoid such “avalanche effects” include individual price signals (e.g. Gottwalt et al. 2011) and dynamic network charges (e.g. Dallinger und Wietschel 2012). Although, the proposed local market concepts would only complement the existing markets, additional research regarding the conceptual design, its implementation and potential interactions is necessary.

5.5 An analytical approach to congestion management in distribution networks

This work aims at finding a congestion management algorithm that is applicable to a market design with uniform pricing which most European countries have adopted. Congestion management is defined as the act of modifying the dispatch of generation and demand within the modeled distribution grid when technical limitations of any grid elements are expected. Congestion management in a market with uniform pricing can be simplified as a process with the following three steps (Figure 14):

1) **Market-based dispatch:** All generation and demand units participate in the wholesale electricity market to buy or sell electricity. Demand and supply is matched regardless of their location and contribution to a potential congestion. Based on the market results, an exact or estimated schedule is to be determined for each generation and demand unit in the system.

2) **Grid constraints:** Grid operators calculate the expected load flow within their grid on the basis of these schedules. If the dispatch is feasible without violating limits, the final dispatch has been found. If parts of the grid are congested, the DSO has to execute congestion management measures in order to manipulate the feed-in at the grid's nodes. We differentiate between the following two approaches:

    a. **Nodal congestion management**: The grid operator triggers flexible load elements on a nodal level and, thus, reaches a spatial resolution of the congestion management equal to the preceding load flow analysis (see Section 3.4.2).

    b. **Zonal congestion management**: The grid operator triggers flexible load elements limited to a zonal level. A zone containing a number of nodes can receive signals only as a whole, meaning that all nodes receive the same signal. The spatial resolution of the congestion management is thus lower than the underlying load flow analysis.

3) The **final dispatch** is determined after the execution of a potential congestion management measure. If no congestion occurred, the final dispatch is solely based on the results of the wholesale energy market.

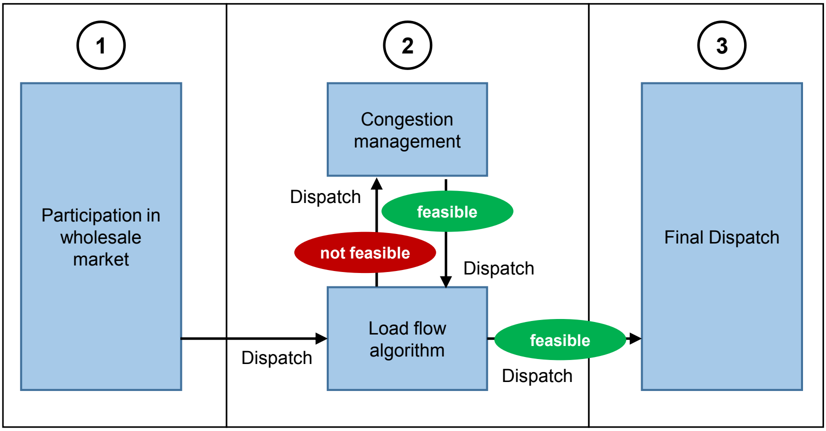

Figure 14: Congestion management as part of a three-step process

Step 1 and 3 are well-known elements of the liberalized energy-only market design implemented in most European countries and are simulated by the existing PowerACE modules (see Section 2.2). In the course of this project, we additionally developed a module to represent distribution grids within the centralized wholesale market. The modeled distribution grids comprise the tasks and processes from step 2 in Figure 14. They receive the result from the wholesale market which tells them how much and where supply and demand will occur within their grid. The DSO then calculates the expected load flow and verifies if the wholesale market dispatch violates any grid constraints. In case of congestion, the DSO carries out congestion management by changing the dispatch (e.g. curtailment of RES-E generation).

Within step 2, the DSO is dispatching the flexibilities considering the prior market result which resembles a decentralized flexibility market. In the following we develop an explicit and simple formulation for the second step of the market-based congestion management algorithm described above.

Current approaches of DSOs for congestion management are neither transparent nor subject to scientific discussion. The regulation about congested distribution grids does not give concrete advice on how to carry out congestion management either. This work aims at contributing to filling this gap.

