ASSESSING THE POTENTIAL OF IMMEDIATE TECHNICAL OPTIONS FOR AN OPTIMIZED RENEWABLE ENERGY SUPPLY

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For Germany to achieve its ambitious political targets for the reduction of greenhouse gas emissions in the electricity sector, major energy scenarios and reports project that the country will have to expand its renewable power generation capacities massively by 2035. As is the case for many countries, Germany will have to heavily rely on variable renewable energy sources (vRES), especially wind and solar photovoltaics. The characteristics of power production from vRES pose challenges for a stable and reliable future power supply system. Accordingly, the research into the technical challenges of integrating large shares of vRES into the power system has therefore attracted much interest in recent years; however, major energy scenarios seem to not cover integration options associated with the fast development of vRES correctly and lag behind the fast development in renewable energy technology.

In this cumulative thesis, selected technical options for the integration of renewable energy sources into the power supply system have been investigated in a case study of Germany and a selected transmission system in Germany. To identify and assess these emerging integration options, the research in this PhD thesis covers the most promising technical options for the integration of vRES in the form of i) system-friendly layouts of wind and solar PV; ii) optimal capacity mixes of vRES; iii) the spatial allocation of wind turbines and the impact assessment of wind turbine allocation; and iv) the contribution of flexible power generation from biomass to complement vRES. Therefore, a mix of methods has been applied, ranging from numerical optimization based on time series data, GIS potential mapping and allocation including a multi-criterial decision analysis.

The results show how the investigated options can facilitate the transition for a power supply system dominated by high shares of vRES in the near to medium term. A faster energy transition with significantly reduced overall vRES power generation capacities, less Excess Energy (EE) generation, improved cross-sectorial energy provision and flexible bioenergy as a complement to vRES are the major findings of the investigated options in this thesis.

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For Germany to achieve its ambitious political targets for the reduction of greenhouse gas emissions in the electricity sector, major energy scenarios and reports project that the country will have to expand its renewable power generation capacities massively by 2035. As is the case for many countries, Germany will have to heavily rely on variable renewable energy sources (vRES), especially wind and solar photovoltaics. The characteristics of power production from vRES pose challenges for a stable and reliable future power supply system. Accordingly, the research into the technical challenges of integrating large shares of vRES into the power system has therefore attracted much interest in recent years; however, major energy scenarios seem to not cover integration options associated with the fast development of vRES correctly and lag behind the fast development in renewable energy technology.

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Zusammenfassung

Um die ehrgeizigen politischen Ziele zur Reduzierung der Treibhausgasemissionen im Stromsektor zu erreichen, stimmen alle relevanten Energieszenarien überein, dass Deutschland kurz- bis mittelfristig bis 2035 seine Kapazitäten zur Erzeugung erneuerbarer Energien massiv ausbauen muss. Deutschland ist dabei wie viele andere Länder auch stark von fluktuierenden erneuerbaren Energiequellen (fEE) abhängig, insbesondere von der Wind- und Solarenergie. Die Spezifika der Stromerzeugung von fEE stellen neue und besondere Herausforderungen an ein zuverlässiges Stromversorgungssystem der Zukunft. Entsprechend hat die Erforschung der technischen Optionen bei der Integration großer Anteile von fEE in das Stromnetz in den letzten Jahren stark an Interesse gewonnen. Allerdings scheinen Energieszenarien die mit der schnellen technologischen Entwicklung einhergehenden Integrationsoptionen bisher nicht korrekt abzubilden.

In der vorliegenden kumulativen Dissertation wurden ausgewählte technische Optionen für die Integration erneuerbarer Energiequellen in das Stromnetz im Rahmen einer Fallstudie für Deutschland sowie ausgewählter Übertragungsnetze in Deutschland untersucht.

Zur Identifizierung und Bewertung der Integrationsmöglichkeiten, widmete sich die Arbeit den vielversprechendsten technischen Integrationsoptionen in Form von i.) systemfreundliche Auslegung von Wind- und Solaranalgen; ii.) optimale Kapazitätsanteile von Wind- und Solaranlagen, iii.) der räumlichen Allokation und Bewertung von Windenergieanlagen in herkömmlicher als auch systemfreundlicher Auslegung; iv.) und dem Beitrag welchen die flexible Stromerzeugung aus Bioenergie als Ergänzung zu steigenden Anteilen an fEE erbringen kann.

Es wurde ein Methodenmix zur Beantwortung dieser Forschungsfragen genutzt, der von der numerischen Optimierung auf Basis von Zeitreihendaten über die räumliche Potenzialkartierung und Allokation bis hin zur multikriteriellen Entscheidungsanalyse reicht.

Die Ergebnisse zeigen wie der Übergang zu einem von hohen Anteilen an vRES gekennzeichneten Stromversorgungssystem erleichtert werden kann. Darunter Möglichkeiten zur Beschleunigung des Umstiegs auf erneuerbare Energien mit deutlich reduzierten Erzeugungskapazitäten von Wind- und Solaranlagen, weniger negative Residuallasten und negativer residualer Energie, verbesserte Sektorenkopplung und die Potenziale der flexiblen Stromerzeugung aus Bioenergie als Ergänzung zu fEE.

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List of Publications

- Tafarte, P., Das, S., Eichhorn M., Thrän, D. (2014): Small adaptations, big impacts: Options for an optimized mix of variable renewable energy sources. Energy.

- Tafarte, P., Eichhorn, M., Thrän, D. (2019): Capacity Expansion Pathways for a Wind and Solar Based Power Supply and the Impact of Advanced Technology—A Case Study for Germany. Energies.

- Tafarte, P., Buck, P. (2017): Integration of wind power — Challenges and options for market integration and its impact on future cross-sectorial use. 14th International Conference on the European Energy Market (EEM), Dresden, Germany, 2017, pp. 1-5.

- Eichhorn, M., Tafarte, P., Thran, D. (2017): Towards energy landscapes - Pathfinder for sustainable wind power locations. Energy.

- Tafarte, P., Hennig, Ch., Dotzauer, M., Thrän, D. (2017): Impact of flexible bioenergy provision on residual load fluctuation: a case study for the TransnetBW transmission system in 2022. Energy, Sustainability and Society.

- Tafarte, P., Das, S., Eichhorn, M., Dotzauer, M., Thrän, D. (2015): The potential of flexible power generation from biomass: a case study for a German region.
  In: Thrän, D., (ed.) Smart bioenergy: technologies and concepts for a more flexible bioenergy provision in future energy systems. Chapter 9.4: The potential of flexible power generation from biomass: a case study for a German region. Springer, Cham, pp. 148 – 159 (2015).

List of Acronyms

dRES	dispatchable renewable energy sources
DSM	demand-side management
FLH	full load hours
GIS	geographic information system
GW	gigawatt
MW	megawatt
RL	residual load
RLDC	residual load duration curve
RQ	research question
SFWT	system-friendly wind turbines/advanced wind turbines
solar PV	solar photovoltaic
STWT	standard wind turbine/baseline wind turbine
TS	transmission system
TWh	terrawatt hours
VRE/vRES	variable renewable energy/variable renewable energy sources
WT	wind turbine

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I. Introductory chapters

1. Introduction

1.1. Background

The first oil price shocks in the 1970s were the trigger for the initial, remarkable development of technologies for modern renewable energy generation, especially wind and solar power. In recent years, the introduction of such alternative energy sources has gained much momentum in many countries, driven again by increasing energy prices, but also by environmental concerns and especially by policies to mitigate climate change from anthropogenic greenhouse gas emissions [7, 8].
In Germany, the coming into force of the Electricity Feed-in Act in 1991 and the Renewable Energy Sources Act (EEG) in 2000 [9] initiated a strong development of renewable power generation. In 2015 already 31.6% of the power consumption in Germany was provided by renewable sources [10]. Reacting to the nuclear incident in Japan in 2011, the German government reformulated its goals for the contribution of renewables in the energy sector. The new objectives stated that up to 45% of power consumption should be covered by renewables in the medium term (2030) and at least 80% in the long-term, by 2050 [11]; recent political statements aim at even more ambitious targets. Additionally, it is expected that renewable power production will also fuel the decarbonization of mobility and of the heat sector and allow for clean industrial production. Thus, the requirement for renewable energy production has grown in line with the expectations and applications, while the cause of climate protection calls for an even faster energy transition and decarbonization. In the case of Germany, the challenge is to speed up this transition while the potentials for renewables are limited due to the specific availability of renewable sources and the limited spatial availability for additional renewable energy infrastructure in a densely populated country.

Regarding the transition towards renewables in the power sector, landmark energy scenarios and reports project that Germany will depend to a large extent on variable and weather-dependent sources of energy, such as wind and solar energy (Figure 1). The inherent variability over time of these variable renewable energy sources (vRES) poses new challenges for their integration into the power supply system, as supply and consumption always have to be balanced. Historically, fossil, nuclear and other dispatchable renewable energy sources (dRES) like hydropower and to a smaller extent bioenergy have dominated power supply. But the existing conventional power generation capacity, the transmission and distribution system as well as the power demand will have to adapt to an increasing share of energy from vRES [12-14]. Consequently, with the projected decline of fossil and nuclear power generation as dispatchable sources and a substantial build-up of new capacities from vRES, the rising volatility in power supply will become a major challenge for power system stability and security of supply.

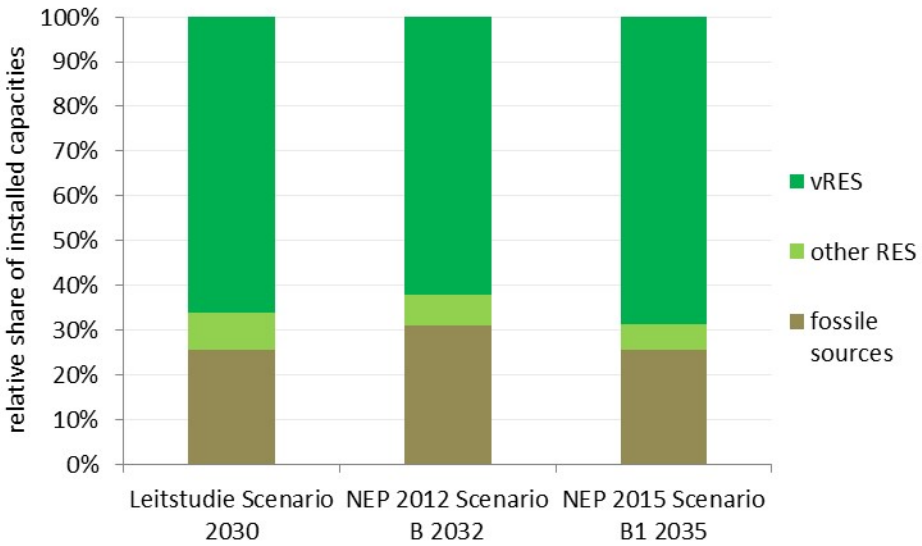

Figure 1: ***relative share of vRES (wind and solar PV), other RES and fossile generation capacities in the overall projected power generation capacities for the 2030-35 timeframe for Germany according to three different energy scenarios and reports. Based on data from [1-3].***

Current research suggests that one of the main challenges of a power system aiming at up to 80% energy supply from vRES is to adapt to large fractions of excess and deficit energy over time [15-17]. With vRES becoming the main source of Germany's future power system, flexibility options like electric energy storage, DSM, grid reinforcements and interconnectors have been identified as crucial aspects in the future [13]. Electric energy storage in particular is regarded as a key asset for integrating high shares of vRES into the power system [18, 19]. However, without a substantial increase in electric energy storage capacity in the short to medium term, which is not to be expected because of current economic and technological limitations [16, 20-26], other options for the integration of vRES are needed to integrate their continuously rising share into the power system.

Other relevant options identified but not researched in detail are centered on the provision of power production from vRES themselves. In this respect, the specific characteristics of vRES, like daily and seasonal patterns in resource availability, are considered to create a reliable, economic and environmentally-friendly power supply system. Additionally, the technology choices for harvesting the different variable renewable energy sources likewise play a critical role for their integration into the power supply system. For example, the productivity and temporal generation characteristics of vRES installations depend not only on the available physical generation potential like solar irradiation for solar PV and the kinetic energy potential for wind power, but also on the utilized technology and layout of the generation systems. Both factors are relevant for the efficient integration of vRES into power systems and major developments in wind and solar power technology can affect to a large extent the shape of future vRES-based power supply systems. Landmark energy scenarios for Germany also have to address this issue, but do these scenarios adequately cover the continuous development of vRES technologies and their potential impact on vRES integration?

1.2. vRES in energy scenarios

Energy scenarios are helpful tools to provide society and policy makers with consistent projections of possible futures for the energy sector. Energy scenarios are well-suited to cover possible long-term developments, can entail optimization methods and can create consistent scenarios based on technical or economic criteria. For Germany, all relevant scenarios coherently [1-3, 27, 28] foresee that the mainstay of Germany's future renewable energy supply will consist of vRES. The options to overcome the inherent challenges of integrating high shares of these vRES are to a large extent dependent on the technological developments in energy technologies. An initial review of existing energy scenarios and projections of the capacity expansion of vRES at the beginning of this PhD project in 2012 showed that the technological developments in vRES are not correctly implemented in the most relevant energy scenarios for Germany's energy transition [1-3]. Energy scenarios do not cover the options for a system-oriented power provision of wind, solar PV and bioenergy and thus leave out important potentials for the integration of high shares of vRES in the power sector. Technical learning processes and barriers associated with the introduction of new technologies have rapidly made projections for vRES technologies outdated in recent years. Examples are the fast techno-economic development of solar PV since 2000 [29] or, in contrast, the very limited progress seen in geothermal power generation compared to the expectations for the expansion of this RES, globally as well as in Germany. This PhD study therefore aims to explore, identify and assess options in the near to medium term to improve the integration of renewable sources in the power sector.

1.3. Technical developments and options for the integration of vRES

With regard to technical options to improve the integration of high shares of energy from vRES, several studies have been published [30] and two major trends and technology advancements for wind and solar PV systems have been identified.

The **first technological option** is solar PV systems with their aperture surface facing east and west [31]. In contrast to the standard orientation of solar PV panels to the south in the northern hemisphere, optimizing their annual energy production, orienting PV panels east and west can mitigate excessive feed-in at noon and shift power production to a limited extent towards morning and evening hours, thus covering consumption profiles better than solar PV system with an azimuth orientation towards the south [31, 32]. The trade-off is that this non-optimal orientation of solar PV systems leads to a reduction in annual energy production (AEP). But the improved feed-in characteristics as well as the possible savings in support structures on rooftops that are not south-facing and the possibility of spatially denser arrangements, especially for larger solar PV systems in open landscape installations, are further advantages of these system-friendly solar PV setups. The latest innovation in the field is bifacial solar PV modules in a vertical installation [33, 34]; these maximize the potential regarding the shift of power production towards morning and evening hours, and are even expected to increase AEP in comparison to the standard monofacial solar PV panels in a south-facing setup.

The **second technological option** is the introduction of horizontal axis wind turbines with a low ratio of installed generator rated capacity in relation to the rotor swept area [W/m²]. Wind turbines with the described characteristics are also called advanced wind turbines (publication one[1]), low wind speed wind turbines, or most recently, system-friendly wind turbines (SFWT, publications two and three).

SFWT became available with the advent of modern adaptive rotor blade systems that can pitch the rotor blades on their longitudinal axis, reducing mechanical forces to the wind turbine and increasing rotor diameters and rotor swept areas considerably [35]. Furthermore, with the expansion of wind power in many European countries, the availability of sites with high wind resources for erecting wind turbines has decreased and new projects have had to deal with lower wind resources on site. As a consequence, hub heights above ground level of wind turbines have increased in order to offset low wind resources [5]. SFWT are therefore characterized by a combination of a low ratio of installed generator rated capacity per rotor swept area [W/m²] and elevated hub heights. The resulting feed-in from these SFWT is characterized by higher full load hours (FLH)[2], higher median power production and reduced peak feed-in in relation to the AEP compared to standard wind turbines (STWT).

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[1] After publication one of this thesis has been published in 2014, a report for the IEA written by Hirth and Mueller [30] likewise covered the aspect of advancements in renewable energy technology, but used the term system friendly variable renewable energy (VRE) instead of the term advanced technologies used by the author of this thesis. Since then, the term system friendly VRE technologies or system friendly wind power became more popular at least in the field of energy economics [30, 36, 71]. As a consequence, this thesis uses both terms synonymously.

[2] Full load hour(s) is a performance indicator for the energy production of a power generation system. Full load hours can be derived by dividing the AEP by the rated capacity of the system.

This provides feed-in characteristics that help to mitigate negative effects associated with a high share of wind energy production in power systems [5, 30, 36-38]. A report from Fraunhofer [39] on the wind energy development in Germany covered SFWT and projected that SFWT will be capable to reach up to 4650 FLH in the northern part of Germany and 2,750 FLH in the southern of Germany by 2033. However, the immanent implication for the power system regarding installed capacities for a targeted renewables share, expansion pathways for renewables, the requirement for electrical energy storage and cross-sectorial use remained uncovered by research. Furthermore, with respect to the spatial allocation of WT, the technological development of SFWT unlocks additional potential sites for wind power with considerably high FLH, as shown in Figure 2 in a comparison with a modern STWT at identical hub height [40-42]. So that the development of SFWT also has a significant impact on the availability of potential sites for wind power generation.

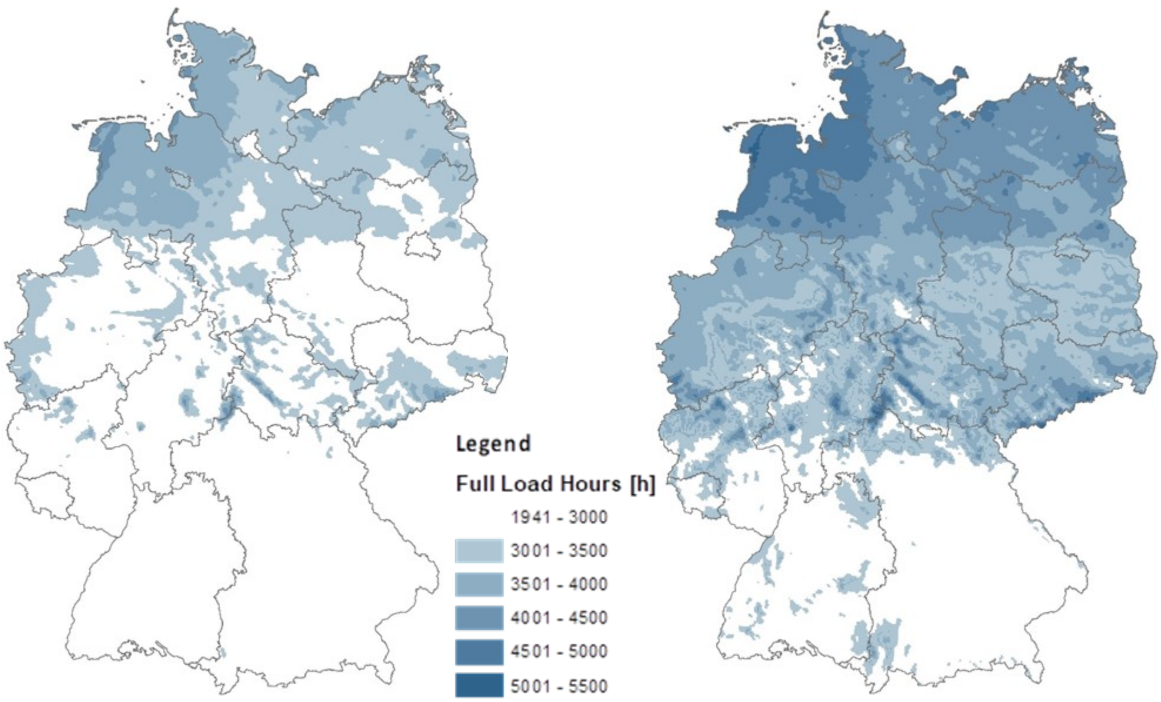


Figure 2: ***Specific AEP with a colored threshold at 3,000 FLH for two different WT models: STWT on the left and SFWT on the right. Calculation and illustration based on wind potential data from DWD and power curves from the manufacturers [40-42] .***

A **third technological option** is the use of bioenergy for power production to complement the significant future vRES generation capacities. Bioenergy, as a renewable energy source which is primarily generated in a thermal conversion process [43-45], offers the potential to complement vRES by offsetting the variability in RL introduced by vRES and serving as a dispatchable source of power. In some respects, it can substitute the still restricted volume of electric energy storage for high shares of vRES in the power supply. Energy scenarios like [1, 2] assume that power production from bioenergy will be dispatched flexibly and adapt to volatile vRES and RL and thus contribute to balance Germany's future power system. The question to what extent current bioenergy technology concepts can operate flexibly in the near to medium term is the subject of current research.

As major studies and energy scenarios [1-3] have so far failed to introduce and model the presented technical options, significant potentials for the improvement of vRES integration have not been properly investigated and are therefore addressed by the following research questions investigated in this PhD.

2. Research questions

Given the options described in 1.3 have not been covered by studies and energy scenarios so far, four relevant research questions have been developed in order to assess the potential offered by selected options in the near to medium term. It is first necessary to verify whether current landmark studies cover the identified technical options in the field of renewable energy technology correctly with regard to the implications for the integration of high shares of vRES into power supply systems. From a technical perspective, this PhD thesis therefore investigates the described options in vRES technology to answer the first research question: **Are there easily adoptable vRES technology options (advancements in wind and solar PV technology), and what potential do they hold to improve the integration of vRES in the near to medium term (RQ1)?**

Based on the technological potentials assessed in research question one, an additional non-technological option to improve the integration of vRES in the power supply is identified: the coordination of the capacity expansion and installed capacities of vRES technologies. By optimizing the capacity mix of different vRES technologies that leads to optimal shares of vRES like wind and solar PV, it is expected that the integration of vRES can be improved by the complementariness of the temporal supply patterns, which are then better matched to the power demand, resulting in less excess energy from vRES having to be curtailed. The combination of these options has not been studied to date, leaving a gap in this area of research.
The second research question of this PhD thesis is therefore formulated as: **Do optimal capacity mixes of different vRES technologies exist which improve their integration into the power system (RQ2)?**

Closely linked to the expansion of vRES capacities and infrastructure, the spatial dimension of this transition towards renewables is increasingly gaining relevance. Bearing in mind the fundamental conceptual work of Brücher [46] regarding the spatial implications of this energy transition, the spatial aspects of this transformation become apparent. The shift from today's predominant fossil fuels with a very high energy and power density towards a renewables-based energy system using almost exclusively direct or indirect solar radiation fluxes with much lower energy and power density will increase land use to provide comparable amounts of energy to that provided by fossil fuels today [47]. The spatial footprint of the necessary infrastructure to collect and transmit most of the RES will potentially conflict with other land uses, especially in Germany with its comparably high population density. In a landscape context, this calls for a careful use of the limited space and resource base available. Social acceptance, nature protection and technical aspects must be taken into account when the substantial increase in power production, especially from wind power, is implemented. The spatial allocation of the expanding vRES capacities is already a critical aspect in the energy transition, and the projected expansion of vRES capacities will put additional pressure on land use. In line with the options and potentials identified for the integration of wind power, namely system-friendly wind power, the spatial land use patterns and land consumption of future wind power installations is investigated for a case study region in Germany. Specifically, the effects are analyzed for STWT as well as SFWT.

This part of the PhD thesis thus addresses a third research question of high relevance: **Which spatial effects result from the options investigated under research questions one and two compared to a reference case (RQ3)?**

The increasing volatility introduced into the residual load by a rising share of vRES poses challenges in the power supply system with its need for a permanent equilibrium of demand and supply of electricity. With the projected decline in dispatchable generation capacities from fossil and nuclear power generation in Germany, power production from biomass is regarded as a renewable dispatchable option for balancing power systems in the future. To address this issue, the modeling of flexible power provision from bioenergy is used to assess the possible contribution of bioenergy in the near to medium future. Based on different bioenergy technologies and their specific suitability for a flexible provision of power, the applied model dispatches bioenergy flexibly in order to minimize volatility in RL in two different TS in Germany.

The aim is to answer the fourth and final research question of this PhD thesis: **Can flexible power provision from bioenergy contribute to an improved system integration of vRES (RQ4)?**

In summary, the individual research questions address relevant questions for the integration of vRES in future power supply systems: which vRES technology and which technology mix should be targeted (RQ1 and RQ2), which vRES technology and technology combination provide efficient capacity expansion pathways (RQ2), what are the spatial patterns and trade-offs for the allocation of onshore wind power as the most relevant vRES technology in the spatial context (RQ3), and finally, to what extent flexible bioenergy can contribute to improve the integration of vRES (RQ 4).

3. Methods applied in this PhD thesis

In the following chapter, an overview of the applied methods and approaches to the individual research questions is given. Table 1 below provides information on the different publications forming this PhD thesis, the individual research questions addressed, the targeted aspects, the applied method, the data used, the study region investigated, the time horizon or framework as well as further relevant comments on the publications. For a detailed description and discussion of the applied methods, readers are referred to the individual publications presented in this PhD thesis.

Table 1: ***Overview of the different aspects of the articles to address the research questions of this PhD thesis.***

Publication	Research questions	Objective	Method	Data	Study region	Time horizon or framework	Comments
One	RQ1, RQ2	Minimizing excess energy including system friendly technologies and optimized vRES mix	Numerical optimization	Time series for wind, solar PV and power consumption	50Hertz	REN share of 50% and 80% on power consumption	No electrical energy storage, no limitations regarding power grids
Two	RQ1, RQ2	Identifying capacity minimal expansion pathways including system friendly technologies	Numerical optimization	Time series for wind, solar PV and power consumption	Germany (all four TS)	Various REN shares for the near-to-medium term	Electrical energy storage from existing PHS, no limitations regarding power grids
Three	RQ1, RQ2	Assessing the market value of wind power generation for different WT types (part one), technical assessment of cross-sectorial use of EE from vRES (part two)	Economic assessment (part one), numerical calculation (part two)	Time series for wind, solar PV, power consumption and spot market prizes	Germany (all four TS)	Year 2015 (part one) and year 2035 (part two)	No power storage considered, no limitations regarding power grids
Four	RQ3	Mono- and multi-criterial optimization of the spatial allocation of WT regarding energetic, social and nature conservation criteria	GIS-based modeling MCDA	Spatial data	50Hertz	40 TWh from onshore wind, derived from the NEP 2016 2035 B1 scenario	
Five	RQ4	Minimizing variability of residual load using flexible bioenergy	Numerical optimization	Time series for wind, solar PV and power consumption	TransnetBW	Year 2022	No limitations regarding power grids
Six	RQ4	Minimizing the variability of residual load using flexible bioenergy	Numerical optimization	Time series for wind, solar PV and power consumption	50Hertz	Year 2011 and year 2030	No limitations regarding power grids

Overall, a set of different methods have been developed and applied in each of the presented publications in order to respond to the different research questions. For the assessment of the technical options for an optimized renewable energy supply, different scientific approaches and methods have been elaborated that focus on the performance of key system indicators. The indicators selected to represent the performance of vRES-based power systems are excess energy (EE) production, the renewables share, the required power generation capacities from vRES and the primary descriptive statistics on RL, including the residual load duration curve (RLDC). This set of indicators provides adequate coverage of the most relevant criteria for the technical performance of power systems with high shares of vRES from a systems perspective [14, 17, 48].

Compared to various economic models for power system analysis or technically detailed models of single technologies, the applied models are restricted to covering these key performance parameters. Hence, the applied modeling of electric energy storage, system-friendly solar PV or flexible bioenergy are simplified in comparison to dedicated models for specific subjects or the real-world operation of these systems. Consequently, the presented approaches do not include factors that are out of the scope of this research, like any sort of (economic) cost, elasticity of power demand or DSM, factors regarding the regulatory framework, power market design or support schemes. In fact, none of the applied models in this PhD thesis directly optimize monetary cost, benefits or welfare. However, many of the utilized key indicators are linked to basic economic aspects, for example the amount of required generation capacities from vRES with its linkage to the volume of necessary investments or excess energy that is connected to the market value of vRES.

With the exception of publication four, all other publications utilize feed-in time series data of vRES. Although synthetic and modeled feed-in data derived from numerical weather models have become popular, the use of registered time series from a common data platform [49] has the advantage of facilitating the comparison of results from different models. Additionally, the use of registered time series data for specific regions in all the presented publications allows applying tested and verified time series. As a downside, the use of registered time series data results in limitations regarding the degree of freedom the model has on the structure of future power systems. To give an example, a possible large-scale spatial reallocation of WT or solar PV capacities over the geographic area of the study regions would allow for a higher geographical smoothing effect in power production that would result in different feed-in time series for wind power. An analogous example on the demand side of the modeling is the exogenously provided consumption time series, which does not cover possible impacts from DSM or changes in temporal power consumption patterns in the future. These aspects are not covered by the presented work. However, for the tasks formulated in the research questions, it was not necessary to apply synthetic time series data or to include the innumerous variations enabled by the implementation of these aspects. Instead, the tested and verified time series which were applied for this modeling approach have the advantage that one can easily adapt existing time series databases [49] for application in other study regions than the ones investigated, and it is a well-established approach for scientific energy models [19, 48, 50-52]. The applied modeling of the time series data for SFWT that forms one of the key aspects investigated in this thesis has been checked against real time series data for individual wind turbine sites as well as by other authors using time series derived from numerical weather models [36, 51, 53].

Publication four is based on a GIS modeling for the identification and mapping of potential sites for WT [54-56] and combines state-of-the-art GIS tools to identify potential areas that are legally and technically feasible for wind power installations. Within the potential sites, a new GIS tool [56, 57] developed by colleagues at UFZ (without any contributions from the author of this thesis) was applied to maximize the number of potential WT for the calculated potential areas. This allows for an assessment of individual WT within the pool of legally and technically feasible potential WT and to optimize the allocation of WT under various criteria, namely human well-being, nature protection and number of required WT to achieve defined renewable targets from wind power. Based on the GIS data, a mono-criterial and a multi-criterial analysis for the optimal spatial allocation of WT were performed taking into account recently published methods in this field of research [58-62].

The focus of research question four (Can flexible power provision from bioenergy contribute to an improved system integration of vRES?), which is addressed in publications five and six, is on the assessment of technical concepts for flexible bioenergy production in the context of a regional power supply with increasing shares of vRES. Based on regional time series data, the daily variances in RL are minimized by dispatching bioenergy generation capacities as the objective function [63]. The applied modeling covers technological concepts for flexible power provision from bioenergy in the near to medium term. Power provision from bioenergy, particularly biogas and solid bioenergy, is modeled in line with the technical potential of the different technological concepts [43-45, 64-66]. Nevertheless, for a broad assessment of flexibility options beyond the technical feasibility of the investigated bioenergy concepts, the applied modeling should be extended to cover the more complex interplay of the various technical options [13, 67].

It should finally be noted that all methods are based on the assumption of an idealized and unlimited transmission capacity (copper plate) and exclude electric energy storage (except publication two) and DSM. These are crucial premises of the presented work. Therefore, a possible future introduction of large-scale electric energy storage will likely affect the presented results significantly and should be kept in mind, as is also the case for substantial limitations in the future power transmission infrastructure, DSM or cross-sectorial use of electric energy.

4. Discussion and conclusion

The overall objective of this PhD thesis is to identify and assess options for the improved integration of high shares of vRES in the power system in the near to medium term. After providing a brief overview of the major results obtained in the six presented publications in Table 2, the discussion of the results will follow the order of the four research questions:

Table 2*: Overview of the most relevant aspects and major results covered by the presented articles of this PhD thesis.*

Publication	Method	Energy source	Study region	Main results
One	Numerical optimization	Wind, solar PV	TSO 50Hertz	• System friendly layouts achieve a 50% (80%) REN share from vRES with 53% (18%) fewer excess energy than standard layouts • System friendly layouts achieve a 50% (80%) REN share from vRES with 30% (32%) fewer installed capacities than standard layouts
Two	Numerical optimization	Wind, solar PV	Germany	• Faster transition towards high vRES shares with optimal capacity expansion • Wind power, especially in system friendly layouts, dominates efficient pathways • A solar PV dominated supply system requires higher installed capacities and additional power storage
Three	Economic assessment, numerical calculation	Wind	Germany	• SFWT allow for up to 11% higher market values in 2015 compared to STWT • SFWT allow for a faster transition towards high renewable shares with reduced installed capacity from wind • Cross-sectorial use of excess energy is facilitated using SFWT
Four	GIS-based modeling, MCDA	Wind	TSO 50Hertz	• Reduction of 31% in WT number and installed capacities possible using SFWT in comparison to STWT for the multi-criterial optimization • Reductions in the range of 19% to 32% in cumulated impacts using SFWT compared to STWT for the multi-criterial optimization
Five	Numerical optimization	Bio-energy	TSO Transnet-BW	• Requirement for flexible bioenergy depends to a large extent on the share of vRES on power consumption, which differs substantially across regions • Flexible bioenergy can reduce daily variability in RL by up to 56% and reduce excess energy production from vRES • Today`s concepts for flexible bioenergy are well capable to complement high shares of solar PV on REN share
Six	Numerical optimization	Bio-energy	TSO 50Hertz	

The following will discuss how this PhD thesis answers the challenges of vRES integration that were addressed by the four research questions above. Regarding research question one (Are there easily adoptable vRES technology options, and what potential do they hold to improve the integration of vRES in the near to medium term?), the presented work, especially publications one, two and three, showed from a system perspective that technological advancements in the form of system-friendly layouts of wind and solar PV systems have a high potential to improve the integration of vRES into power supply systems. In all presented publications, it was assumed that for the near to medium term electric energy storage capacities will be one major bottleneck for the integration of large shares of vRES into the power supply. In publication one, the capacity combination of wind and solar PV to achieve the defined renewables share was optimized in order to minimize excess energy production (or cumulative negative residual load) and thus improve the effectiveness of vRES in power supply in the absence of electric energy storage or any demand-side response [68]. In the case study for the 50Hz transmission system, the optimization for two scenarios, for a renewables share of 50% and 80%, showed that advanced technologies provide significant advantages regarding the amount of excess energy produced and the required overall vRES capacities. A reduction of the required capacities from wind and solar PV by 30% (Figure 3) for a 50% renewables share (32% for 80% renewables share respectively) was achieved using system-friendly layouts, while excess energy was likewise reduced by 53% (18% for 80% renewables share).

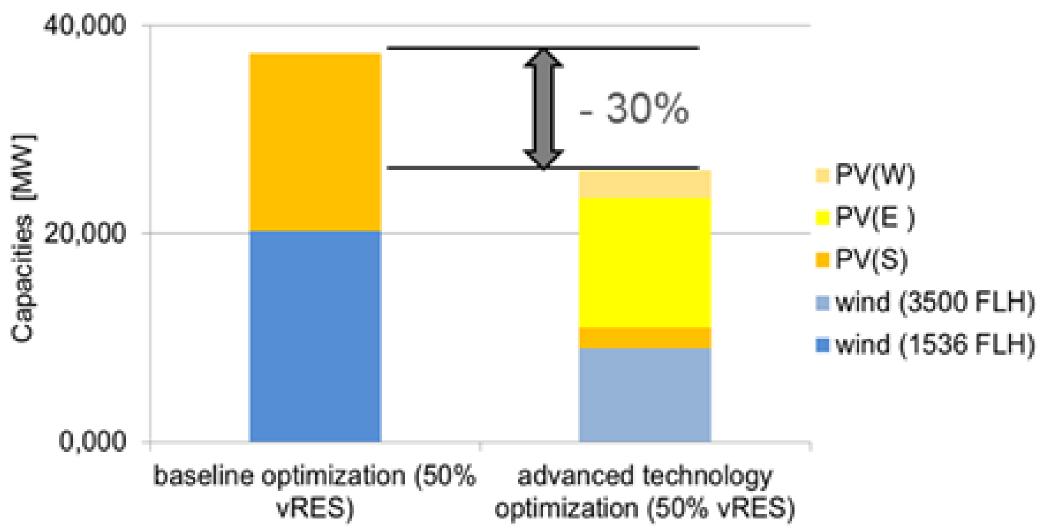


Figure 3: ***Graph showing the differences in the optimizations including either only standard technologies or also advanced technologies from wind and solar PV. Up to 30% in overall installed vRES capacities can be spared for the 50% renewables share goal [68].***

System-friendly wind turbines (SFWT) in particular enable significant improvements in terms of required capacities to provide the targeted renewables shares, the reduction of excess energy and maximum feed-in from vRES. Solar PV systems in contrast provide only marginal improvements in the modeled system-friendly layout, as feed-in patterns are still very similar to those of standard setups while the lower productivity in terms of FLH must be compensated potentially by higher installed capacities.

Publication three ("Integration of wind power — Challenges and options for market integration and its impact on future cross-sectorial use") entails an ex-post assessment of 2015 market values of power production for various wind turbine types (STWT and SFWT) based on actual wind measurement data at different sites in Germany [69]. This part of publication three is based on the master's thesis of co-author Patrick Buck, who was supervised by the author of this PhD thesis [70]. This first empirical assessment of market values for actually registered wind speed and power generation time series data from wind turbines instead of modeled wind power production time series or modeled market data revealed an increased market value of up to 11% for SFWT compared to legacy STWT. The results support the outcomes of other studies [36, 38, 71, 72] that are based on modeled data for wind and spot market prizes.
In the second part of publication three, which was developed and written by the author of this thesis and introduced as a part of it, the technical impact of system-friendly wind power for future power supply scenarios was investigated with a focus on renewables shares and the cross-sectorial use of excess energy. As already shown in publication one in the form of RLDC, the structure of EE is significantly affected by system-friendly layouts of vRES, and so the impact of SFWT was further investigated with regard to potential cross-sectorial uses of EE. To do so, the baseline scenario case with a rather low 2,007 FLH projected for 2035 in accordance with the NEP 2016 2035 B1 scenario for Germany[3] was compared with two alternative scenarios that included wind power generation from SFWT with a higher average FLH of 3,000 h, as modeled in publications two and four. The resulting differences in volume and structure of excess energy from vRES were calculated and are presented in Table 3.

Table 3: ***Scenario framework and results of time series calculations from publication three. Solar PV capacities remain at 59.9 GW as well as total power demand of 535.4 TWh [68].***

[3] Only onshore wind power capacities where subject to alterations throughout the different scenarios. Solar PV as the other ain vRES remained unchanged at the level projected in NEP 2016 2035 B1 scenario, so that no optimal vRES mix from wind and solar PV was simultaneously targeted in article three.

	Scenario framework			Results			
	Installed capacity wind onshore [GW]	AEP [TWh]	Full Load Hours [h]	Renew-able share [%]	Excess energy [TWh/a]	Max excess power [GW]	Hours of excess [h/a]
Baseline							
NEP 2035 B1	88.8	178.2	2,007	42.7	7.7	44.7	635
System-friendly wind scenarios (SFW)							
SFW I	59.4	178.2	3,000	43.3	4.3	36.9	543
SFW II	88.8	266.4	3,000	54.7	31.6	66.3	1,588

The temporally resolved analysis for Germany shows that the introduction of SFWT has a very significant impact on the volume and temporal structure of excess energy from vRES. In the first alternative scenario (System-friendly Wind I or "SFW I"), in which an identical annual energy production from wind energy is targeted compared to the NEP 2035 B1 baseline scenario, a reduction in wind power capacity of 29.4 GW in comparison to the 88.8 GW in the baseline scenario can be achieved using SFWT. Additionally, excess energy from vRES is reduced by 40% while the resulting renewables share is even slightly increased by 0.6%.

In a second alternative scenario (System-friendly Wind II or "SFW II") that assumes an identical overall wind capacity of 88.8 GW compared to the baseline NEP 2016 2035 B1 scenario, the renewables share can be increased by 12% and excess energy is available for over 1,500 h per year using SFWT, providing a much broader energetic and temporal basis for cross-sectorial uses compared to the 635 h of excess energy in the baseline NEP scenario.

As a result, SFWT allow either for a significant reduction in overall capacities to achieve defined renewables targets (SFW I) or, for the same installed wind capacity as in the baseline scenario, an improved energetic and temporal basis of excess energy for cross-sectorial use with the benefit of a much higher renewables share (SFW II). From this perspective, the identified impact of SFWT on the key system indicator excess energy is very relevant for energy transition scenarios in Germany in the coming years, as it allows for a faster transition towards higher renewables shares while in the longer term cross-sectorial applications can benefit from the improved temporal availability of excess energy provided by SFWT.

One can therefore conclude from the modeling in publications one and three that the substantial technological advancements in the field of vRES, especially in the form of SFWT, are capable of improving the integration of vRES in the near to medium term. Both publications show that the increase in FLH and the improved temporal feed-in patterns from SFWT offer either a faster transition to set renewables shares, as less overall capacities are required for a set renewables target, or higher renewables shares and excess energy for cross-sectorial applications at a given wind power capacity in terms of installed MW. These advancements have so far not been incorporated into landmark energy scenarios for Germany.

These robust findings from publications one and three are underlined by the rapid development of SFWT during the writing of this PhD thesis, which further contributed to the innovation gap of landmark energy scenarios and projections. Wind turbines implemented in 2016 in Germany are estimated to operate at 2,721 FLH [5] while new SFWT designs available from 2019 onwards are designed to achieve FLH in the range of 3,400-4,200h at reference site wind conditions (excluding losses [6]). In contrast, energy scenarios and studies [1-3] assume FLH to reach only 2,007–2,300 FLH by 2030/32 for the overall wind power generation capacity (Figure 4). So the productivity in terms of FLH of recently installed WT in 2016 is already 19-36% higher than the productivity expected for 2030/32, and new SFWT designs available from 2019 onwards promise additional gains in FLHs, more than a decade ahead of 2030/32.

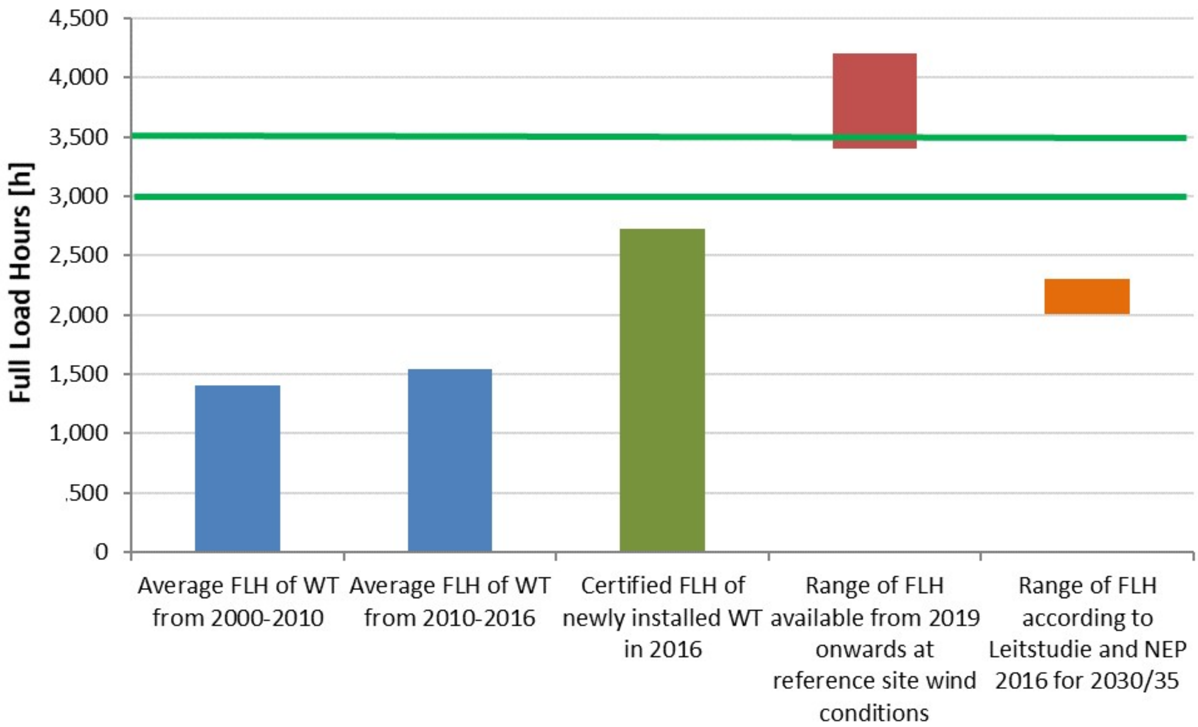


Figure 4: ***Comparison of historic FLH of German on-shore WTs (blue), certified FLH of WT installed in 2016 (green) and the potential FLH of WT available from 2019 onwards (red) in contrast to the rather modest projections of NEP 2016 and Leitstudie 2011 for 2030/35 (orange), green bars indicating own parametrization for average FLH in articles one to three (own illustration based on [1, 3-6])***

Bearing in mind the 2,721 FLH of the newly installed WT in 2016 together with the average operational lifetime for a WT of about 20 years and the current trend for WT with even higher productivity in terms of FLH, the assumed 3,000 FLH from an almost completely repowered wind turbine inventory in Germany by the year 2035 appear absolutely plausible [73]. 3,000 FLH represent an almost 50% increase in FLH, compared for example to the 2,007 FLH projected in the NEP 2035 B1 scenario – a delta in specific AEP of about 1,000 FLH. In terms of the energy produced, this is equivalent to the AEP of solar PV for the same installed capacity, which on average achieves about 1,000 FLH in Germany. So regarding the AEP, the ongoing introduction of SFWT can increase renewable energy production by an amount equivalent to the AEP of solar PV of the same installed capacity. This additional delta in FLH from SFWT alone implies a substantial impact on the required capacity expansion for renewables targets in the power sector [74][4], on RL and especially on excess energy from vRES. Recent publications [32, 36, 38, 71, 72, 75] underline these findings in system performance and are attracting further interest as the significant improvements are likewise related to the economic performance as well as to the market integration of vRES. The impacts on key performance parameters of these technological options make clear that energy scenarios should take into account the development of advanced technologies for wind and solar PV.