One of the main challenges is how to integrate the demand side in the congestion management mechanism. The planned generation of power suppliers has been early if not always subject to regulation. However, traditionally the schedule of planned electricity consumption is not matched to the specific situation of the energy system. The proposal of the authors provides for an integration of demand into the congestion management approach based on the price signals revealed within the day-ahead auction of the spot market.

Figure 15 shows an illustrative result of the German/Austrian day-ahead auction for power. Remarkably, there is a considerable amount of demand bids that have a positive willingness to pay but are not accepted. If those bids lie within a congested grid area, they could help alleviate congestion utilizing the otherwise curtailed RES-E for value creation.

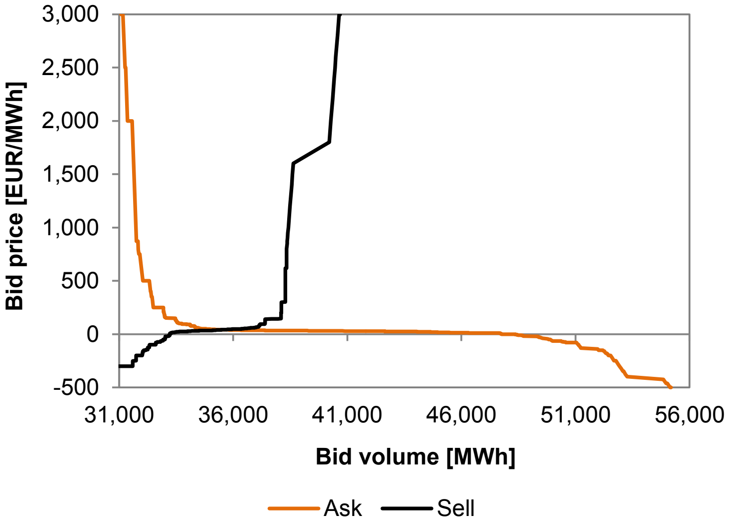

Figure 15: Aggregated bid curves in the day-ahead auction for 13:00-14:00h on June 9, 2015 (own illustration; data from EPEX SPOT)

In order to coordinate the congestion management, a formal optimization framework is defined:

Minimize the costs for congestion management: $\min(c) = (1) + (2)$

(1) Costs to substitute curtailment at day-ahead spot market

$$p^{DA}(P^c) \cdot P^c \cdot \Delta t$$
$$P^c = \sum_n P_n^c$$
$$\rightarrow p^{DA}(P^c) \cdot \sum_n P_n^c \cdot \Delta t$$

p^{DA}	Day-ahead spot market price to substitute curtailed energy
P^c	Total curtailed power in local market area
P_n^c	Curtailed power at node n

$$s.t.\ P_l^c \leq \sum_n \sum_l P_n^c * \mu_{nl}$$

P_l^c	Required curtailment at line l to clear congestion
μ_{nl}	Sensitivity of reducing power at node n to congestion at line l

(2) Costs (or revenues) to increase load or decrease generation

$$\sum_n \sum_i (P_{ni}^c * p_{ni})$$
$$P_n^c = \sum_i P_{ni}^c$$

P_{ni}^c	Day-ahead spot market price to substitute curtailed energy
p_{ni}	Price of bid i at node n

The cost minimization of the congestion management takes three different aspects into account. Firstly, the costs associated with the congestion of RES-E are considered explicitly. If RES-E has to be curtailed and there is a positive residual load, other generation units have to ramp up their generation which typically causes additional costs. To quantify these costs, the developed model for decentralized electricity systems is coupled with the PowerACE model for electricity wholesale markets. The PowerACE model simulates the dispatch of the conventional power generation which most likely backs up the missing RES-E. The costs for this back-up electricity have to be taken into account by the DSO.

Secondly, the DSO managing congestion within the respective distribution grid has to undertake actions which will reduce the net feed-in to the public grid in order to decrease the stress to the grid caused by strong RES-E feed-in. Currently, DSOs exclusively curtail RES-E feed-in to clear congestion within their grid, which is cost-neutral since the curtailed generators are compensated either way. However, if the DSO uses the information from the day-ahead bid stack which reveals consumers having a positive willingness to pay below the current market price, they might alleviate congestion while generating returns.