With regard to **research question two** (Do optimal capacity mixes of different vRES technologies exist which improve their integration into the power system?), publication two investigates how different capacity mixes of wind and solar PV serve power consumption in Germany and which capacity expansion pathway achieves the fastest increase in renewables shares per installed capacity [76]. As is the case in publication one, wind and solar PV in both standard and advanced technology setups are included (Figure 5).

[4] In the cited press release, FfE stated an increase of 11% in renewables share until 2025 and 19% until 2035 from SFWT alone [74]: „Technische Entwicklungen bei Windkraftanlagen werden laut aktuellen Untersuchungen der FfE im Rahmen des Projektes Merit Order der Energiespeicherung 2030 (MOS 2030) zu etwa 3000 anstatt gemeinhin angenommenen 2000 Volllaststunden führen. Zusammen mit einem unterstellten Ausbau nach EEG 2014 und Repowering bestehender Anlagen könnte der EE-Anteil am Bruttostromverbrauch bereits 2025 bei 60 % und 2035 bei bis zu 85 % liegen.“

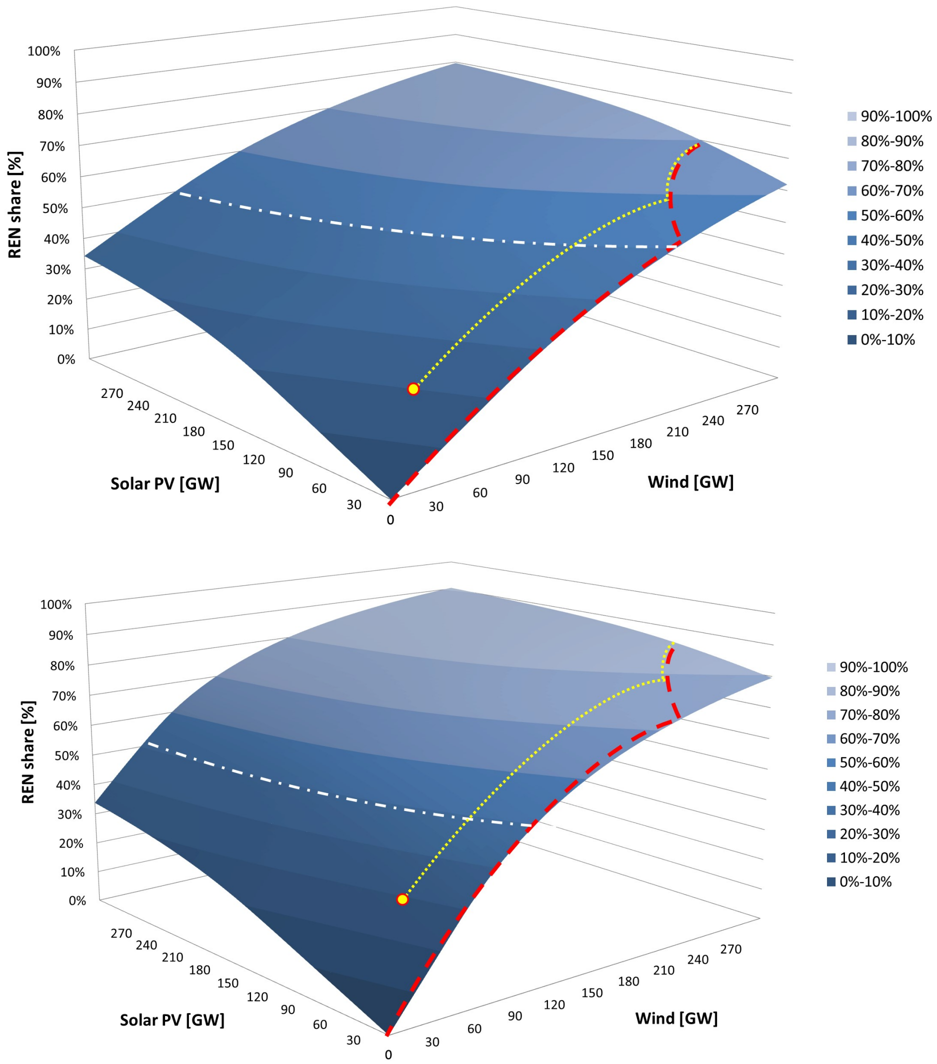


Figure 5: Comparison of resulting renewables shares and efficient pathways for standard technologies (top) and advanced technologies (below). In both cases wind power dominates the efficient pathway and the achieved renewables shares are substantially higher for advanced technologies, allowing for a faster transition and improved integration of vRES into the power system [77].

In contrast to the approach selected in publication one with the objective of minimal excess energy production at a given renewables share, the minimal capacity expansion pathway was selected in publication two as the objective, which at the same time allows for the most efficient transition to a given renewables share. Both objectives are of high relevance and allow assessing different vRES technology mixes and capacity expansion pathways from a system perspective. Publication two provides surface plots that present the renewables share and excess energy production as a function of the various capacity mixes of wind and solar PV to enable a quick perception of renewables shares and excess energy depending on the various vRES capacity mixes, advanced technologies and electric energy storage.

The surface plots illustrate that renewables shares, RL and excess energy are strongly affected by the capacity mix combination of wind and solar PV and the available technology options and only to a minor extent by electric energy storage in the form of existing PHS. In addition to the results for the 50% and 80% renewables share scenarios in publication one, the surface plots provide a broader picture of the overall relation of the capacity mix and the investigated key indicators. In line with the results from publication one, especially SFWT enable significant reductions in required overall vRES capacity and at the same time translate into a faster transition towards high renewables shares. It should be noted that the higher efficiency of SFWT is no mere effect of the higher productivity of SFWT in terms of FLH, but is closely linked to the altered temporal feed-in patterns of advanced technologies, as demonstrated by the key system indicators in publications one, two and three. This also enables a possible deferral of the introduction of large-scale electric energy storage as an enabling technology for the integration of vRES, as higher renewables shares are achievable with lesser excess energy, which otherwise would make electric energy storage a necessity. But the advantages of a wind-dominated expansion pathway should not lead to the conclusion that solar PV is not an essential asset in a future vRES-based supply and that the expansion of solar PV can be neglected. Instead, a sound reading of the results stresses that wind power is essential for high shares of vRES and should be a priority until very high vRES shares are achieved. Solar PV is complementarily, especially after specific thresholds in the renewables share are superseded. And in order to accelerate the transition towards renewables, solar PV can accelerate the energy transition in the power sector.

In the supplementary material provided in the appendix to this work, the modeling developed in publication two has been extended to calculate the optimal capacity mix of wind and solar PV for various renewables shares that provides minimal excess energy generation, similar to the objective in publication one. The results are differentiated for standard wind and solar PV setups as well as for system-friendly layouts as described in publication two. The two figures provided in the appendix underline that the optimal capacity mix is a function of the targeted renewables share as well as of whether standard or advanced technologies are used.

From the findings in publications one and two one can deduce that different optimization objectives result in different optimal mixes of wind and solar PV. For the objective of a minimal capacity expansion of vRES, wind power dominates the expansion pathways, as demonstrated in publication two, whereas the excess energy minimal capacity mix, especially in a storage-restricted power system, requires a substantial contribution from solar PV, as shown in publication one. Consequently, no universal and constant optimal capacity mix of wind and solar PV capacities can be identified for the presented models. Cost, welfare, nature protection and other possible optimization objectives will presumably deliver diverse results regarding the optimal capacity mix.

The significant potentials from advanced technology in wind power in the form of SFWT identified in publications one to three have been transferred to the spatial landscape by investigating how future wind power generation capacities can be allocated in a greenfield approach that considers environmental and socio-economic aspects. To address **research question three** (Which spatial effects result from the options investigated under research questions one and two compared to a reference case?), in publication four the impact of SFWT was calculated and compared to modern STWT [55]. Eastern Germany and Hamburg (representing the 50Hz TS) were used as the case study region, and the same wind energy production target of 41 TWh/a had to be achieved by onshore wind energy in all cases investigated. The AEP for the identified potential sites were derived from wind resource data [40] and certified power curves for both STWT and SFWT, so that the assumptions regarding FLH are based on the actual wind resources available for the study region and WT models commercially available in 2017. Additionally, a 10% reduction in AEP for the individual WT at the potential sites is included to take energy production losses into account. Key criteria for the comparison in publication four were the required number of wind turbines as well as indicators for human well-being and nature conservation.

The results show that the spatial allocation patterns depend on the objective for which WT sites were selected and that the trade-offs between the respective criteria are considerable. Targeting to minimize the number of WT leads to a concentration of WT in high wind speed areas, mainly in the coastal region in the north of the study region, while targeting the lowest impacts on nature protection or human well-being leads to a much wider distribution and distinctive patterns of WT across the study area.

The comparison of technological setups revealed that SFWT outperformed STWT in the cumulated impacts for all individual criteria and enabled a reduction of up to 31% in turbine numbers in a greenfield approach. In such a greenfield approach even an absolute reduction of onshore WTs is possible by 2030 compared to the number in 2015. With both selected STWT and SFWT types having 3 MW of installed capacity per turbine, the results show that the overall installed capacity likewise can be reduced by 31% using SFWT. This is a direct effect of the higher productivity of SFWT in terms of FLH, which was verified in publication three on the basis of the representative wind resource data [40] and again in publication four using certified power curves. In line with the reduction in the number of turbines and installed capacity, the overall impact on nature and human well-being as well as the energy produced, SFWT potentially allow for a reduction of the cumulated environmental indicator of up to 19% and on the human well-being indicator of up to 32% in the multi-criterial optimization (Figure 6).

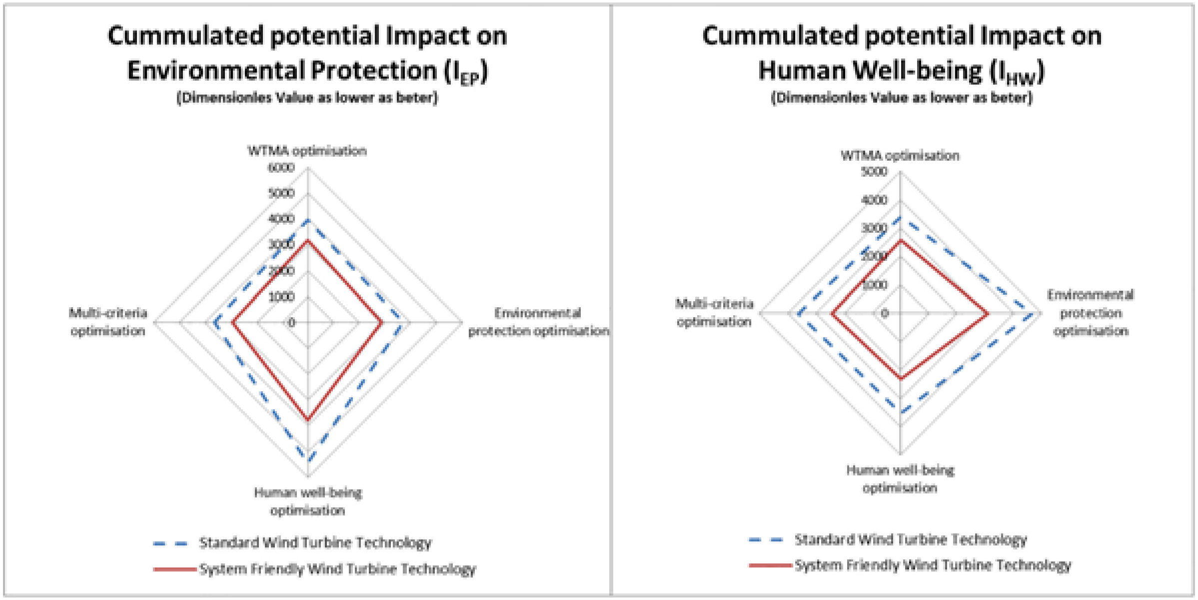
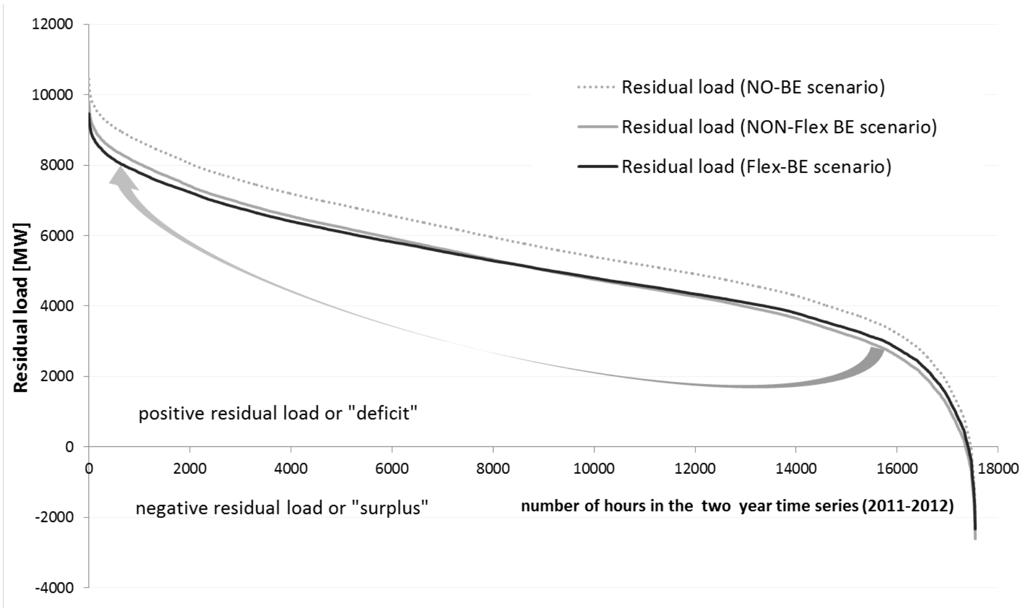


Figure 6: Cumulated potential impact on environmental protection and human well-being from different optimization approaches for STWT and SFWT [55].

However, the trade-off is that the individual impacts per WT are higher on average compared to STWTs. So although the overall cumulative potential impact might be reduced, the individual SFWT on average has a higher impact on human well-being and nature protection. It should also be clearly noted that the negative impacts of infrastructure like wind turbines are widespread and have not been entirely covered by the set of three proxies selected to address the dimensions of human well-being, nature conservation and energy production.
The approach and the published results nevertheless underline the fact that spatial allocation of future WT on a broader regional scale has significant potential for minimizing the number of WT and overall cumulated impacts. Furthermore, a set of robust potential sites can be identified and selected under all individual criteria as well as under the multi-criterial optimization, and these robust potential sites can thus be further investigated by regional planning authorities as a direct outcome of the published results.

Having addressed the technological options and spatial effects from advanced technology, **research question four** (Can flexible power provision from bioenergy contribute to an improved system integration of vRES?) was then investigated in publications five and six [77, 78]. The assessment of the technical suitability of flexible bioenergy concepts was performed using a bioenergy power production model with the aim to offset daily fluctuations in RL on the level of the TS in two different case study regions.

In the investigated scenarios for 2022 (TransnetBW) and 2030 (50Hertz), the requirement to offset RL fluctuations from vRES are different. The share of solar PV in power production is again a relevant criterion and its daily to seasonal periodicity can be well complemented by flexibility concepts from bioenergy, especially from flexible biogas as a dispatchable renewable energy source (dRES). In contrast, RL that is affected by large shares of wind power is characterized by a mostly stochastic temporal generation pattern with longer periods of high feed-in compared to the mostly deterministic daily and seasonal cycles in the generation pattern of solar PV (Figure 7).



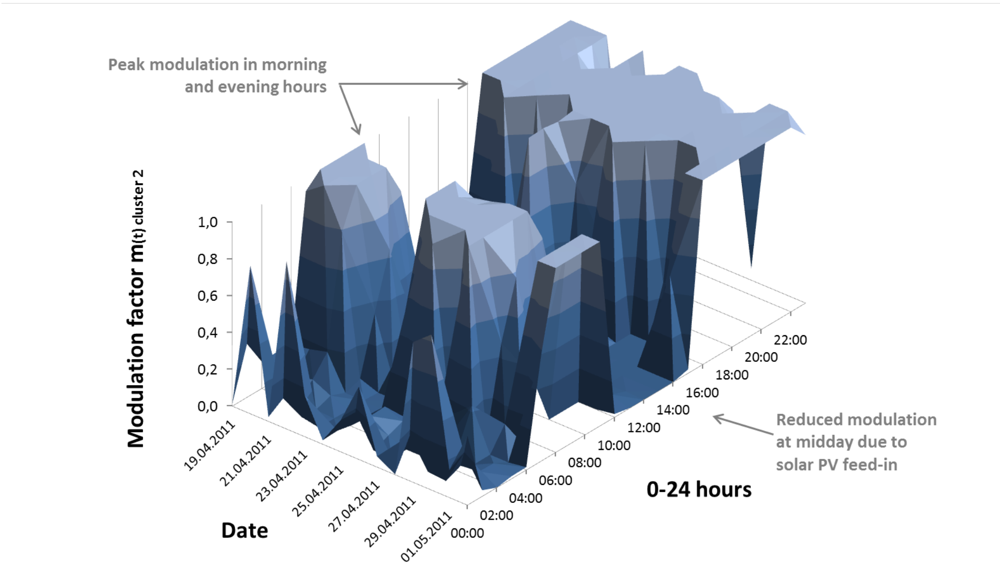


Figure 7: Residual load duration curves (RLDC) for the TransnetBW TS with flexible and non-flexible bioenergy (on top) and typical modulation of power generation from flexible bioenergy plants during several days in springtime (below) in order to adapt to high solar PV feed-in (below) [77, 78].

One consequence of high shares of wind power is that especially biogas storage in biogas plants would have to be significantly expanded to avoid excess power production from bioenergy during periods of high feed-in from wind power. Alternatively, the feed-in of upgraded biogas (biomethane) into the natural gas grid would be required to overcome the limitations of biogas stored on site (similar results have been obtained for a more complex modeling applied in the research project BalanceE [79]).

To summarize the results of the case studies on the system integration of vRES, one can conclude that in the near to medium term, technical concepts for flexibility from bioenergy will allow offsetting fluctuations in RL of up to 30%, especially in regional power systems with high shares of solar PV. The investigated concepts for flexible bioenergy are therefore capable of contributing to the required flexibility in the supply side of power systems in the near to medium future.

However, the overall requirement for flexibility options like bioenergy is not yet clear in the investigated time frame until 2030 and beyond [19, 52, 80-82]. It depends to a large extent on the regional contribution of other renewables including vRES, the structure of power provision from non-renewables, including so called Must-Run requirements, and to what extent competing flexibility options will be available by 2030 [12, 13, 19, 52, 83, 84]. Overall, the available feed stock for bioenergy is limited and competition amongst demand sectors for the limited biomass resources will likewise determine the future availability of bioenergy in the power sector [1, 85-87]. With a variety of technologies and flexibility options to respond to increased fluctuation in power supply from large shares of vRES, bioenergy should be regarded as one possibility among others, with specific potentials and limitations. Pumped hydro and new electric energy storage systems, are competing technologies in the power sector apart from DSM, cross-sectorial use of excess power and the already described options of system friendly vRES and the optimal mix of vRES.

So while existing technical concepts for the flexible provision of bioenergy in regional power systems with high shares of vRES are technically capable of offsetting fluctuations in RL introduced by vRES, publications five and six only provide an initial assessment that does not give a complete picture from which a final conclusion can be drawn.

4.1. Summary of the main findings

Overall, the presented results form a consistent picture of how Germany and potentially many other countries can improve the integration of renewables while relying heavily on vRES for their future renewable power supply. The following bullet points provide a summary of the main findings from the investigated case studies:

- The development of advanced technologies, or alternatively system-friendly renewables, enables a significant reduction in the vRES capacities required to achieve the defined renewables targets. Higher productivity in terms of FLH, but also improved temporal production profiles, allow for a significant reduction in installed capacity, especially in the case of wind energy.

- The optimal capacity mix of wind and solar PV reduces some of the challenges associated with high shares of vRES. The optimal capacity mix depends on the optimization criteria, the available vRES technologies and the targeted renewables share.

- The share of solar PV is higher in a vRES-based power system that minimizes the amount of excess energy for a set renewables share target instead of a capacity mix that minimizes the installed capacities from wind and solar PV.

- The complementarity in power production from wind and solar PV can avoid excess energy. Solar PV, although less productive than wind power, nevertheless contributes as an effective complement and also enables very high direct renewables shares.

- The efficient expansion pathway in terms of renewables share per installed capacity is a pathway dominated by wind. Advanced technologies in the form of SFWT increase the comparative advantage of wind even further, due to the higher productivity and the temporal production pattern of SFWT.

- SFWT either allow of a faster transition towards renewables in the power sector as fewer installed capacities are required to achieve set renewable shares. Or if the same capacity of SFWT are deployed instead of STWT, a substantial amount of excess power can be utilized more easily and transferred to new cross-sectorial applications for renewable electricity.

- There are significant trade-offs for the spatial allocation of WT between the required number of turbines and the overall impacts on human well-being and nature protection. The spatial allocation of WT in the landscape benefits from SFWT, as lower cumulative impacts can be realized in comparison to STWT.

- Bioenergy as a dispatchable RES can reduce fluctuations in RL as well as excess energy from vRES and therefore contribute to improving the integration of vRES. Existing technical concepts for bioenergy are capable of offsetting fluctuations in RL when operated flexibly. Major determining factors for the requirement for such flexible bioenergy concepts in the power sector are the overall renewables share of the regional power system and the mix of wind and solar PV capacities.

4.2. Transferability of results and methods

The results presented in publications one to three present a conclusive picture regarding future vRES expansion and its impact on the key indicators investigated. Furthermore, they complement and extend the findings from other studies regarding vRES and advanced technologies in the field of system analysis [17, 48, 88], engineering [37, 89] and energy economics [32, 36, 38, 75].

Although the presented case studies were performed for Germany or selected regions in Germany, the applied methods can be transferred to other regions, while the individual results of each case study depend to a large extend on the region's specific vRES potentials, feed-in and consumption patterns as well as the complementary infrastructure. Thus the individual results, like the optimal capacity mix, capacity expansion pathways or spatial allocation of WT, cannot be generalized or directly transferred to other regions.

The use of time series data, spread-sheet or commonly used computer algebra systems (MathLab) should allow for a good transferability of the applied methods described in publications one to three. The multi-criterial decision analysis in publication four for the allocation of WT, including a comparison of STWT and SFWT, enables identifying the trade-offs in different allocation criteria. The established framework can easily be transferred to other regions than the selected study region (50Hertz TS) to provide regional planning with a tool to address conflicting targets in allocating WT in the landscape. Again, specific results are expected to be largely dependent on the regional characteristics regarding the structure and spatial distribution of settlements and nature conservation areas, wind potentials and targeted AEP from wind power, to name just the most important factors for such an analysis.

For the case of flexible power generation from bioenergy, the results provided are to a large extent specific to the German case study regions investigated. Furthermore, the relevance of a flexible power provision from bioenergy, especially for biogas plants to offset high variability in RL induced by vRES, is still a relative new aspect. As already mentioned, for a future assessment of (flexible) bioenergy in the power sector and beyond, an integrated modeling should extend the focus to cover the highly complex aspects associated with bioenergy.

4.3. Relevance and outreach

The overall field of research into the integration of vRES into power systems has gained in importance since many countries worldwide made the shift towards a renewable energy

system that relies heavily on vRES. While the economic and technical aspects of specific renewable energy technologies have been studied in detail, various systemic aspects were rather neglected when work on this PhD thesis started in 2012.
A major difference between this thesis and previous approaches is the focus on the provision of vRES itself in the form of an optimized mix of vRES capacities and system-friendly layouts of these vRES technologies. System-friendly technologies or advanced technological setups of vRES are a relatively new field of research and have until recently not been covered in system analyses that include key system indicators like excess energy (EE), required capacity expansion for defined renewables targets for power demand and the impact on the technology mix. Both optimized capacity mixes of vRES and system-friendly layouts of wind and solar PV can be regarded as basic and effective options for the integration of vRES, as they determine key parameters in the supply side of a power system and have the potential to facilitate the transition towards renewables in the power sector. In the possible absence of new large-scale energy storage and/or highly flexible demand implemented in the near to medium term, the combination of all other supporting measures for the integration of vRES, namely system-friendly wind and solar PV, optimized capacity mixes of wind and solar PV and flexible bioenergy, should be considered. But system-friendly wind and solar PV not only improve power supply from vRES in power systems with limited electric energy storage, but also provide benefits with regard to excess energy for cross-sectorial use, as shown in publication three of this PhD thesis.

All the findings underline the essential role that wind power provides for the transition towards high vRES shares in power systems with a resource and infrastructural basis comparable to the ones in the investigated study region of Germany. The integration of high shares of solar PV into a vRES-based power supply system in contrast depends to a much larger extent on the future availability of new electric energy storage and/or highly flexible demand, as indicated by the results presented in publication two.

Regarding the governance of and political support for the energy transition in Germany, the identified potentials for reduction in infrastructural requirements can contribute to maintaining high societal acceptance for the energy transition in coming years, as fewer wind turbines, less installed overall vRES capacity and connected power grid capacities are needed. The potentials to speed up the transition towards renewable energies, as demonstrated in the results of publications one to three, should likewise be considered, especially in the face of Germany missing its renewables and emission reduction targets for 2020 and 2030.

The transition of many European renewable energy support schemes to a competitive bidding scheme with tenders for technology-specific generation capacity instead of feed-in tariffs potentially enables expansion pathways to be directly and more precisely governed. With the use of tenders for technology-specific capacity expansion, an approach like the one applied in publication two allows us to assess the effect of the capacity expansion for each vRES technology on the key performance indicators, for example the renewables share that is the central indicator and objective in energy policy. The efficiency of the expansion pathways could then be easily assessed ex-ante and technology-specific capacity expansion pathways could be modeled, studied, planned and monitored to be compliant with national and European renewables and climate protection legislations and commitments.

For the necessary expansion of wind power in coming years, the presented multi-criterial approach for the spatial allocation, including economic, social and nature conservation aspects, can open up new spatial optima in the search space compared to commonly applied mono-criterial optimization methods. Economic, social and ecological trade-offs in allocation of WTs can be assessed and minimized with this approach. With a set of robust potential sites identified and selected under all single criteria as well as under the multi-criterial optimization, preferential sites with reduced overall impacts can be explored and developed. Governmental institutions tasked with the spatial planning for wind energy can thus improve the search for the most appropriate allocation of WT.

Flexible bioenergy provision as a complementary technology for the integration of vRES has been modeled to assess its contribution to future power systems. Depending on the specific supply and demand side characteristics of regional power systems, flexible bioenergy provision with today's technical concepts is already capable of improving the integration of vRES compared to the nonflexible provision that predominates today. However, especially regional power systems with high shares of wind power will require improvements to the existing concepts in order to avoid production of bioenergy in times of excess energy from vRES. The interaction of flexible power generation with other flexibility options (electric energy storage, DSM, cross-sectorial use) should be further investigated to assess the individual contribution each option can provide in future vRES-dominated power systems.

Overall, the findings stress the importance of a greater awareness of technological advancements when drawing up energy scenarios. For future energy scenarios, the implementation of means to cover the accelerated techno-economic developments in the energy sector should be improved. An open review and consultation process should be considered to maintain an accurate information base on which energy scenarios are established, as it has been implemented into the German grid development plan.

Given that the presented Phd thesis had an explorative character onto integration options and therefore was restricted in its scope, further research should be directed towards implementing the identified options in a broader energy system model and integrate the described options into interdisciplinary approaches covering the most relevant technical, spatial, social and economic aspects.

5. Appendix

This appendix contains additional unpublished results of the modeling from publication two (Tafarte, P., Eichhorn, M., Thrän, D. (2019): Capacity Expansion Pathways for a Wind and Solar Based Power Supply and the Impact of Advanced Technology - A Case Study for Germany. Energies).

In order to extend the findings from publication one beyond the 50Hertz TS for which only two optima at 50% and 80% renewables share were calculated, the appendix provide additional optimized capacity mixes for a broader picture on the resulting capacity mixes for this approach. The objective, as in publication one, is to minimize the excess energy production or cumulated negative RL. Now extended over the four-year time series from 2012-2015 for hole Germany (all four TS). Optimized capacity mixes for renewables shares from 30% to 80% in 5% steps are calculated and represented by the circular markings in the graphs presented in this appendix. As no electric energy storage or other means of providing flexibility in power demand is included, the renewables share is therefore calculated as the fraction of power demand that is directly served by power generation from wind and solar PV (direct renewables share as calculated in publication one). Time series have been scaled to a FLH for baseline technologies of 1,536 h for wind and 950 h for solar PV and, in the case of system-friendly technologies, of 3,000 h for wind and 826 h for an east- and west-facing orientation of solar PV systems. The modified time series for system-friendly setups are calculated in accordance with publications one and two. The following figures give the minimal excess energy capacity mix of wind and solar PV for discrete renewables shares together with the resulting annual excess energy production, differentiated for either standard (Figure 8) or system-friendly wind and solar PV (Figure 9).

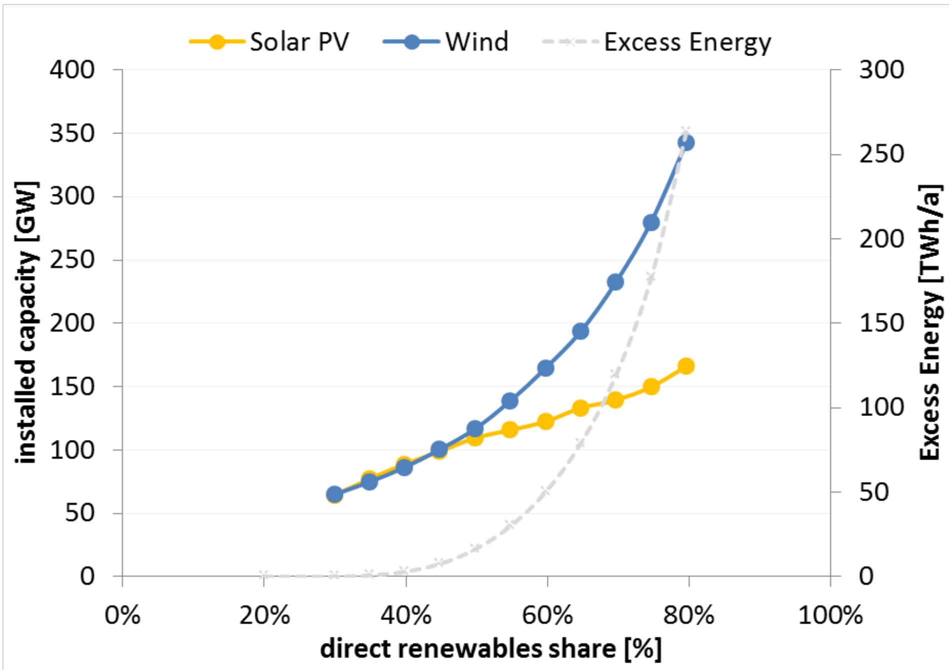


Figure 8: vRES capacity mix providing a minimal excess energy production for rising direct shares of renewables in power consumption, using standard technologies.

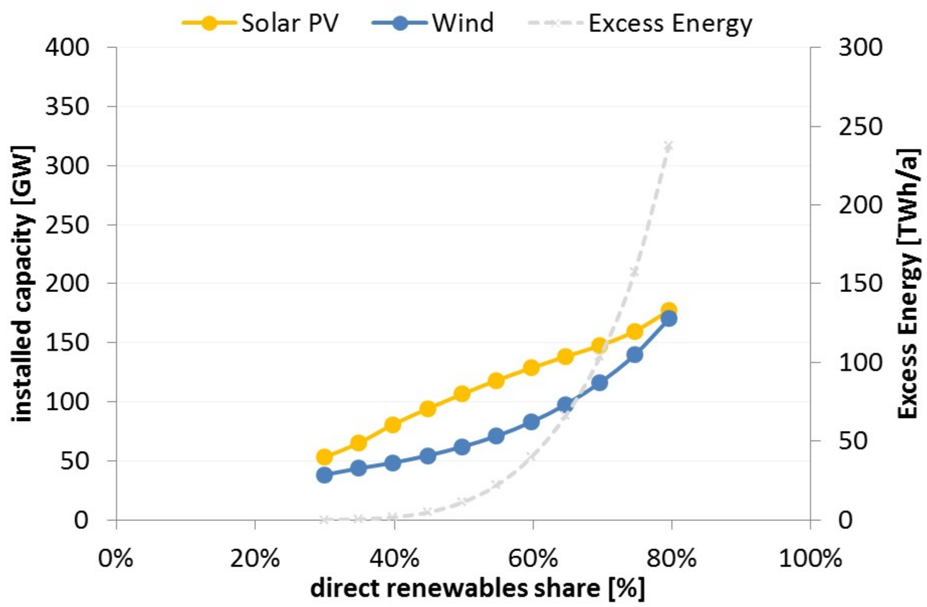


Figure 9: vRES capacity mix providing a minimal excess energy production for rising direct shares of renewables in power consumption, using system-friendly technologies.

The graphs depict how wind and solar PV are combined to directly contribute to the power consumption time series to minimize the volume of annual excess energy from these vRES. Excess energy production increases progressively after a threshold of about 40% in renewables share is reached in a standalone wind and solar PV supply system. This increase is more pronounced for the case using standard technology.

For renewables shares of up to 50%, solar PV and wind power in baseline setups using standard technology are ideally expanded almost proportionally. For renewables shares beyond 50%, wind capacity should increase faster. This is primarily due to the highly temporal concentration of solar irradiation, with only marginal additional contributions to the renewables shares without electric energy storage. For very high penetration rates of up to 80% direct renewables share provided by 342 GW wind and 166 GW solar PV, a progressive increase in excess energy of up to 263 TWh/a is produced using standard technology.

In the case of system-friendly technologies, slightly more solar PV capacities should optimally be deployed, but the overall capacity of wind power is significantly reduced and does not surpass the solar PV capacity at any given renewables share. The higher productivity of system-friendly wind power allows for a reduction in required capacity from wind power, as was demonstrated in the results laid down in publication three. Excess energy at a 50% renewables share is reduced by 32% compared to the case using standard technologies. For an 80% share of direct renewables from system-friendly technologies only, the required wind capacity decreases to only 170 GW (-50%), whereas solar PV capacities increase slightly to 177 GW (+7%) compared to the standard technology case. Excess energy likewise is decreased to 237 TWh/a (-10%) using system-friendly technologies.

Therefore, the application of different time series data for Germany provides consistent results in comparison to the results in publication one with the restriction to a 50% and an 80% renewables scenario. The differences in the optimal capacity mix in publication two can be traced primarily to the fact that the objective there was a minimal capacity expansion pathway that favors wind power over solar PV along the efficient expansion pathway.

Regardless of the differences caused by the two different objectives of the optimization, the advantages of system-friendly layouts in terms of the reduction in excess energy and installed capacities of both wind and solar PV persist with either an excess minimal capacity mix or an overall capacity minimal mix for a specific renewable share as calculated for publication two, independent of the different time series and study regions used for the calculations.

6. Literature

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7. Appended publications and the individual contribution to the publications

This PhD thesis comprises six publications written with the co-authors Marcus Eichhorn, Daniela Thrän, Subhashree Das, Martin Dotzauer, Christiane Hennig and Patrick Buck. The publications and the individual contributions of the authors to these publications are given below:

- Tafarte, P., Das, S., Eichhorn, M., Thrän, D. (2014): Small adaptations, big impacts: Options for an optimized mix of variable renewable energy sources. Energy.

    - Tafarte had the idea, developed the model, carried out all the modeling and calculations and wrote the paper. Das, Eichhorn and Thrän provided feedback on the manuscript.

- Tafarte, P., Eichhorn, M., Thrän, D. (2019): Capacity Expansion Pathways for a Wind and Solar Based Power Supply and the Impact of Advanced Technology - A Case Study for Germany. Energies.

    - Tafarte had the idea, developed the model, carried out all the modeling and calculations and wrote the paper. Eichhorn and Thrän provided feedback on the manuscript.

- Tafarte, P., Buck, P. (2017): Integration of wind power — Challenges and options for market integration and its impact on future cross-sectorial use. 14th International Conference on the European Energy Market (EEM), Dresden, Germany, 2017, pp. 1-5.

    - Buck had the idea, developed the model and carried out all the calculations provided in the first part of the publication and gave feedback on the manuscript. Tafarte had the idea, developed the model and carried out all the calculations for the second part of the publication and wrote the publication.

- Eichhorn, M., Tafarte, P., Thran, D. (2017): Towards energy landscapes - Pathfinder for sustainable wind power locations. Energy.

    - Eichhorn wrote the publication. Tafarte and Eichhorn had the idea and developed the model. Eichhorn carried out the majority of the GIS modeling and calculations. Thrän contributed to the discussion and conclusion as well as to the overall study design. Tafarte and Thrän provided feedback on the manuscript.

- Tafarte, P., Hennig, Ch., Dotzauer, M., Thrän, D. (2017): Impact of flexible bioenergy provision on residual load fluctuation: a case study for the TransnetBW transmission system in 2022. Energy, Sustainability and Society.

    - Tafarte carried out the data collection, preparation and processing and the major parts of the modeling and contributed to the results, discussion and conclusion section as well as to the overall study design. Hennig wrote the introduction and contributed to the discussion and conclusion as well as to the overall study design. Dotzauer provided the bioenergy plant clustering in the modeling section. Thrän contributed to the discussion and conclusion as well as to the overall study design.

- Tafarte, P., Das, S., Eichhorn, M., Dotzauer, M., Thrän, D. (2015): The potential of flexible power generation from biomass: a case study for a German region. Chapter 9.4: Complementing Variable Renewable Energies with Flexible Bioenergy
In: Thrän, D., (ed.) Smart bioenergy: technologies and concepts for a more flexible bioenergy provision in future energy systems. Springer, Cham, pp. 148 – 159

    - All authors contributed to the idea. Tafarte developed the model, carried out all the modeling and calculations and wrote the paper. Das, Eichhorn and Thrän provided feedback on the manuscript.

8. Curriculum Vitae

9. Selbstständigkeitserklärung

Hiermit erkläre ich eidesstattlich, dass ich diese Dissertation selbstständig und ohne fremde Hilfe verfasst habe. Andere als von mir angegebene Quellen und Hilfsmittel habe ich nicht benutzt und die den benutzten Werken wörtlich und inhaltlich übernommenen Stellen als solche kenntlich gemacht.

Hiermit erkläre ich, dass die vorgelegte Dissertation weder im Inland noch im Ausland in gleicher oder in ähnlicher Form einer anderen Prüfungsbehörde zum Zwecke einer Promotion oder eines anderen Prüfungsverfahrens vorgelegt und insgesamt noch nicht veröffentlicht wurde.

Hiermit erkläre ich, dass ich die Promotionsordnung der Wirtschaftswissenschaftlichen Fakultät der Universität Leipzig, vom 12. Oktober 2010 anerkenne.

Philip Tafarte Leipzig

II. Appended publications

Publication One

Small adaptations, big impacts: Options for an optimized mix of variable renewable energy sources.

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Small adaptations, big impacts: Options for an optimized mix of variable renewable energy sources

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ABSTRACT

The on-going energy transition in Germany aims at a power system dominated by RES (renewable energy sources) with more than 80% in 2050. The primary contributions are expected to come from inherently vRES (variable renewable energy sources), especially wind and solar power. Under currently insufficient storage capacity and limited flexible RES, alternatives for the integration of increasing shares of vRES are urgently needed.

This paper aimed at optimizing feed-in patterns to improve system integration of vRES in central Germany for vRES targets of 50% (2030) and 80% (2050). Numerical optimization for optimal shares of wind and solar was conducted for baseline and advanced technology set-up using minimization of excess energy as an indicator for system integration. Results show that for the 50% vRES target, advanced technology reduced excess energy by up to 53% and optimal shares in capacity include 34% wind and 66% solar. Further, the demand for installed wind capacities could be reduced by as much as 55%. This reduction can translate into lower land demand, thereby supporting sustainability concepts. This article concludes that there is a high potential of system integration of increasing shares of vRES in the near to middle-term, especially by the adoption of advanced technologies.

1. Introduction

The rapid development of renewable energy in Germany was first introduced via the feed-in law for renewable electricity generation in the year 2000 [1]. Revision of the national energy legislation in 2011 [2] aims to further increase the share of RES (renewable energy sources) in electricity provision. In 2011, about 20% of the gross electricity consumption was generated by renewables, of which ~40% came from wind power, ~16% from solar PV (photovoltaic), ~30% from biomass (including sewage, landfill gas and organic waste) and ~14% from hydro power [3]. Geothermal and tidal power are only marginal sources up to now. National policy goals aim at increasing the shares from RES (renewable energy sources) in the electricity consumption to a minimum of 35%, 50%, 65% and 80% corresponding to the years 2020, 2030, 2040 and 2050 respectively [4].

Germany is highly dependent on wind and solar resources to achieve its energy transition goals as tidal and geothermal energy offer only a limited potential [5] and biomass resources for energy compete directly with food and feed production [5,6]. However, wind and solar are vRES (variable renewable energy sources), therefore their intermittent and stochastically varying power output needs to be complemented by other sources for a balanced and stable energy supply [7,8] (see Fig. 1).

Current research suggests that one of the main challenges of a power system aiming at an energy supply from vRES up to 80% is to adapt to large fractions of excess and deficit energy over time [9–11]. Several scientists have identified storage systems as a key asset to integrating high shares of vRES into the power system [12]. However, in Germany, the future potential of PSH (Pumped Storage Hydroelectricity) as an electricity storage technology is limited by legal constraints of nature conservation as well as high investment costs [13,14]. Other possible technologies include batteries, fly wheels and capacitors; however these technologies are currently neither economically viable nor scaled to the required magnitude of storage capacities (TWh range) [15–17].

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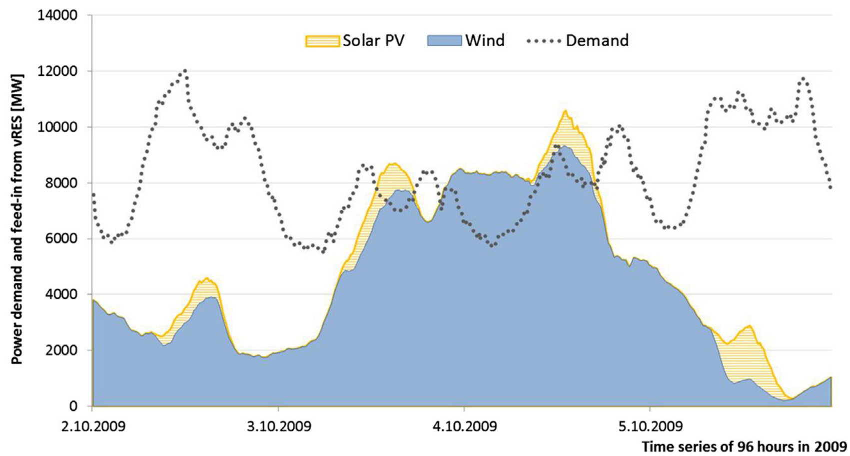

Fig. 1. Example of fluctuating feed-in from PV and wind compared to the demand during 4 days in 2009.

With the limited availability/capacity of storage, DSM (Demand Side Management) interconnectors for export, rising shares of vRES often result in energy production that surpasses the total demand, especially at times of high vRES feed-in and/or low power demand. This excess energy is often curtailed to avoid destabilization of a power system and is hence viewed as “wasted potential”. Lower Capacity Factors of vRES systems (9–19%) as compared to conventional systems (41–97%) [18] lead to higher installed capacities of vRES, eventually leading to higher excess energy generation. Current level of excess energy in the German electricity system is negligible [19] (described in detail in Section 2.2).

Therefore, minimization of excess energy is a crucial component of future systems based on vRES. The fraction of excess energy produced in a system with a given vRES share can be used as an indicator of the level of vRES integration in an electricity system with lower excess energy production corresponding to a better integration [20,21]. Research on providing adequate solutions for large scale electricity storage is underway [15], but is likely to be a long-term option. Grid extension as an option for wind power distribution through Europe has been studied by Pforte [22], Rasmussen [23] and Bove [24]. Research indicates that despite techno-political limitations of an inter-connected grid, spatial integration remains a useful option. However, in the absence of a large scale trans-continental grid that integrates the spatio-temporal variations in vRES production, this potential is likely to remain partially untapped in the near to medium-term future.