Thirdly, the congestion management algorithm proposed in this study, explicitly takes into account the sensitivity of a net change in load at a node within the analyzed grid on the grid elements considered for congestion. In case there is no flexible demand to be scheduled during congestion, the approach minimizes the amount of energy that is curtailed which corresponds to the regulation today. Therefore, this scheme can be assessed as a no-regret mechanism.

6 Conclusions and Outlook

6.1 Designing and operating future electricity systems

Current challenges in electricity systems, in particular on a decentralized level, need to be analyzed in a comprehensive and systematic way. In this study, a flexible modeling toolbox for decentralized electricity systems with an agent-based simulation approach at its core has been developed. In Section 3.2, two RES-E generation models for wind and PV each with a high temporal and spatial resolution are presented. Approaches to model specific aspects of the demand side in detail are introduced in Section 3.3. The implementation of an AC load flow algorithm is outlined in Section 3.4. In the course of the project, the existing multi-agent simulation model PowerACE, originally designed to simulate the German electricity wholesale market, was extended in several ways. For instance, the load flow analysis module and selected approaches of congestion management were fully integrated. Moreover, basic interactions between decentralized electricity systems and wholesale electricity markets can be analyzed from now on using the model. Furthermore, substantial input data for an illustrative system was prepared (Section 1).

On this basis, several case studies with respect to current and future challenges in operating as well as designing (decentralized) electricity systems are presented (Section 1). In particular, we present diverse quantitative results in the context of analyzing decentralized electricity systems. We cover concrete indicators measuring the similarity and applicability of weather data and develop a methodology to generate synthetic PV load profiles by stochastic simulation (Section 5.1 and Section 5.2). Furthermore, we analyze the potential for demand-side flexibility down to the low voltage grid and measure the upsides and downsides of demand-side flexibility reacting to signals, such as variable prices (Section 5.3 and Section 5.4). Finally, we propose a concept of a market-based congestion management mechanism based on market price signals in Section 5.5. We summarize our findings as follows:

- Energy systems develop a more and more decentralized character, both on the (renewable) generation and the demand side. The expected ever increasing stress on the electricity grid infrastructure was confirmed in this study. We can face this challenge by reinforcing the grid infrastructure and making the grid stronger or by improving the congestion management mechanism and making the grid smarter, as described in this work. In any case, grid constraints will have to be considered in the further development of energy systems with a high and growing share of renewable energy.
- Dynamic electricity prices, down to the household level, are widely seen as one or even “the” solution to an increasing need for flexibility and the growing importance of grid constraints. We demonstrate the concrete potential of household flexibility and its effect on the grid load. Our results show that the tariff setup is crucial to avoid a deterioration of critical grid situations. Moreover, we found that centralized market signals alone may not be sufficient to support local grid stability.
- The design process of decentralized markets that carry out market-based congestion management has to happen under consideration of the effects on the centralized system. This challenges the application of traditional optimization models common in energy systems analysis, since the heterogeneity of stakeholders is much higher when analyzing decentralized systems and data is required on a much higher resolution.

There are a number of barriers, why current congestion management approaches are not yet improved in a way as proposed in this study:

- Foremost, there is little information and data on grid congestion caused by RES-E and the way DSOs are dealing with it. While TSOs are obliged to publish information about the transmission grid, DSOs face little obligation to publish data that is essential for conducting research on their grid. Consequently, there exists little research on how to efficiently manage congestion under the uniform-pricing market design of most European countries.

There are a number of general ideas for improving congestion management (e.g. Brandstätt et al. 2011; Trepper et al. 2013 ; Regionale Flexibilitätsmärkte 2014 ; Bundesverband der Energie- und Wasserwirtschaft (BDEW) 2015b). However, concrete concepts and quantitative studies on a more efficient and market-based congestion management are scarce.