The approach used by Pforte, Rasmussen and Bove, thus, does not consider the possible benefits of combining solar PV with wind as an additional vRES. Apart from expansion of grid infrastructure, storage technologies, DSM, optimization of the composition of various vRES (with patterns of fluctuating energy generation) is a crucial measure to minimize the imbalances between demand and supply [25]. Combining solar PV and wind for optimal integration has been studied by Lund [20], Heide [26,27] and Wagner [11]. Wind and solar power production can play complementary roles since wind power installations generally have higher production during winter while solar power production peaks during summer. Heide [27] has reported an optimal mix of 55% wind and 45% solar energy in energy production to achieve 100% RES based power supply in Europe, with a corresponding reduction of storage requirements by 50% as compared to power generation exclusively by either wind or solar.

Technological options to improve vRES integration have been studied by Leijon [28], Skoglund [29] and Molly [30,31]. Molly has outlined the potential effects of WEC (Wind Energy Converter) with lower specific Rated Power (W/m^2) on storage, grids and system integration. The research inferred that new designs of wind turbines with relatively lower specific Rated Power (below 350 W/m^2, see Section 3.1.1) offer higher CF (Capacity Factor) than standard WEC thereby reducing fluctuations in energy output. Consequently the new designs of WECs require significantly lower storage capacity in the system while enabling a better utilization of the transmission grids. If additional costs and storage related losses are accounted for, this approach of an integrated vRES system is assumed to offer high potentials for economic and technical optimization [30].

Contrary to the findings of Molly, a report published by Achner [32] assessed the possibilities of compensating fluctuating feed-in from vRES by applying the above mentioned new WEC designs and east-west facing solar PV. The study concluded that the effects of these WECs and east-west PV orientation are marginal with respect to the compensation of fluctuations. Additionally the study discussed that this technological approach may result in negative effects such as reduction in energy generation compared to standard WEC and regular south facing solar PV.

Against the backdrop of differing opinions emerging from current research, the focus of this study is to assess the effects of a combined approach – optimizing vRES (wind and solar PV) shares with advanced technology (WEC with low Rated Power in combination with east–west facing solar PV) in the near to medium-term future (up to 2050) for a case study region in Germany. While we agree with approaches that address advanced technologies for vRES by Molly [30,31] and those that aim at deriving optimal composition of vRES by Heide [26,27], we recognise that investigating these factors in combination could potentially offer improvements. The main objectives of this paper are (i) identifying optimal shares of vRES (wind and solar) for medium and high share of renewables and (ii) calculating minimal requirement of future capacities of wind and solar installations. As opposed to other studies which account for energy optimization with innovative future technologies, we restrict our study to technological improvements that are either already developed or are in advanced stages of development and hence have very high probability to be imminently operational (see Section 3.1). Further, expensive (and currently debatable) options such as grid expansion, extensive battery/capacitor storage systems, PSH and power to gas have also been precluded from our analysis. This study uses renewable

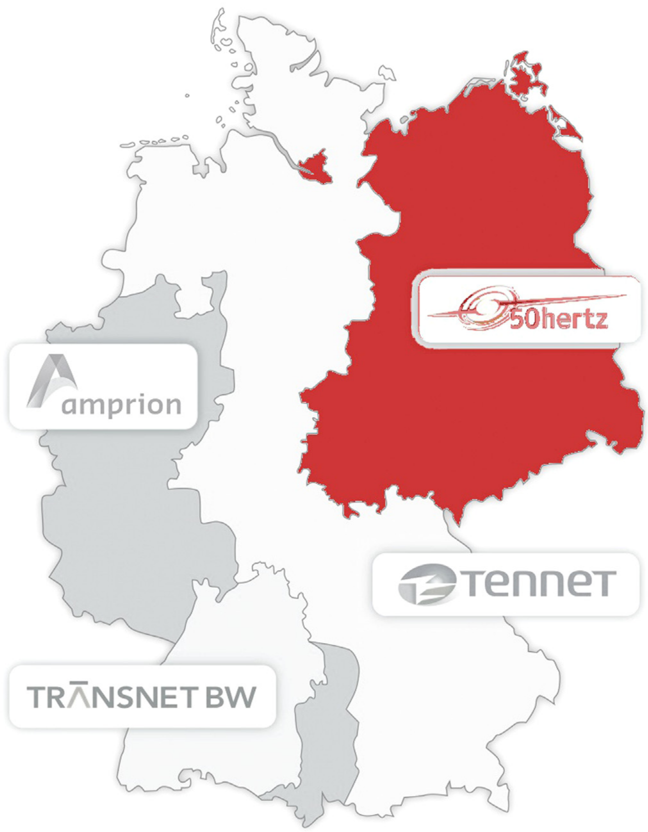

Fig. 2. Study area.

energy targets from current national policy described as 'Cases' (see Section 3.2) – 50% renewables until 2030 and 80% until 2050 [4].

In Section 2 we introduce the study area and describe the input data, followed by Section 3 that provides details on the technological options, description of the cases and optimization procedures. The results of the study are presented in Section 4, followed by Discussion in Section 5 and Conclusions in Section 6. The Appendix section provides additional details on the modelling.

2. Study region and input data

2.1. Study region

The study region corresponds to the area served by one of the four major German transmission grid operators-the 50 Hertz transmission GmbH. It includes the federal states of Berlin, Brandenburg, Hamburg, Mecklenburg-Vorpommern, Saxony, Saxony-Anhalt and Thuringia in Germany (Fig. 2) covering a total area of 109,340 km^2. The operator serves ~21% of the total German population and supplies an average of 84 TWh of electric energy annually in the 50 Hertz area [33]. The region has integrated large capacities of vRES (4070 MW of PV and 11,719 MW of wind in 2011) in its electricity supply mix.

2.2. Input data

We used quarter-hourly electricity feed-in (from wind and PV-2009, 2010, 2011 [34]) and net load data (representing electricity demand [33]) provided by the transmission grid operator 50 Hertz. The high temporal resolution of the data and the 3 year time slice enables the coverage of a wide variability of vRES production and electricity demand.

The effect of the rapid expansion of new capacities of PV (8 fold since 2009) and wind (1.25 fold since 2009) is reflected in the data that clearly shows this increase in feed-in in relevant years (Fig. 3). In order to normalize this effect relative to the installed capacities at the end of 2011, we adopted a similar approach to Kreifels [19] wherein we scaled the feed-in values with the average cumulated capacity at the beginning and end of the actual month in the time series (Equation (1)).

$$\text{feed-in PV}_{(t)\ \text{normalized}} = \text{feed-in PV}_{(t)} * 2 * \left[\frac{\text{CAP PV}_{\text{dec 2011}}}{\text{CAP PV}_{\text{month}\times\text{beginning}} + \text{CAP PV}_{\text{month}\times\text{ending}}}\right] \quad (1)$$

Monthly CAP (cumulated capacity) for PV (CAP PV$_{\text{month} \times \text{beginning}}$, CAP PV$_{\text{month} \times \text{ending}}$ and CAP PV$_{\text{dec2011}}$) were taken from published data [35]. The resultant- (feed-in PV(t) normalized) thus represents a feed-in concurrent to the installed capacities at the end of 2011.

An analogous normalization was performed on the data for wind power. Table 1 presents key figures for the 50 Hertz grid area

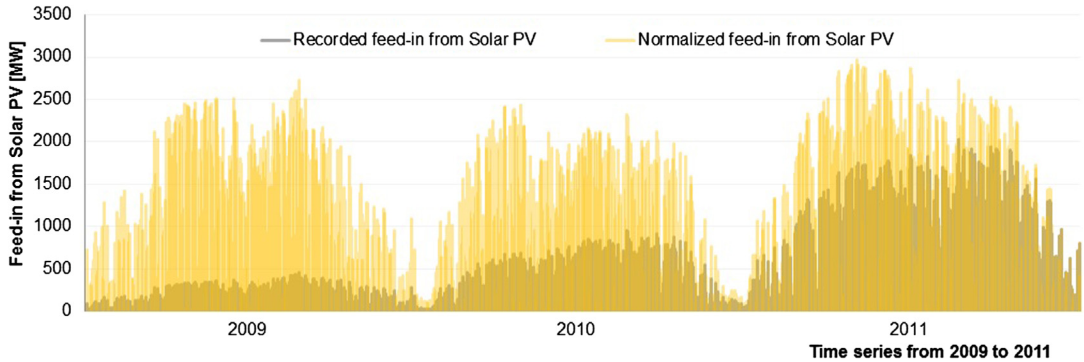

Fig. 3. Recorded feed-in from PV in 2009, 2010 and 2011 and the feed-in normalized to the installed capacity at the end of 2011.

calculated on the basis of the normalized feed-in data for 2009, 2010 and 2011.

If the normalized feed-in is considered, PV and wind would have been able to provide 4% and 21% respectively of the 84 TWh in annual demand during 2009, 2010 and 2011, resulting in a combined supply of 25% of demand. At this level of vRES penetration, excess energy amounts to only 0.1 TWh or 0.08% of annual demand (84 TWh). While achieving a 25% share in vRES, the maximum positive and negative residual loads during 2009–2011 indicate a high level of fluctuation against demand. With −13,414 MW of positive residual load or "deficit" in power production from vRES during the time series, wind and PV hardly contributed at all at this point in the time series. On the other hand 3074 MW of maximum negative residual load or "excess" power production has been contributing to the excess energy production of 0.1 TWh/a. Conclusively, we would like to emphasize that residual loads already show a high amplitude in the supply from vRES at a relatively modest share of vRES on power supply.

3. Method

As mentioned above, this study explores the contribution of a combined approach on the electricity system-using advanced wind and PV technologies in optimal configurations. Section 3.1 explains technological modifications for wind and PV and their resulting effects on the integration of vRES, Section 3.2 describes the optimization procedure for combining wind and PV and finally Section 3.3 introduces the Cases investigated in the study.

3.1. Technology options

We studied the effect of one technological option each for wind power and PV to determine if their introduction can help improve system integration of vRES. In accordance with Molly [30,31] and Achner [32], the proposed technology options (called advanced technologies) entail – (i) technologically advanced WEC with low specific Rated Power and (ii) standard PV installed in an east or west facing orientation.

3.1.1. Advanced WECs

The trend of using WEC with low specific Rated Power started almost a decade ago in Germany and was primarily driven by the necessity of utilising low to medium wind speed sites. With a decline in low specific Rated Power from values in the range of 380–520 W/m^2 to values <350 W/m^2 (see also Ref. [31]), the utilization in terms of FLH[1] (Full Load Hours) of the installed capacity has been increasing. Fig. 4 depicts a timeline of selected WEC types in the German market with their FLH values and the year of their introduction. Evidently advanced WECs are increasingly capable of generating >3500 FLH at reference site conditions[2] at hub heights greater than 130 m.

As shown in Fig. 4, the advanced WECs operate at more than twice the average FLH recorded for all existing WECs in 2009/2010/2011 (1536 FLH). Here it is important to provide a comparison to assumptions drawn in the Leitstudie [5] – widely accepted as one of the most relevant scenario studies on the German energy transition. Leitstudie assumptions indicate 2300/2600 FLH for 2030/2050. These values are considerably low when compared against current advancements in performance of WECs under good wind conditions. We estimate the impact of the on-going trend towards advanced WEC by modelling the normalized feed-in with 3500 FLH for the current (2011) set of installations as shown in Equation (2):

$$\text{CAP wind}_{\text{dec 2011}} * 3500\,\text{FLH} = s * \sum \text{feed} - \text{in}_{\text{wind}(t)1536\,\text{FLH}} \qquad (2)$$

where CAP winddec2011 is the installed capacity of wind at the end of 2011 in [MW], FLH is 3500 [h] and '*s*' is the scaling factor that is applied on the existing cumulated feed-in from wind [MWh] with 1536 FLH. Consequently, both the left and right sides

Table 1
Key figures for the 50 Hertz grid area calculated on the basis of the normalized feed-in data.

Baseline 2009/2010/2011			
vRES	Capacities [MW]	Share of total vRES installed capacity [%]	Share in electricity demand [%]
PV	4070	26	4
Wind	11,719	74	21
Resulting statistics			
Excess energy [TWh/a]			0.1
Maximum positive residual load 2009–2011 [MW]			13,414
Maximum negative residual load 2009–2011 [MW]			3074

[1] Note: the widely used term "Full Load Hours" (FLH) describes the relation between the energy generated in a given time and the Rated Power of a converter. In Fig. 4, the *Y*-axis in the graph uses hours [h], as energy (kWh) is divided by the power (kW). The principle relation is also described as the Capacity Factor (CF) as another performance parameter. CF is defined as the ratio of the energy actually produced by an energy converter to the energy that could have been produced if the converter ran at its rated power over a given time period. For the period of one year, the CF can be converted to the FLH by multiplying the dimensionless CF with 8760 h (one year), thereby converting CFs of 0.19 and 0.40 to 1536 FLH and 3500 FLH respectively.

[2] For the Vestas V-126 3.0 MW at 137 m hub height: 3505 FLH; Enercon E-115 2.5 MW at 149 m hub height: 3912 FLH; Nordex N117/2400 at 141 m hub height: 3962 FLH; All calculations were performed for reference wind conditions with data provided by the manufacturers.

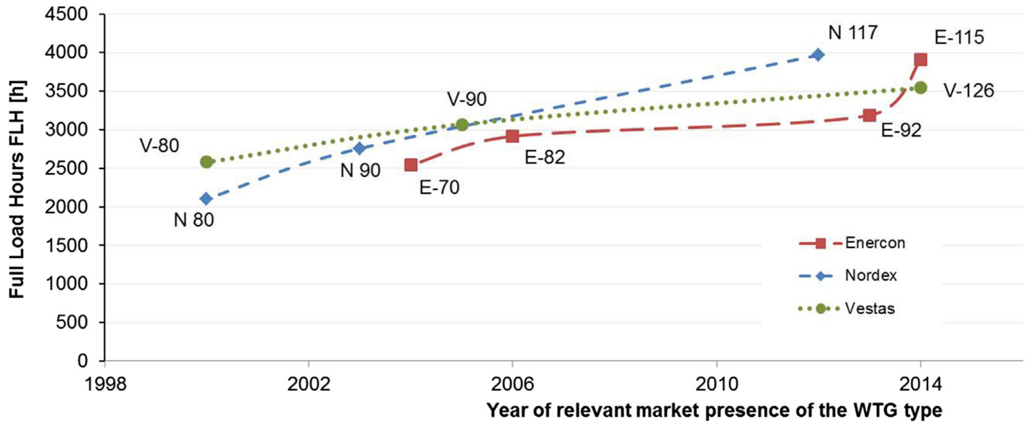

Fig. 4. Development of Full Load Hours (FLH) of representative WEC types from 2000 to 2014 in the German market.

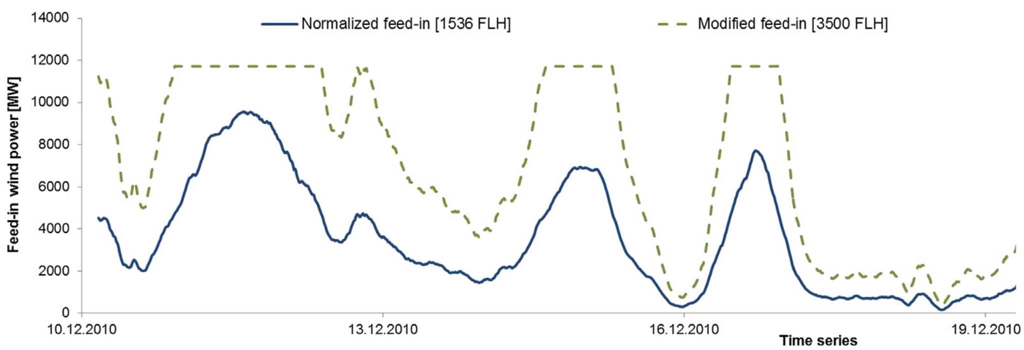

Fig. 5. Comparison of the normalized feed-in vs. modified feed-in for time slice ten days in December 2010.

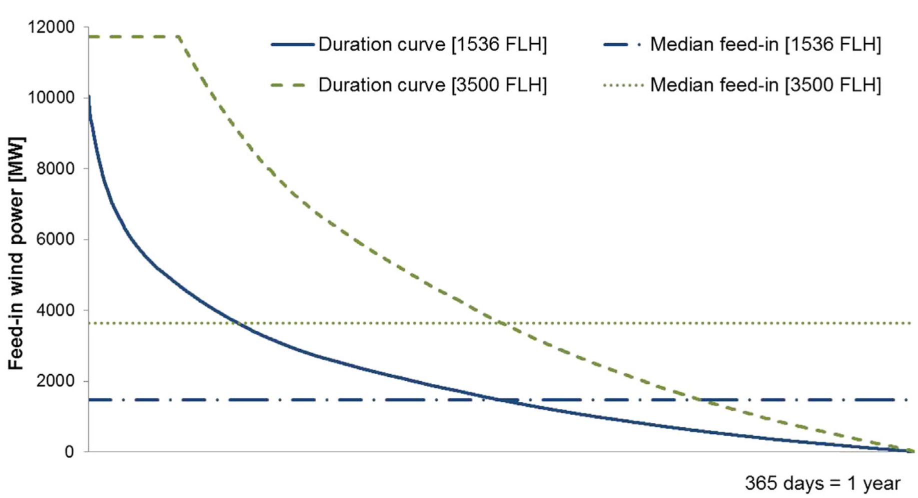

Fig. 6. Comparison of the power duration curves for normalized (1536 FLH) and modified (3500 FLH) feed-in.

of Equation (2) represent the AEP (Annual Energy Production) from advanced WEC. The scaling factor '*s*' is a dimensionless value that is constant over time and is numerically calculated to fulfil Equation (2); '*s*' is hence applied to the quarter-hourly data sets throughout the 3 year time series.[3] '*s*' is iteratively calculated until AEP, FLH (3500 h) and CAP winddec2011 are fulfilled while ensuring that the feed-in at any time point does not exceed the CAP winddec2011. A comparison of the original and the modified time series is given in Fig. 5.

Fig. 6 depicts the comparison of the power duration curves of the normalized and modified feed-in. The Area Under the Curve for both 1536 FLH and 3500 FLH represent the AEP. As is evident in the graph, for 3500 FLH-AEP and median feed-in are higher than for 1536 FLH while maximum feed-in is limited to CAP winddec2011. Thus, advanced WECs deliver a higher median power output

[3] This estimate does not take some effects into account e.g. power curve characteristics of advanced WEC optimized for low wind speed or wind characteristics at elevated heights.

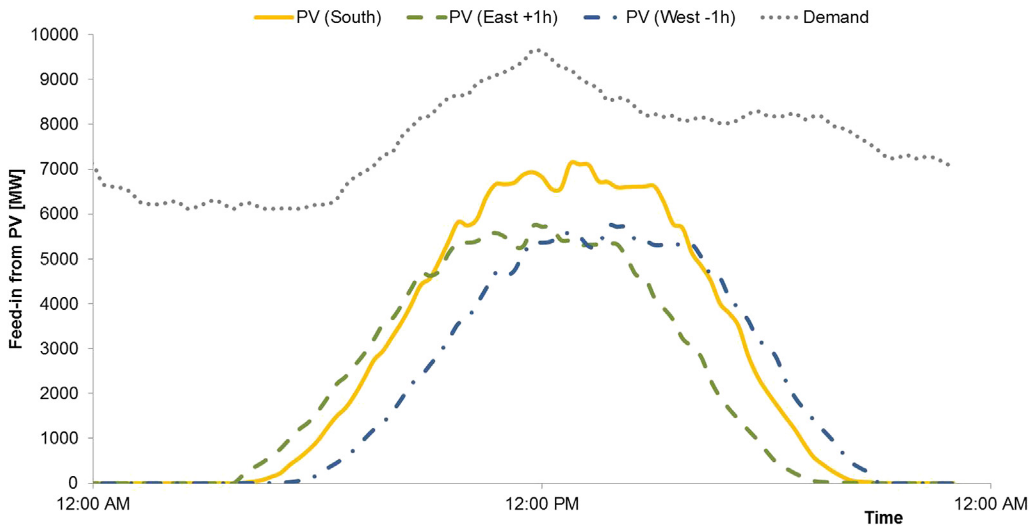

Fig. 7. Comparison of normalized feed-in (PV(S)) vs. modified feed-in PV(E) & PV(W) installations over 24 h.

although some power production is lost due to limitations of the lower Rated Power.

This approach of adjusting feed-in data to variations in FLH or capacity factors was cross checked with an alternative approach applied and published in the EnergyPLAN software [36] developed at the Aalborg University. A comparison of the two different approaches is given in the Appendix of this article.

3.1.2. Solar PV

The variation in azimuth angle of PV modules in an East–West orientation is expected to show a positive effect on the reduction of excess energy as it enables better coverage of temporal demand profiles [37]. South-facing modules have historically contributed to fulfilling mid-day peak demand. With increasing installed capacities instances of excess energy production are rising in mid-day while residual loads in the morning and evening hours remain unmet. The installation of PV systems with azimuth angles facing east (PV(E)) and west (PV(W)) instead of the currently predominant south oriented systems (PV(S)) shifts the feed-in pattern towards morning PV(E) or evening PV(W) hours and does not require new technology. This scheme offers potential to reduce feed-in peaks and excess energy while incurring only some disadvantages in terms of lower AEP per installed capacity.[4]

To approximately capture the effect of feed-in from PV(E) or PV(W) oriented installations, the normalized feed-in is modelled to get a modified feed-in by shifting the existing time series to 1 h back PV(W) or forth PV(E) [32], as depicted in Fig. 7. The figure indicates that changing the orientation to east and west has advantages in feed-in patterns (e.g. broadening of the production profile) at the cost of a reduction of about 20% in AEP.[5]

3.2. Cases

Optimization was performed for two Cases – (i) 50% (2030) share of vRES (ii) 80% (2050) share of vRES, corresponding to current political aims [4]. The average annual demand in the region of 84 TWh during 2009–2011 [33] was used as a constant annual demand for the optimization runs. Hence, in this study, the 50% Case aims at 42 TWh/a and the 80% Case aims at 67.2 TWh/a from vRES. The underlying assumption in both cases is that the entire vRES share (50% and 80%) is generated from a combination of wind and PV (although in more realistic terms a smaller share would also be available from other renewables[6]).

The objective was the identification of an optimal vRES mix with minimal excess energy generation. For each Case we performed two optimization runs – (i) baseline optimization and (ii) advanced technology optimization (see Section 3.3 for details on the optimization routines).

The simulation runs are named:

I. 50% vRES Case
   ○ baseline optimization
   ○ advanced technology optimization

II. 80% vRES Case
   ○ baseline optimization
   ○ advanced technology optimization

3.3. Optimization

The definition of the goal function for an optimized composition of vRES capacities differs with research questions as shown in studies by Heide, Ostergaard, Wagner and Kempton [11,26,38,39]. Literature reveals that the most relevant criteria for optimization are:

1. storage capacity – since electricity storage is a very limited and costly asset

[4] The effects of azimuth angles on solar energy production can be assessed by various models calculating AEP from PV. A free scientific purpose tool used is available under: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php.

[5] Values taken from PV-GIS calculator for a reference installation in Magdeburg, with 963 kWh/kWp for south facing installation vs. 765 kWh/kWp for east facing AEP.

[6] The obtained time series for the feed-in from biomass, hydro power and geothermal do not show significant variations in time and are not included in the calculation. The installed capacities from these RES can be seen as a viable source for renewable balancing power generation to complement the vRES energy production and are not added up to the calculated renewable shares in the Cases presented here, as the focus is set on the optimized composition of vRES only.

2. maximum positive residual load (deficit power) – since additional back up is needed to complement vRES
3. excess energy production (cumulated negative residual load) – since a critical component as curtailment is related to additional costs

As per previous studies by Lund, Ostergaard, Bove, and especially Kreifels [19,20,24,38] we selected the minimization of excess energy (criteria 3) as the most appropriate single objective function for an optimal composition of vRES capacities. Excess energy can be seen as a cumulative indicator for the integration of vRES into an electrical power system. We define this as the goal function in this study based on the premise that it results in a combined feed-in which best fits the fluctuations in demand.

This approach does not include refinements such as storage, DSM, integration into the heat and transport sector or import and export of electricity to other interconnectors, although these are seen as important options for the integration of vRES [32].

For each Case two optimization routines were run:

(i) Baseline optimization

This is performed with the normalized feed-in data from current technologies (PV(S)) and WEC with 1536 FLH using Equation (3) for the time series from 2009 to 2011. The results of the baseline optimization serve as a reference for comparison against optimization results of the advanced technological options. The goal function is achieved in Equation (3) by summing up only positive values on the right hand of the equation (=excess energy).

$$\min \rightarrow f(a_t,\ x_t,\ t) = \sum a_t + x_t - \text{demand}_t \tag{3}$$

The key variables used in the Equation (3) are given below:

a = scaling factor for capacity of PV from south facing installations × feed-in from PV(S)
x = scaling factor for capacity of wind installations with 1536 FLH × feed-in from Wind with 1536 FLH
demand = electricity demand
t = time step (feed-in and demand 2009–2011 in 15 min time interval)

(ii) Advanced technology optimization

This routine encompasses the optimization of vRES with the use of advanced technologies in wind (WEC with 3500 FLH) and solar power (PV(E) and PV(W)) as detailed in Sections 3.1.1 and 3.1.2. The underlying algorithm used in the simulation is presented as Equation (4). Here, we assume that a minimum of 50% of the 2011 PV(S) capacities (existing technology) would remain operational in future and therefore retain the corresponding fraction of installed capacity (2035 MW) in the calculation. In order to conclusively analyse whether advanced technologies offer any improvement over baseline technologies, the optimization routine was designed such that the choice of the feed-in data (either normalized feed-in or modified feed-in) aimed at achieving the goal function. In other words, the program is allowed to select either baseline technologies or advanced technologies to achieve minimal excess energy generation while fulfilling the shares of vRES on energy supply of 50% or 80%. Results from these simulations allow the quantification of the specific effects of the use of advanced technologies. As in Equation (3), the goal function is achieved in Equation (4) by summing up only positive values of excess power.

$$\min \rightarrow f(a_t,\ b_t,\ c_t,\ x_t,\ y_t,\ t) = \sum a_t + b_t + c_t + x_t + y_t - \text{demand}_t \tag{4}$$

The key variables additionally used in Equation (4) are given below:

b = scaling factor for capacity of PV from east facing installations × feed-in from PV(E)
c = scaling factor for capacity of PV from west facing installations × feed-in from PV(W)
y = scaling factor for capacity of wind installations with 3500 FLH × feed-in from WEC with 3500 FLH

By independently varying a, b, c, x and y, the optimization algorithm minimizes excess energy (goal function) for 2009–2011. Additionally we quantified the individual potentials of advanced wind and advanced PV towards minimizing excess energy production by selectively introducing/removing either resource in Equation (4) during optimization runs.

4. Results

We present the results in three following sub-sections-excess energy calculations for a continuously increasing vRES share of

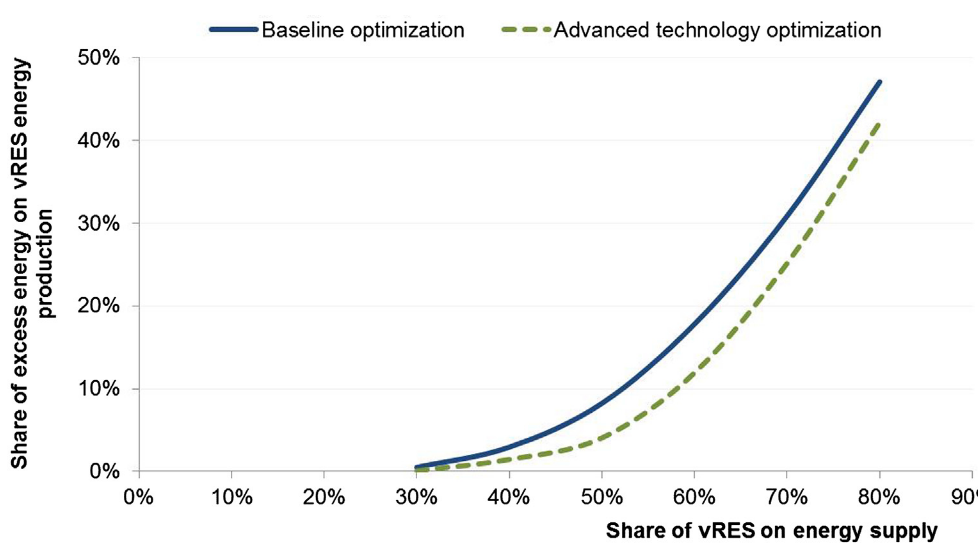

Fig. 8. Shares of vRES vs total excess energy after baseline and advanced technology optimization.

30%–80% (4.1) and discrete shares-50% and 80% vRES as Cases covering excess energy, optimal shares and future requirements of installed capacities (4.2 and 4.3). To the best of our observation, all calculations are reproducible. Since no field data for future cases of higher vRES shares are available, no direct comparison of the calculated outcomes was possible. However, a cross-check based on published studies for selected elements of the approach was performed [11,19,20,23,27].

4.1. Excess energy

To determine the general relation between vRES shares on energy demand and excess energy of optimally composed systems, the calculations of optimal compositions were performed as a continuous series. The following graph (Fig. 8) shows this relation.

Total excess energy production becomes relevant only when vRES shares cross 30%–40% but thereafter increases progressively. In case of very high vRES shares-up to 80%, excess energy amounts to >40% in the baseline and ~50% in the advanced technology case of the overall vRES production. As apparent in Fig. 8 the introduction of advanced technologies reduces excess energy throughout the calculated range from 30% to 80% of vRES on annual energy supply.

4.2. 50% vRES Case

The results for the case with 50% vRES share, expected to be reached in 2030, are of special interest as additional vRES capacities are expected to be installed while no significant storage capacities are foreseeable. Tables (Tables 2a and 2b) present the optimization results (optimized shares of vRES and other related outputs) for baseline and advanced technology.

The baseline layout (Table 2a) shows that the intended share of 50% renewables (42 TWh) in electricity supply in 2030 can be fulfilled for the 50 Hz grid with limited amounts of excess energy (3.8 TWh), equivalent to 8.4% of the AEP from wind and PV in the baseline configuration. However, the use of modern WEC for the repowering of the existing turbines and new PV(E) and PV(W) in the advanced technology case can also fulfill the 50% share but with a reduced amount of excess energy (1.8 TWh), a reduction of 53% compared to the baseline case (Table 2b).

With respect to future requirements of installed capacities, the overall solar PV capacity (PV(S) + PV(E) + PV(W)) from the two optimization runs remains similar for the baseline (17,112 MW) and advanced technology (17,136 MW) layout. For the independent calculation run for the advanced technology layout including additional PV(E) and PV(W), the resulting capacities for PV of 17,136 MW consisted of 2025 MW of PV(S), 12,445 MW of PV(E) and 2656 MW of PV(W). In contrast, advanced WEC enables a substantial reduction from 20,209 MW (baseline set-up) to only 8992 MW, equivalent to a 55% reduction in installed capacity.

Table 2a
Overview of the results for the 50% baseline.

Baseline optimization – 50% vRES			
vRES	Capacities [MW]	Share of total vRES installed capacity [%]	Share in electricity demand [%]
PV(S)	17,112	46	17
Wind	20,209	54	38
Resulting statistics			
Excess energy [TWh/a]			3.8
Maximum positive residual load 2009–2011 [MW]			13,518
Maximum negative residual load 2009–2011 [MW]			14,031

Table 2b
Overview of the results for the 50% advanced technology.

Advanced technology optimization 50% vRES			
vRES	Capacities [MW]	Share of total vRES installed capacity [%]	Share in electricity demand [%]
PV (S)[a]	2035	8	2
PV (E)	12,445	48	10
PV(W)	2656	10	2
Wind (1536 FLH)	0	0	0
Wind (3500 FLH)	8992	34	37
Resulting statistics			
Excess energy [TWh/a]			1.8
Maximum positive residual load 2009–2011 [MW]			13,507
Maximum negative residual load 2009–2011 [MW]			11,339

[a] A preset minimum for PV(S) of 2035 MW or 0.5 in scaling factor is set with regard to existing PV installations that are expected to be installed up to 2050. Note: all numbers are rounded off to one decimal place.

Advanced technology enables a reduction in maximum excess power production or maximum negative residual load from 14,031 MW to 11,339 MW (Tables 2a and 2b). The maximum positive residual load or deficit power during the course of the three years, almost no change was registered as 13,518 MW for the baseline was calculated against 13,507 MW for the advanced set-up.

The share of required installed wind capacity in relation to the combined capacity from wind and solar reduces to 34% in the advanced technology from 54% in the baseline set-up. This significant difference in installed wind capacity is the result of the much higher FLH from advanced WEC although the share in AEP from wind remains almost stable at a 37%–38%. As a consequence of the higher FLH of advanced WEC, the optimal share of necessary installed capacities of wind is significantly reduced compared to baseline WEC.

To differentiate between the impact of advanced wind in contrast to advanced PV, the selective introduction and removal of either the advanced PV or wind technology options in Equation (4) was performed on the calculation runs as described in Section 3.3. Results show that advanced WEC exclusively contributes to 87% of the excess energy reductions achieved by the combined options, while PV(E) and PV(W) installations contribute only a marginal 3%. The remaining 10% are achieved by the combined effect of advanced wind and PV. This finding corresponds to the economic assessment of azimuth adjustments in solar PV performed by Denholm [40].

Fig. 9 shows the relation between excess power [MW] and the cumulated excess energy [MWh] in the 50% vRES Case, again differentiated into the baseline and advanced technology layouts. The graph orders excess power production values on the x-axis, starting with the lowest value on the left up to the highest value on the right versus the cumulative excess energy from these values on the y-axis. These excess power vs. excess energy curves show the composition of excess energy production over the course of one year. When comparing the excess energy production from vRES, the differences between the baseline and advanced technology set-ups become obvious, as higher installed capacities in the case of the baseline optimization are responsible for higher excess power [in MW] and excess energy [in MWh].

With respect to the possible introduction of storage capacities, these differences can have a significant impact. As an example (dashed lines in Fig. 9), for excess power of up to 3000 MW, almost identical cumulative excess energy is registered for both set-ups.

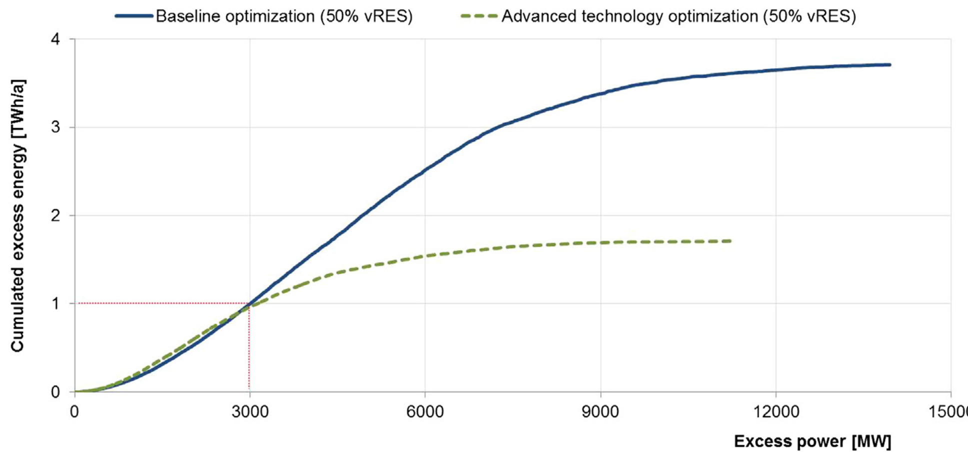

Fig. 9. Excess power vs. cumulated excess energy for the 50% vRES case (baseline and advanced technology).

With possible storage facilities (PSH, power to gas, etc.) with a 3000 MW input power capacity, about 1 TWh of excess energy can be stored in both cases. In the case of the advanced technology layout for vRES, about 0.8 TWh of the overall 1.8 TWh of excess energy would need to be curtailed due to limitations in storage capacity of 3000 MW. In the case of the baseline optimization, this energy amounts to 2.8 TWh, as cumulative excess energy increases further beyond 3000 MW until it reaches the 3.8 TWh in excess energy.

To summarize, the advanced technology optimization offers a 30% reduction in requirements for future installed capacity from wind and PV with a 53% lower excess energy production while fulfilling the 50% RES target.

4.3. 80% vRES Case

The results of this Case provide insights into the challenge of integrating very high shares of vRES. It can be regarded as an unlikely scenario giving the constraints in modelling (no storage, no interconnectors, no DSM) and is only intended to underline the non-linear increase in excess power production with rising shares of vRES and the potential that advanced technology offers in such a scenario. Tables 3a and 3b give the results for 80% vRES.

Analogous to the results in the 50% RES Case, the optimization including advanced technology shows significant reductions in overall requirements of installed capacities by 32% and a decline in maximum excess power by 26% compared to the baseline optimization.

With shares of 80% vRES, excess energy increases to 61.3 TWh or 73% of the annual energy demand in the baseline set-up. This figure is reduced to 50.1 TWh or 59% of the annual electricity demand for the optimization with the proposed advanced technology from wind and PV. With advanced PV contributing 1.9 TWh or 17% to the excess energy reduction, advanced wind again offers the larger fraction 7.2 TWh or 64% of the total 11.2 TWh reduction. The remaining 19% are achieved by the combined effect of advanced wind and PV.

Fig. 10 shows the relation between excess power [MW] and the cumulated excess energy [MWh] in the 80% vRES Case.

Similar to the 50% vRES case, the distribution of excess power and the excess energy do not differ much for excess power values between 1 and 13,000 MW. Storage facilities of ~30 GW maximum capacity would almost cover the entire excess energy production (50.1 TWh) in the advanced technology set-up (see dashed line in Fig. 10). Comparably, the same amount of storage capacity-30 GW would result in the loss of excess energy of ~10 TWh in the baseline set-up. The above calculations show that advanced technologies provide distinct advantages over current technologies with respect to the introduction of storage capacities or transmission grid infrastructure as lower storage capacity would be required to store the same amount of excess energy.

Fig. 11 displays a final comparison of the main findings. In Fig. 11(A) and (C), a decline in required future capacities for the advanced technology optimization is apparent for both Cases-50 and 80% vRES. With wind power capacities declining significantly, the capacities from PV are slightly increasing and shifting towards east and west oriented installations. In terms of energy production shares, about three fourth is generated by wind power for the 50% and the 80% vRES Cases as displayed in Fig. 11(B) and (D).

Table 3a
Overview of the results for 80% baseline case.

Baseline optimization 80% vRES			
vRES	Capacities [MW]	Share of total vRES installed capacity [%]	Share in electricity demand [%]
PV (S)	33,833	34	33
Wind	65,046	66	119
Resulting statistics			
Excess energy [TWh/a]			61.3
Maximum positive residual load 2009–2011 [MW]			13,376
Maximum negative residual load 2009–2011 [MW]			56,491

Table 3b
Overview of the results for the 80% advanced technology case.

Advanced technology optimization 80% vRES			
vRES	Capacities [MW]	Share of total vRES installed capacity [%]	Share in electricity demand [%]
PV (S)[a]	2035	3	2
PV (E)	20,965	31	17
PV(W)	19,442	29	15
Wind (1536 FLH)	0	0	0
Wind (3500 FLH)	25,183	37	104
Resulting statistics			
Excess energy [TWh/a]			50.1
Maximum positive residual load 2009–2011 [MW]			13,384
Maximum negative residual load 2009–2011 [MW]			42,018

[a] A preset minimum for PV(S) of 2035 MW or 0.5 in scaling factor is set with regard to existing PV installations that are expected to be installed up to 2050. Note: all numbers are rounded off to one decimal place.

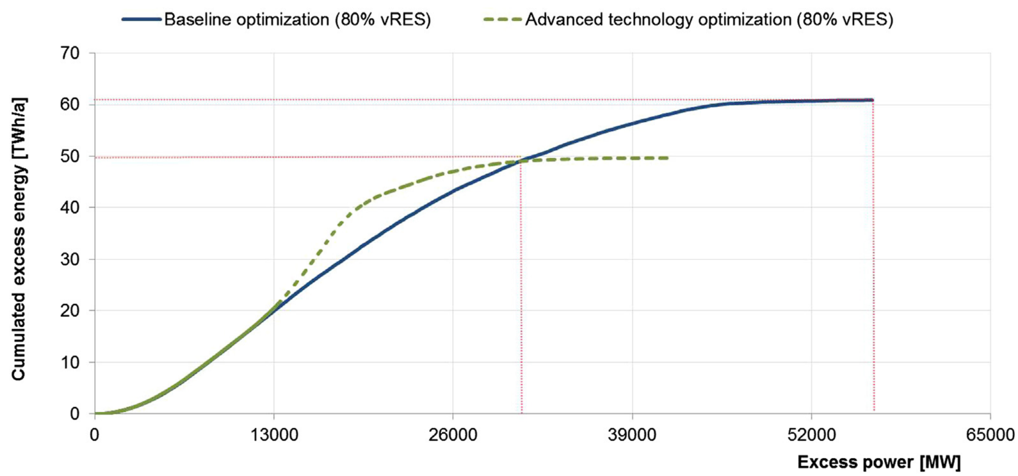

Fig. 10. Excess power vs. cumulated excess energy for the 80% vRES case (baseline and advanced technology).

5. Discussion

The main objectives of this paper were (i) identifying optimal shares of vRES (wind and solar) for medium and high shares of renewables (50% & 80%) and (ii) calculating required future capacities of wind and solar installations. The calculations are based on time series data of demand and feed-in from wind and solar PV from 2009 to 2011 for the 50 Hz grid in Germany. We consider excess energy as an indicator for system integration, while excluding options for the integration of vRES like storage, capacity extension of interconnectors for import and export to other power grids or DSM.

While current rates of excess energy production in the 50 Hz grid are low (0.1 TWh/a) for a calculated 25% share from vRES, excess energy would rapidly increase beyond 30% (50% vRES) and 40% (80% vRES) of AEP.

The advanced technology options studied in this article consistently provided substantial reductions in excess energy production. The algorithm used in this study consistently selected advanced technologies over baseline technologies in the optimization runs to minimize excess energy production. The observed reductions in excess energy is related to the lower overall capacities needed in the advanced technology set-up as they operate with higher FLH from WEC and higher temporally diversified production from PV.

In the 50% vRES case, advanced technology reduced the production of excess energy by 53% (1.8 TWh/a from baseline of 3.8 TWh/a). For the 80% vRES case, the relative reduction achieved

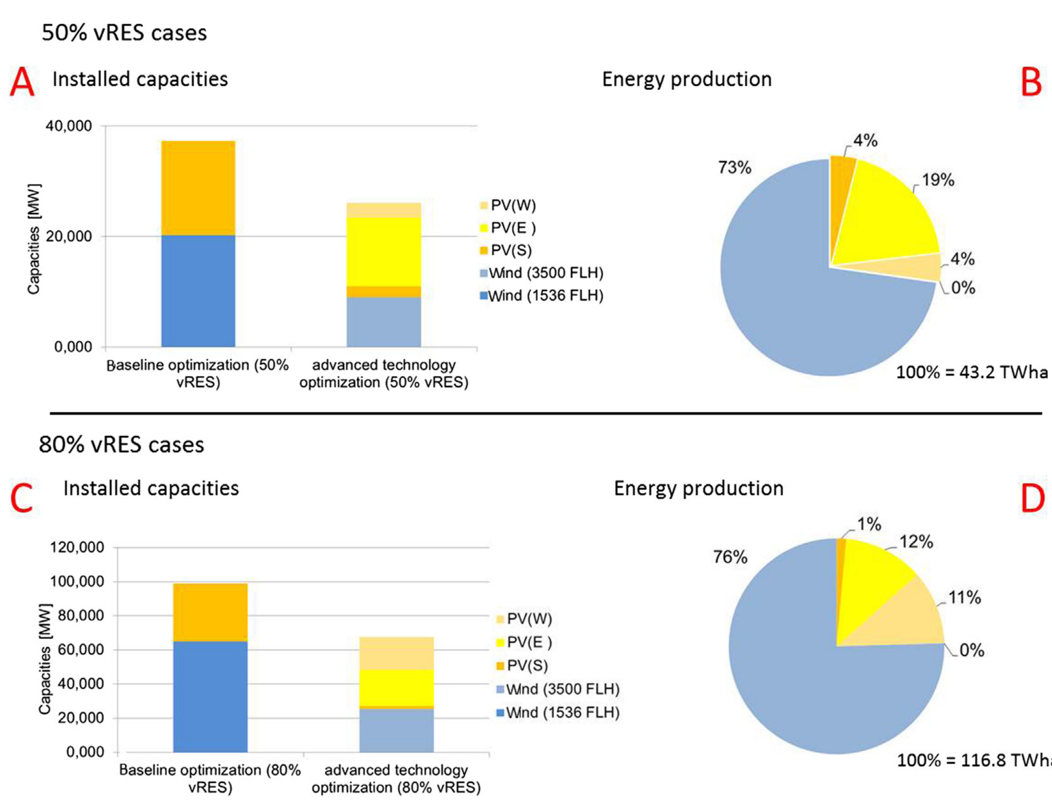

Fig. 11. Required future capacities (A: 50% vRES and C: 80% vRES cases) and energy production shares for the advanced technology set-up (B: 50% vRES and D: 80% vRES cases).

by advanced technology was 18% as excess energy declined from 61.3 to 50.1 TWh.