- Another barrier for improving congestion management on distribution grid level is the regulation which does not incentivize the DSO to implement efficiency raising measures during times of congestion. This prevents the DSOs to develop enough interest themselves in becoming more efficient through a decentralized market scheme.
- Finally, “smart grid technology” allowing communication and control of a large number of distributed electricity resources is penetrating the market only for a short time now. Once the majority of demand and supply fits in a standardized communication and control protocol as a part of an internet of things, business models to concert these resources in an economically efficient way will become attractive and more and more players will start working on their implementation. Researchers have to anticipate this situation and develop designs on how to concert beforehand.

6.2 Critical review of project limitations

Given the trade-off between scope and conceptual as well as computational manageability it is generally helpful to focus during research and thus limiting the methodological application. In this work we developed and applied a simulation model that suffers from some general limitations which have to be taken into account when interpreting the model results:

We considered only one illustrative decentralized system due to the underlying project constraints. Consequently, a generalization of our findings is not directly possible. For instance, we cannot transfer our results to the whole market area of Germany. Though, the region of Schleswig-Holstein can be considered as a show case for current and future challenges in electricity systems with a high share of RES-E and offers viable links for relevant studies. Similarly, we only model selected input data and agent types in detail (e.g. RES-E feed-in). In turn, different features of decentralized electricity systems are not explicitly covered (e.g. controllable RES-E plants, storage options) and, thus, the systems' flexibility is not fully considered in our analyses. Such limitations are inevitable given the volume of data and the complexity of underlying agent decisions on the required spatial and temporal resolution. From a methodological point of view, the various congestion management schemes which have been addressed during the research are not yet fully implemented and as such a model-based comparison between them is not possible.

6.3 Future research issues

Given the limitations of the research project at hand, several methodological extensions and new applications of the modeling toolbox as well as the processing of additional input data are envisaged for the future. We are planning to combine the congestion management mechanism with our modelling approaches of decentralized flexibility in order to quantify positive effects on grid congestion. Furthermore, some modules of the modeling toolbox are currently not coupled or only to a limited degree which offers potential for future research. Combining the bottom-up model for residential demand with the studies regarding the impact of demand flexibility on distribution networks offers further possibilities for subsequent analyses. Summarized we see the following issues for future research:

- Stronger integration of other energy carriers (e.g. heat, gas) and the transport sector as well as of their potential interactions with electricity systems
- Considering different storage systems and technologies
- More detailed modeling of other electricity consumer types (e.g. services, industry)

- Representation of additional decentralized systems and up-scaling to market area level
- Extension of the considered approaches to congestion management in distribution grids
- Integration of additional wholesale markets (e.g. reserve markets, capacity mechanisms)

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Appendix

Publications and awards resulting from the DEMO research project

Awards

Best Reviewer Award 2014, Energy Research & Social Science (ERSS), ISSN: 2214-6296

Best Reviewer Award 2015, Energy Research & Social Science (ERSS), ISSN: 2214-6296

Networking Grant 2015, Karlsruhe House of Young Scientists (KHYS), Karlsruhe Institute of Technology (KIT)

Publications and conference presentations

Hayn, M., Bertsch, V., Fichtner, W., 2014. Electricity load profiles in Europe: The importance of household segmentation. Energy Research & Social Science 3, pp. 30–45.

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Schermeyer, H.; Bertsch, V.; Fichtner, W., 2014. Validation and utilization of numerical weather model data in energy systems analysis of decentralized electricity production. in: Proceedings of the 7th International Scientific Conference on Energy and Climate Change, 8.-10.10.2014, Athens.

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The increasing electricity generation from renewable energy sources (RES) as a result of the German "Energiewende" leads to the expansion of distributed generation capacities of various technologies. This trend is expected to continue and causes major challenges for the traditional electricity sector, which originally was designed for large generation units and low fluctuation. In this study we develop a flexible modeling toolbox for decentralized electricity systems with an agent-based simulation approach at its core. Two RES-E generation models for wind and PV each with a high temporal and spatial resolution are presented and approaches to model specific aspects of the demand side in detail are introduced. The implementation of an AC load flow algorithm is described and the concept of a market-based congestion management mechanism based on market price signals is outlined.

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