Nevertheless, the increase in excess energy from 1.8 TWh/a (50% vRES case) to 50.1 TWh/a (80% vRES case) in the advanced optimization results substantiate the fact that the share of excess energy production progressively increases with an increasing share of vRES. Finally, if 80% electricity demand is supported by vRES, the vRES production alone would amount to 138% (Table 3b) of the demand as a significant fraction would be excess energy. The installation of the correspondingly large capacities of wind and solar would be a realistic option when complemented by additional means for transportation and storage of excess energy. Further, the integration of the power system into the heat, transport or material production system can be useful [11,40–42].

When differentiating between the impact of either advanced WEC or east-west facing solar PV, the results show that the effect of advanced WEC proved to be larger, exclusively achieving 87% (50% vRES) of the combined reduction in excess energy. This underlines the potential of advanced wind power capacities for reductions in excess energy production and system integration of vRES. In the 80% vRES case, advanced technology offers advantages as grid and storage capacities can be better utilized since excess power production does not reach as high levels as those for the baseline set-up (advanced technology is 25% lower than baseline set-up).

Results indicate that optimal shares of wind and solar in the total energy production are almost identical for both the baseline and the advanced technology set-ups in the 50% and 80% vRES Cases. Throughout the two cases, a 69–76% of the AEP is provided by wind power and the remaining 31–24% is generated from solar PV. This composition remains unaffected even when advanced technology is applied, thereby indicating that the optimal shares in the region are likely to remain stable irrespective of different policy instruments (e.g. renewable energy targets) and technology developments. The optimal shares of future capacities identified by Kreifels [19] correspond well with the findings in our study, although different datasets, modelling parameters and constraints were applied. For the 50% renewables case, Kreifels identifies a 42% PV and 58% wind share in capacities as an optimal mix, which is close to the calculated optimum of 46% PV and 54% wind in our study. Our findings differ from the 45% share in AEP from solar calculated by Heide [27] at a pan-European scale with a 100% vRES supply. The higher contribution from solar PV published by Heide presumably originates from differences in demand and supply side characteristics, the larger spatial scale as well as the targeted 100% vRES supply.

Although the shares of wind and solar in AEP do not differ significantly in the 50% and 80% vRES Cases, installed capacities differ substantially. As a major outcome, the results of this study indicate a significant reduction in vRES future capacities when using advanced technology to achieve renewable targets. Presuming that almost all current WEC will reach their 20 year operational lifetime by 2030, the complete renewal of the capacities from wind power would allow for a reduction of wind capacities from 20.2 GW to 9 GW in the 50% vRES case using advanced WEC. Our calculations show (see Section 4.2) that if advanced set-up is preferred over baseline, 64% lesser wind turbines would be necessary to generate the 50% share in AEP. Consequentially, land requirement for wind energy establishments would be lower thereby reducing land-use conflicts and increasing public acceptance of wind power.

Despite the obvious advantages (reduced excess energy and required future capacities) of vRES integration as shown in our study, the importance of back-up capacities, storage and/or interconnected grids cannot be overlooked. This is corroborated by the calculations presented here as the maximum residual load (or deficit power) after vRES feed-in remained almost identical throughout the calculated configurations.

6. Conclusion

This study adds important dimensions to the discourse of vRES share integration in the German electricity system. We conclude that there is a high potential of the inclusion of vRES into an integrated system through the combined use of technical advancements and optimal mixes in the near-medium time frame. However, long-term planning should additionally include efficient and economically viable storage systems, flexible generation and improved grid integration.

The results showed that political targets of RES can be achieved along with significant reductions in excess energy production and the required installed capacity from wind and solar. Further, the potentials of advanced technologies, especially for WEC are clearly exemplified in this study. Current landmark studies on the German energy transition e.g. Leitstudie [5] do not cover these on-going advancements that can lead to significant improvements in grid integration and reductions in excess energy production as shown by us. Furthermore, the expected capacity installations [5,43] is significantly higher than those from our calculations.

Economic evaluation of the presented integration options (e.g. advanced technologies) will be helpful to prioritize investments. From this study it is clear that excess energy reduction should have a high priority in future and be further compounded with identification of alternate end-uses. Successful transition to a renewable power future would also be dependent on the extent to which other renewables such as bioenergy can contribute to complement vRES.

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Appendix. Feed-in modelling by the EnergyPLAN software.

A slightly different approach for the modification is used by the EnergyPLAN software to adapt existing time series for energy generation to higher or lower AEP values. The idea of the equation [36] for the modification is to maintain zero and maximum production values of the original time series while raising or lowering all intermediate values between.

$$eRes' = \frac{eRes}{[1 - FACRes*(1 - eRes)]} \tag{5}$$

with $eRes'$ the hourly electricity production after correction, $FACRes$ as the correction factor and $eRes$ the hourly electricity production or element of the feed-in time series.

After parameterization of the equation by the $FACRes$ factor, the resulting modified time series increases the relative frequencies of mid-range power production values in comparison to the original time series.

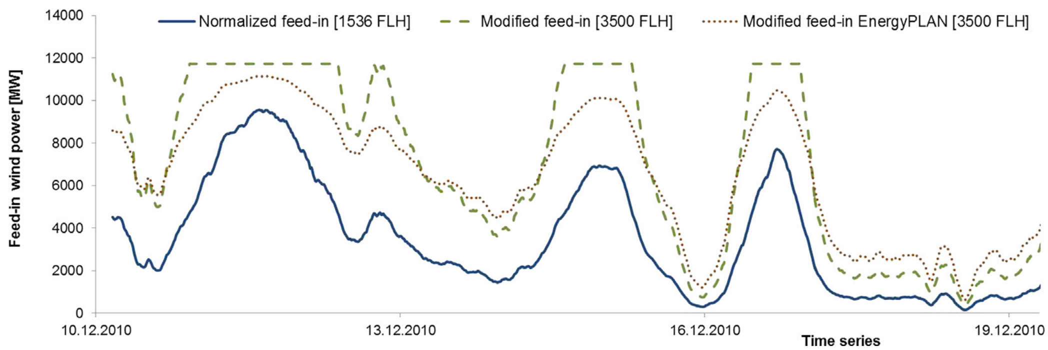

Fig. A1. Comparison of the current feed-in, the modified feed in for 3500 FLH as described in paragraph 3.1.1 and the feed-in modification applied on the EnergyPLAN software for a selected part of the time series.

When comparing the approach used by the EnergyPLAN software parameterized to achieve the same 3500 FLH with Equation (2) applied in this paper, Equation (2) used in this study generates higher frequencies of full power production from the combined set of WEC whereas EnergyPLAN's time series only attains the maximum combined power output only once in the time series in trade for higher power generation in the mid-range (see Fig. A1).

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Publication Two

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Capacity Expansion Pathways for a Wind and Solar Based Power Supply and the Impact of Advanced Technology—A Case Study for Germany

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Abstract: Wind and solar PV have become the lowest-cost renewable alternatives and are expected to dominate the power supply matrix in many countries worldwide. However, wind and solar are inherently variable renewable energy sources (vRES) and their characteristics pose new challenges for power systems and for the transition to a renewable energy-based power supply. Using new options for the integration of high shares of vRES is therefore crucial. In order to assess these options, we model the expansion pathways of wind power and solar photovoltaics (solar PV) capacities and their impact on the renewable share in a case study for Germany. Therefore, a numerical optimization approach is applied on temporally resolved generation and consumption time series data to identify the most efficient and fastest capacity expansion pathways. In addition to conventional layouts of wind and solar PV, our model includes advanced, system-friendly technology layouts in combination with electric energy storage from existing pumped hydro storage as promising integration options. The results provide policy makers with useful insights for technology-specific capacity expansion as we identified potentials to reduce costs and infrastructural requirements in the form of power grids and electric energy storage, and to accelerate the transition to a fully renewable power sector.

Keywords: variable renewable energy sources; wind power; solar energy; Germany; pumped hydro storage; system-friendly renewables

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1. Introduction

The rapid expansion of renewable energies worldwide has resulted in a steep increase in installed capacities in recent years. Wind and solar photovoltaics (solar PV) in particular have seen a significant increase in global installed capacities and have displaced conventional sources in terms of annually added capacities worldwide. Climate protection is one of the key drivers for renewables, and especially wind and solar PV have become cost-competitive in comparison to established non-renewable sources [1].

Despite this dynamic expansion of renewables, there are several challenges ahead, since climate protection aims call for an even faster transition to keep on track with greenhouse gases (GHG) emission reduction [2]. Wind and solar PV are variable renewable energy sources (vRES). These inherently volatile sources pose major challenges for their integration into the power supply system [3–9] and the transition to a fully renewable power supply system [10–13].

Approaches to integrate the growing capacities from vRES are therefore the focus of much research. For the technical integration of vRES, three important elements have been identified: (a) electric energy storage; (b) an optimized capacity mix of different vRES; and (c) the introduction of advanced technologies in wind and solar PV systems, also called system-friendly layouts of vRES.

Electric energy storage is regarded as a key element for the integration of vRES to address the volatility of vRES, to utilize excess energy (EE) and to balance supply and demand to maintain a secure power supply [14–17]. Nevertheless, new storage technologies face either technological or economic constraints and are still not available in the required TWh range. Mature, large-scale electric energy storage solutions such as pumped hydro storage (PHS) face limitations in the physical potential of many countries, as well as restrictions due to nature conservation. In fact, electric energy storage capacities have not kept pace with vRES expansion in recent years [6,11,18–23].

A second important option is the optimization of the capacity mix of wind and solar PV [7,12,24–29]. Optimizing their shares allows exploiting the complementary production patterns of wind and solar PV over various time scales, ranging from the apparent daily patterns of solar PV production to seasonal patterns for both wind and solar PV [25,30]. In contrast, achieving high shares of vRES using either wind or solar PV alone leads to higher variability in power supply and higher EE [29,31–33] for a set renewable share (REN share) target. EE itself is likewise associated with a decline in the marginal utility of additional vRES capacities, as the energy produced in times of EE is not substituting non-renewable energy sources [3,5,10,34]. With many countries pursuing REN strategies with annual capacity targets for specific REN technologies, optimal mixes of vRES can contribute to effectively attaining these targets. Tenders for new renewable generation capacity in many countries could, in principle, allow governing the future capacity mix through the expansion pathways for each REN technology. However, there is to date little knowledge about an effective pathway for wind and solar PV regarding REN shares to achieve future REN share goals.

A third option for the integration of vRES has been identified in technologically advanced wind energy converters (WEC) and solar PV systems. Advanced technologies entail WEC with increased hub heights and low specific power ratings compared to the rotor swept area (W/m^2), as well as solar PV panels facing east or west instead of the traditionally south-facing panels in the northern hemisphere or north-facing panels in the southern hemisphere [35,36]. East-west-facing solar PV offers improved technical system integration compared to standard technology, especially when introduced in power systems with high shares of vRES [34,37,38]. The International Energy Agency (IEA) "Grid Integration of Variable Renewables" research project (GIVAR) published a report in 2014 [39] describing the contribution of advanced technologies in wind and solar PV to addressing the challenges associated with the expansion of significant vRES capacities. These "advanced technologies" [38] or "system-friendly" layouts of wind and solar PV installations [40] are important options for the improved integration of high shares of vRES into power systems [39,41–43].

Existing studies cover only one or two of the three selected options: either optimized generation mixes of vRES [11,28,44,45], the interplay of vRES with electric energy storage [15], or advanced technologies for future vRES-based power systems [38,40,46]. Among these, Killinger et al. [46] introduced advanced technology from solar PV with different azimuth and inclination angles and determined the optimal regional vRES mix regarding economic efficiency, environmental sustainability and the security of supply. This therefore covers a wide range of important options and targets. Nevertheless, the article does not include electric energy storage capacities or the expansion pathways towards the identified optimal mix from vRES. Becker et al. [28] investigated wind and solar PV build-up pathways for different regions in the United States. Their analysis covers pathways for the minimization of back-up energy as well as for economic cost. Central to the approach is the mismatch of vRES power production and power consumption. A variety of cost-minimal pathways were identified for the different regions, underlining that region-specific factors like the spatio-temporal potentials for vRES as well as power demand play an important role, meaning that the analysis has to be performed specifically for each region of interest. Unlike the approach presented in this article, two of the three identified options for the integration of vRES are not covered: storage (option a) and system-friendly technologies (option c). The incremental efficiency of every added capacity of wind and solar PV on the renewable share is likewise not directly addressed, as build-up pathways are calculated in dependence of REN shares, which are not directly linked to capacity expansion as REN shares are negatively affected by EE from vRES.

To overcome the identified limitations in the research for optimized pathways in vRES capacity expansion, the approach presented here examines the effect of all three options on the efficiency of vRES expansion pathways. This will allow identifying the most effective pathways to achieve future REN goals from an overall capacity and REN share point of view and will enable us to assess the performance of alternative configurations of vRES capacities and electric energy storage. Using capacity expansion as the basis and calculating the resulting REN share offers a direct linkage to renewable support schemes, as many countries implement technology-specific tenders that allow directly governing capacity expansion for every vRES technology.

The main objectives of this paper are therefore to (i) provide a broad picture of how wind and solar PV can be combined to achieve efficient pathways in capacity expansion to fulfill future REN targets, (ii) identify the impact of advanced technologies in wind and solar PV against baseline technology, and (iii) to investigate the impact of electric energy storage. Therefore, we developed an algorithm to assess the incremental expansion of wind and solar PV by its impact on renewable shares (REN shares). This is built on the vRES optimization model published in 2014 [38] and is extended to calculate a wide range of capacity combinations, including electric energy storage from PHS as well as the identification of efficient pathways in capacity expansion in wind and solar PV.

For our case study we selected Germany, as it is one of the countries that has already seen a large expansion of vRES since 2000, exceeding 36.2% in REN share in 2017 [47]. Renewables, excluding wind and solar, made up for 11.2% in power consumption in 2017, so that wind and solar PV will have to provide more than 85% for the transition to a 100% renewable power supply at current consumption levels. In combination with the implemented tenders for the expansion of wind and solar PV capacities, Germany is a very suitable case study region.

The paper is structured as follows: in Section 2 we describe the input data, the investigated technologies and the study cases. Section 3 provides details on the methods and modeling. The results of the study are presented in Section 4, followed by a discussion in Section 5 and our conclusions in Section 6.

2. Input Data, Technology and Study Cases

2.1. Input Data

We used hourly electricity feed-in (from onshore wind and solar PV, including capacity factors) and net load data (representing electricity demand) for the years 2012 to 2015 for Germany, provided by the Open Power System Data Platform [48]. Net load data was adjusted on an annual basis to comply with the governmental projections for power consumption of 535.4 TWh/a [49,50]. The normalized feed-in time series for wind and solar PV covers the variability in vRES production over a time period of four years, and are up-scaled in order to model the future expansion of vRES capacities [38].

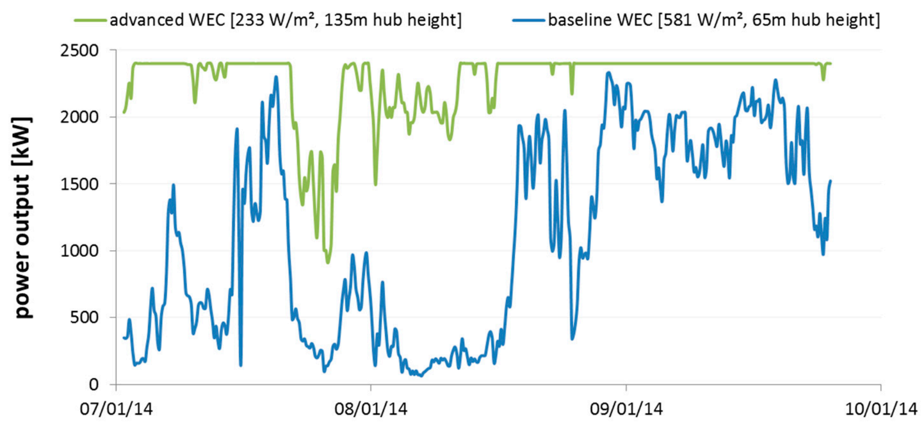
2.2. Technology Options

In accordance with [38–40,51], advanced technologies or system-friendly layouts include technologically advanced WEC with low specific rated power and solar PV in a mixed setup of south, east and west-oriented systems.

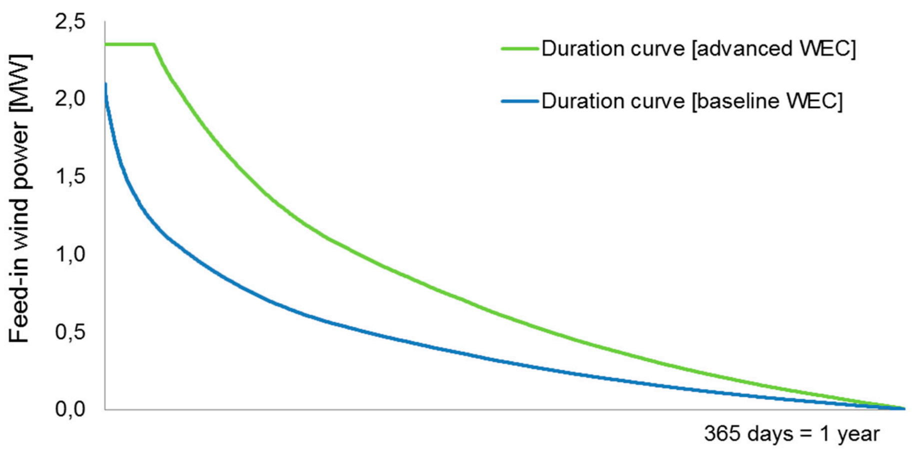
2.2.1. Advanced and Baseline WECs

The technology options considered in this study included onshore WEC with low specific rated power which were developed for application in low wind regimes. In recent years, a decline in specific rated power per rotor swept area from values in the range of 380–520 W/m^2 (baseline technology) to values well below 350 W/m^2 (advanced technology) can be observed for new WEC models [38,40,43,52,53]. Larger rotor diameters and increased hub heights allow increasing the energy output per installed capacity in terms of full load hours (FLH) (this principal relation, called the Capacity Factor (CF), is another performance parameter. CF is defined as the ratio of the energy actually produced by an energy converter to the energy that could have been produced if the converter ran at its rated power over a given time period. For the period of one year, the CF can be converted to FLH by multiplying the dimensionless CF with the 8760 h of one year.). Legacy onshore WEC achieved only 1576 FLH per year on average in the 2012–2015 period according to the feed-in time series data, whereas advanced WEC enable almost double the FLH and accordingly productivity per installed capacity [54,55]. Furthermore, advanced WEC offer significant advantages in the reduction of EE generation and the required overall installed capacity to achieve set REN share goals along with reduced economic costs at high penetration rates [56,57].

Figure 1 provides an impression of the significant differences between baseline and advanced WEC based on a short period of registered wind speed data from a wind farm in Germany (a) and the effects on the annual duration curves (duration curves are created by ordering all hourly feed-in or RL values in a descending order. The highest value is located on the very left of the graph and the lowest value on the right side.) (b). It becomes apparent that although the two different WEC (Enercon E-70 and Nordex N-117) have comparable rated power of 2.3 to 2.4 MW, their temporal production characteristics (Figure 1a) and annual duration curves (Figure 1b) differ significantly, as advanced WEC deliver twice the energy per installed capacity (equivalent to the area under the curve in Figure 2b).



(**a**)



(**b**)

Figure 1. Comparison of the time series for power production based on actual wind and performance data from a wind farm in Germany (**a**) and generalized feed-in duration curves for baseline and advanced wind energy converters (WEC) (**b**).

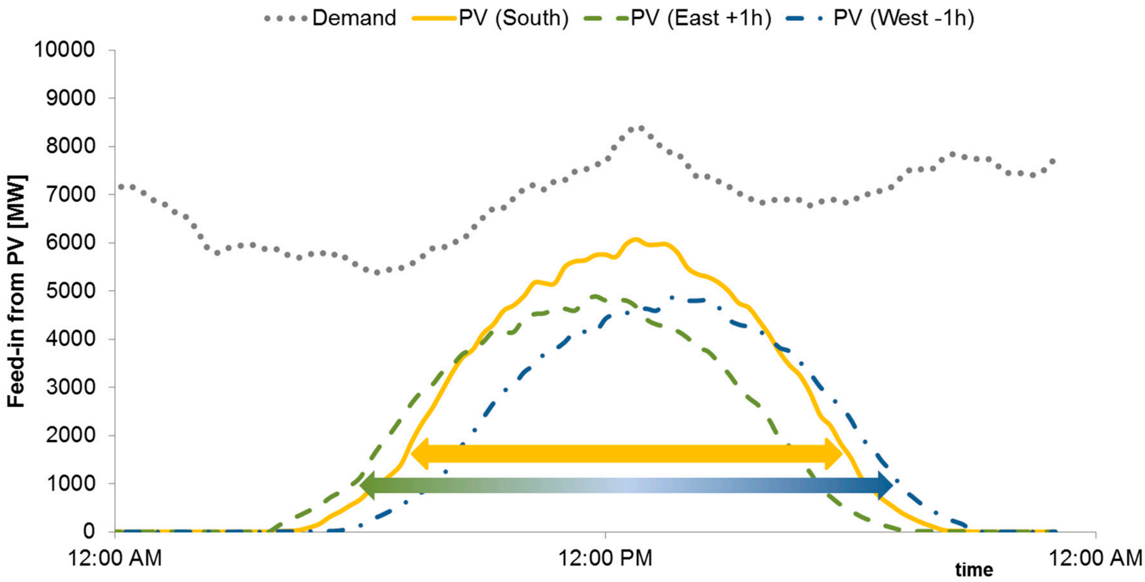


Figure 2. Comparison of normalized baseline feed-in (PV(S) vs. modified advanced feed-in PV (E) and PV (W) installations over 24 h.

The modeling of the time series data for advanced WEC was performed according to [38] based on the registered time series of WEC feed-in in Germany. A scaling factor was iteratively determined so that the time series reach 3000. The applied modeling has been published and cross-checked [38,40,58] and a similar approach to modify feed-in time series is documented and used in the ENERGY Plan Simulation model [59].

2.2.2. Advanced and Baseline Solar PV

Advanced layouts in solar PV, especially an east or west azimuth angle of solar panels and solar PV systems, have been identified as an option to improve the integration of solar PV into the power system [39,60–63]. Solar PV modules in an east-west orientation show a positive effect on the reduction of EE as they enable a better coverage of temporal demand profiles [64] (Figure 2). With increased capacities of solar PV systems in a south-facing azimuth, instances of EE production rise at mid-day, while residual loads in the morning and evening hours remain unmet. Solar PV systems with fixed azimuth angles facing east (PV(E)) and west (PV(W)) shift the feed-in pattern towards morning PV(E) and evening PV(W) hours and therefore smooth feed-in profiles and reduce EE [65]. As a trade-off, these solar PV setups have slightly reduced FLH in comparison to south-facing setups that maximize energy production [35,36,61,66].

A composition of solar PV systems with an equal distribution of solar PV setups oriented south, east and west were selected for the modeling of advanced solar PV. Solar PV systems facing east PV(E) are modeled with feed-in one hour earlier and solar PV systems facing west PV(W) with feed-in delayed by one hour compared to south-oriented setups. East and west systems also have reduced FLHs of 869 compared to the 1000 FLHs assumed for baseline setups facing south PV(S) (see Figure 3).

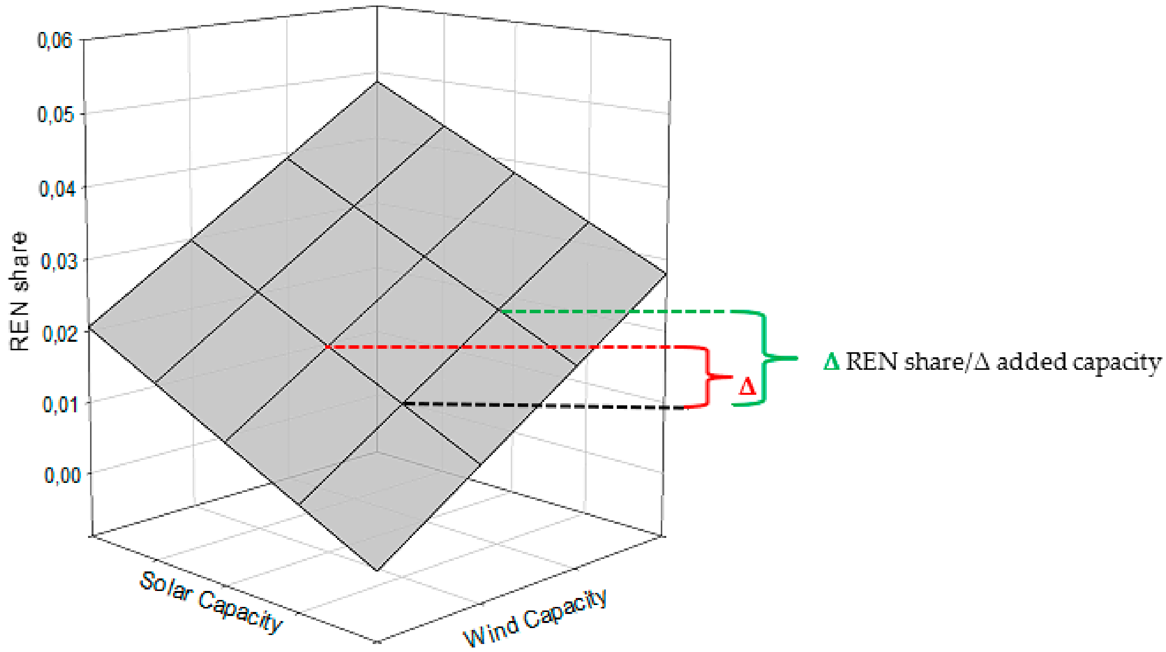


Figure 3. Illustration of the incremental evaluation of additional capacity from either wind or solar PV on the REN share surface plot with higher gradient for wind compared to solar PV (red: REN share delta solar PV, green REN share delta wind).

2.2.3. Electric Energy Storage

To implement the effect of electric energy storage [11,14] into the modeling, we included existing electric energy storage from pumped hydro storage (PHS) currently installed in Germany. For the modeling, we refered to the 9 gigawatt (GW) of PHS with a storage capacity of approximately 66 gigawatt hours (GWh) installed in Germany [14,50].

Other options for the integration of vRES, such as interconnectors for import and export or demand side management (DSM), [67] were not considered.

2.3. Study Cases

This study aims to determine efficient vRES development pathways for both "baseline" and "advanced" technologies and with and without electric energy storage from PHS. Therefore, we established four cases illustrating the respective options (Table 1).

Table 1. Introduction of the four study cases.

Case	Wind Power	Solar PV	Electric Energy Storage
Case (B)—Baseline (non-advanced) technology	380–520 W/m^2 1576 FLH	oriented south 100%	no storage
Case (BS)—Baseline (non-advanced) technology + electric energy storage	380–520 W/m^2 1576 FLH	oriented south 100%	PHS: 9 GW/66 GWh
Case (A)—Advanced technology	<350 W/m^2 3000 FLH	east 33%, west 33%, south 33%	no storage
Case (AS)—Advanced technology + electric energy storage	<350 W/m^2 3000 FLH	east 33%, west 33%, south 33%	PHS: 9 GW/66 GWh

For Cases B and BS, we used baseline or non-advanced setups from wind and solar PV, whereas in Cases A and AS we applied advanced setups [38]. Cases BS and AS also included the modeling of storage from PHS, so that EE production from wind and solar PV can be utilized and consequently contribute to achieving higher REN shares (see storage section).

The overall annual net electricity demand for Germany was set constant at the projected level of 535.4 TWh/a [50]. Other important factors for the integration of vRES into power supply systems, especially conventional Must-Run or other renewable energy sources (bioenergy, hydropower, geothermal), can be included but are not presented here [15,39,68–70], primarily because the focus of this study is on the inter-temporal patterns of demand and supply from vRES, and secondarily because the simplicity of the approach should be maintained to provide a better understanding of the basic interplay of vRES in power systems.

3. Methods

This study aims to investigate pathways for the effective capacity expansion of volatile renewable energy sources. As key indicators, we calculated the renewable energy share (REN share) and the cumulated negative RL, or simply EE. By comparing the indicators for different development pathways, we can identify efficient pathways in the sense of maximizing REN share per additionally installed capacity. All calculations were performed using MATLAB and all key components are presented in this section.

3.1. Calculation of Key Indicator Renewable Energy Share

The renewable energy share (REN share) is the amount of wind and solar PV energy generated and directly serving the power demand. EE from vRES does not contribute to the REN share in Cases B and A, whereas in Cases BS and AS we modeled electric energy storage from PHS as an integration infrastructure to make EE available to serve power demand and contribute to REN shares accordingly. The resulting direct REN share over the course of the 4-year time series was calculated for every capacity combination as:

$$REN\ share = 100 - 100 * \left(\frac{\sum\ RL\ pos_t}{\sum\ Demand_t} \right) [\%], \quad (1)$$

where *REN share* = renewables share, $Demand_t$ = electricity demand, $RL\ pos_t$ = positive Residual Load (see Equation (3)), t = time step of 1 h in the 2012–2015 time-series data. RL neg or EE from vRES is not accounted for. The Residual Load (RL) is the result of the scaled feed-in time series data for wind and solar PV subtracted from the hourly time series data for demand:

$$RL_t = Demand_t - (S_{wind} * Wind_t + S_{solar\ PV} * Solar\ PV_t), \quad (2)$$

where $Wind_t$ and $Solar\ PV_t$ are the normalized time series data for wind and solar PV representing the feed-in of 3 GW installed capacity each, and scaling factors S_{wind} and $S_{solar\ PV}$ range stepwise from 1 to 100 in order to reach from 3 to 300 GW in the calculation runs (see Section 2.3 Input Data). We selected a step size of 3 GW, which is roughly equivalent to the annual capacity expansion target for wind and solar PV in Germany.

Positive and negative RL is separately accounted for over the course of the 4-year time series data:

$$\sum RL\ pos_t\ in\ case\ of\ Demand_t > (S_{wind} * Wind_t + S_{solar\ PV} * Solar\ PV_t), \quad (3)$$

$$\sum RL\ neg_t{}^{*}\ in\ case\ of\ Demand_t < (S_{wind} * Wind_t + S_{solar\ PV} * Solar\ PV_t). \quad (4)$$

* or simply EE from vRES.

For the cases including electric energy storage (BS and AS), Equations (2)–(4) were extended so that the discharge from the combined electric energy storage is likewise subtracted from the hourly demand data and thus increases the REN share accordingly.

$$\begin{gathered} RL < 0\ AND\ C_{PHS} < C_{PHS\ max}\ then, \\ RL_t = Demand_t - (S_{wind} * Wind_t + S_{solar\ PV} * Solar\ PV_t) + P_{PHS} * \eta, \end{gathered} \tag{5}$$

$$\begin{gathered} RL > 0\ AND\ C_{PHS} > C_{PHS\ min}\ then \\ RL_t = Demand_t - (S_{wind} * Wind_t + S_{solar\ PV} * Solar\ PV_t) - P_{PHS} * \eta. \end{gathered} \tag{6}$$

The variables used in Equations (5) and (6) are:

C_{PHS} = energy stored in PHS. Further constraints were set for $C_{PHS\ max}$ = maximum storage capacity (=66 GWh), $C_{PHS\ min}$ = minimum storage capacity (=0 GWh), P_{PHS} = maximum storage power in/output (=9 GW) and a single cycle efficiency η of 90% [16] in the model code.

We modeled electric energy storage to identify how it enables the use of EE production from vRES which is otherwise not contributing to the REN share and progressively curtailed. The modeled PHS stores any EE in times of negative RL from vRES, and discharges the stored energy in times of positive RL to contribute to the power supply whenever vRES are not fully meeting power demand. This presented technical modeling of PHS is deterministic, so that no uncertainties are introduced. Its performance was checked by a comparison to a spreadsheet calculation and proved to be adequate for this specific approach.

All four investigated cases cover all combinations of wind and solar PV installations ranging from 0 to 300 GW with a step size of 3 GW, resulting in a 100 × 100 array with 10,000 possible capacity combinations. The calculated results for REN shares and EE were visualized as a surface plot and are given in the Results section.

3.2. Algorithm for Efficient Pathways

To identify efficient pathways, we applied an incremental evaluation of the discrete values for a REN share compared to its neighboring value in the 100 × 100 array by calculating the discrete gradient between the neighboring REN share values on the surface (7):

$$\frac{\Delta\ REN\ share_{\ ws}}{\Delta\ added\ capacity_{\ ws}}, \tag{7}$$

where w is the indexed capacity from wind power in the 100 × 100 array and s is the indexed capacity from solar PV in the 100 × 100 array.

By dividing the increase in REN share through the 3 GW of additionally installed wind or solar PV, we calculated the resulting gradient per additionally installed capacity for every neighboring grid node in the REN share array (see Figure 3). Following the highest gradients from grid node to grid node forms a pathway in capacity expansion, which results in the highest increase in REN share per installed capacity of wind or solar PV. This way, the most efficient pathways in the calculated 100 × 100 REN share array are identified, beginning at an initial point and performing an incremental assessment and selection (this approach is, in principle, also applicable to more than two RES sources. The necessary higher dimensional space needed to integrate more RES sources in one graph would be less suited for a quick visual interpretation and is therefore not realized in this study). All resulting REN share surface plots in this study show a convex or concave surface, enabling this basic algorithm to identify efficient pathways.

The necessary discrete starting point can be, for example, a combination of 0 GW of wind and 0 GW of solar PV for no initial vRES deployment, or the capacity combination of 50.5 GW of wind and 42.4 GW of solar PV installed in Germany at the end of 2017 [47]. This overall approach was used to check the various combinations in vRES technologies and identify efficient pathways, as a higher value for the gradient leads to a more efficient capacity expansion pathway compared to a lower value.

In Section 4.4 we will apply this algorithm to the calculated results to identify optimal pathways and we will present residual load duration curves (RLDC) of selected results to showcase the immense impact different pathways have on the structure of the residual load and especially on EE.

4. Results

In this section, we present the results calculated for all four cases: baseline and advanced technology, with and without pumped hydro storage. The results are presented through surface plots and tables.

4.1. Baseline Technology Case B

4.1.1. Key Indicator REN Share Case B

The resulting REN share surface plot of the various capacity combinations on the 100 × 100 array forms a bi-directional concave surface. Figure 4 shows a surface plot for the resulting REN share in Case B, with REN share plotted on the vertical axis and installed capacities of wind on the horizontal right hand axis and of solar PV capacities on the horizontal left hand axis.

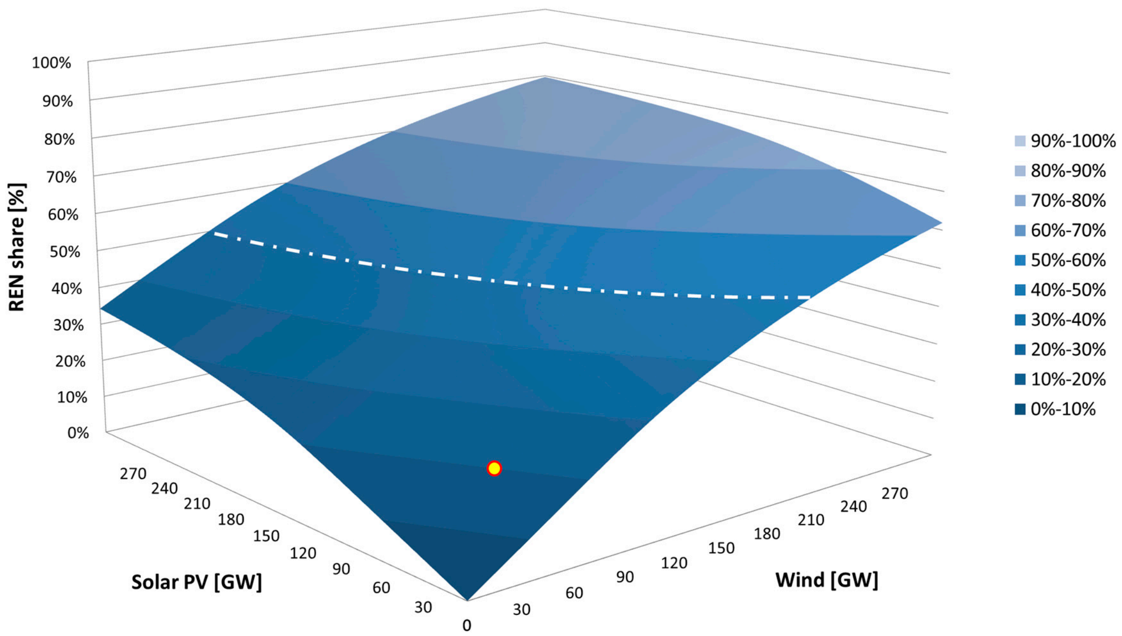


Figure 4. REN share surface plot for Case B, including the 2017 capacities from wind and solar PV (point marking), and the 50% REN share marking for various combinations resulting in a 50% REN share (mixed dotted-dashed line).

Starting either at a 0% REN share with 0 GW installed capacity for both wind and solar PV or with 50 GW of wind and 42 GW of solar PV which were installed in Germany at the end of 2017, every unit of capacity added results in an increase in REN share in the surface plot. Initially, additional wind capacities on the right hand axis of the surface plot result in a steeper increase in REN share compared to adding the same amount of solar PV capacities on the left hand axis. The initial gradient on the left hand axis, representing additional solar PV capacities, is lower (0.89% per 3 GW of solar PV) than the initial gradient for additional wind capacities (1.48% per 3 GW of wind). Furthermore, a sole solar PV deployment of 300 GW only achieves a maximum REN share of 36%, compared to the 62% for wind for the same amount of installed capacity. REN shares above 62% can only be achieved through a combination of both wind and solar PV. Overall, a declining gradient of the REN share for a sole deployment of either wind or solar becomes apparent in the surface plot, which forms a concave surface.

4.1.2. Key Indicator EE (Negative Residual Load) Case B

Figure 5 shows the development of EE production in Case B. EE is also presented as a surface plot and plotted on the vertical axis, with installed capacities of wind on the horizontal right hand axis and of solar PV capacities on the horizontal left hand axis.

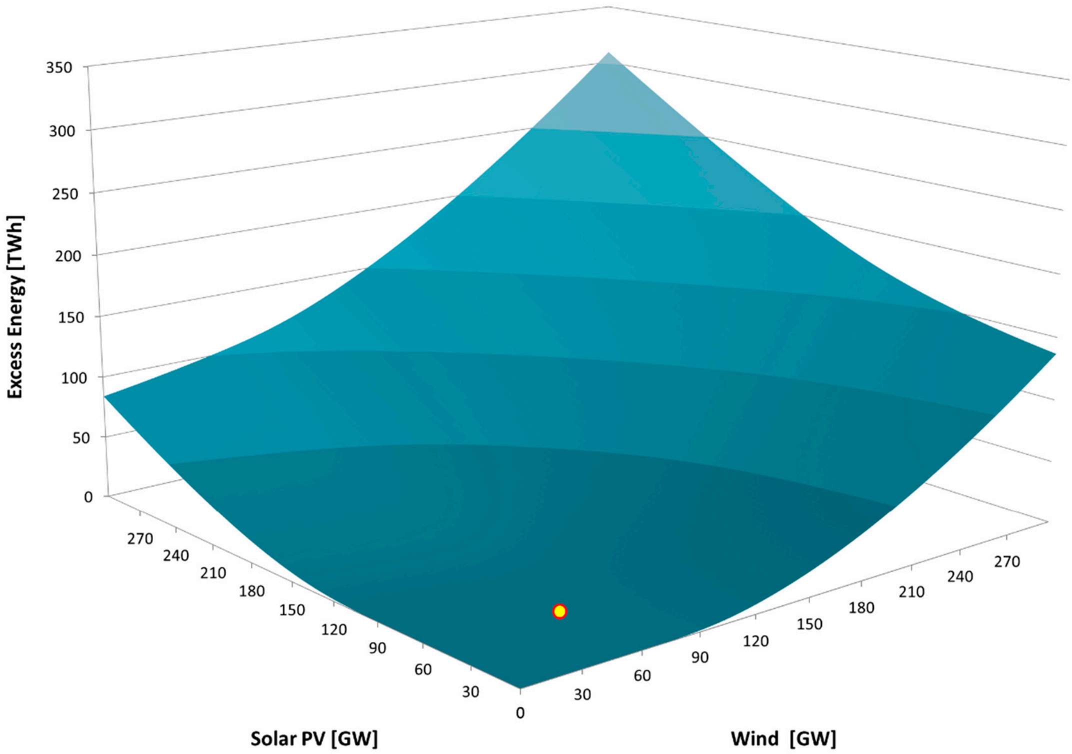


Figure 5. Excess energy (EE) surface plot Case B including the 2017 capacities from wind and solar PV (point marking).

After a threshold of roughly 20 GW from wind or solar is surpassed, a progressive production of EE is apparent in Figure 5. In contrast to the REN share surface plot in Figure 4, the EE surface plot forms a bi-directional convex surface. The convex surface of the progressive increase in EE is the reason for the concave surface of the REN share surface plot in Figure 4, as without electric energy storage EE does not contribute to serve the power demand and thus does not increase REN share.

Figure 6 demonstrates that EE is generated progressively when additional vRES capacities surpass a threshold of roughly 20 GW from wind or solar PV. This is the tipping point of the marginal improvement of additional capacities in the REN share plot given in Figure 5.

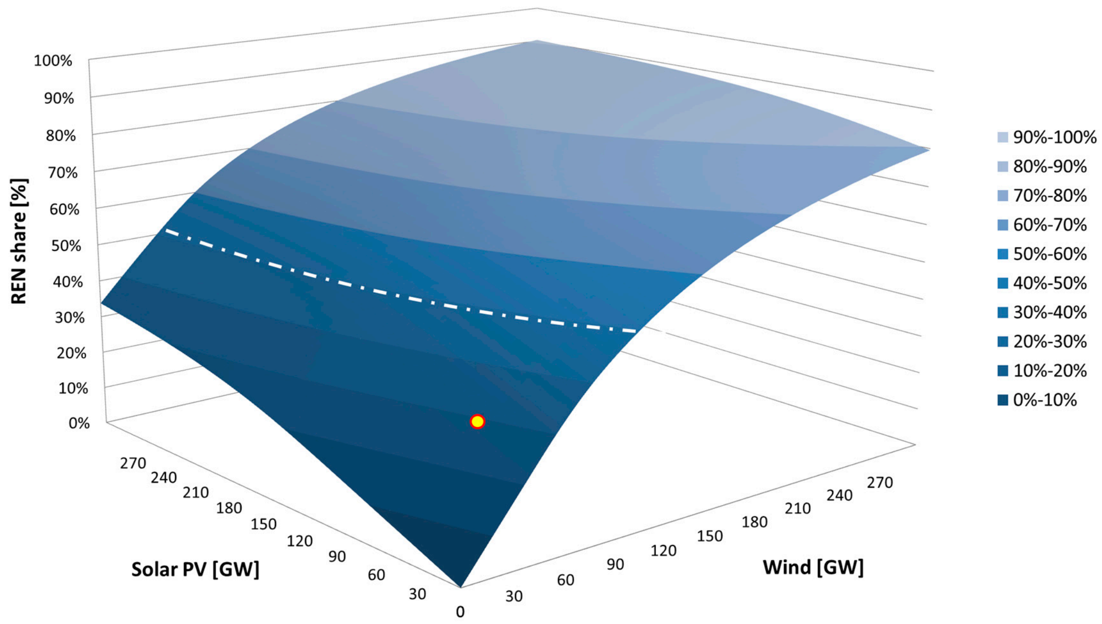


Figure 6. REN share surface plot for Case A, including the 2017 capacities from wind and solar PV (point marking), and the 50% REN share marking for various combinations resulting in a 50% REN share (mixed dotted-dashed line).

4.2. *Advanced Technology Case A*

4.2.1. Key Indicator REN Share Case A

The corresponding surface plot for the advanced technology case (Figure 6) shows significant differences from the baseline REN share plot (Figure 4).

While advanced solar PV again reaches about 40% REN share in a sole deployment of 300 GW, additional capacities from advanced wind power boost REN shares faster than in the baseline case, and a sole deployment of 300 GW of wind pushes REN share above 80%. The initial gradient on the left hand axis for additional solar PV capacities is significantly lower (0.78% per 3 GW of solar PV) than the gradient for additional wind capacities (2.87% per 3 GW of wind). REN shares beyond 80% are only achieved by a combination of both wind and solar PV.

The results reflect the much higher energy production per installed capacity of wind compared to solar PV in the advanced technology case (3000 FLH from advanced wind compared to 1536 FLH in the baseline case; 869 FLH for advanced solar PV compared to 1000 FLH in the baseline case). As a consequence, it is possible to achieve higher REN shares with the same installed capacities using advanced technology in wind power.

4.2.2. Key Indicator EE (Negative Residual Load) Case A

The corresponding EE surface plot (Figure 7) indicates a much higher EE production compared to the baseline case (Figure 5), especially from advanced wind power along the right hand horizontal axis. However, the higher EE production does not contradict the greater effectiveness of advanced WEC from a REN share point of view, as shown in Figure 7.

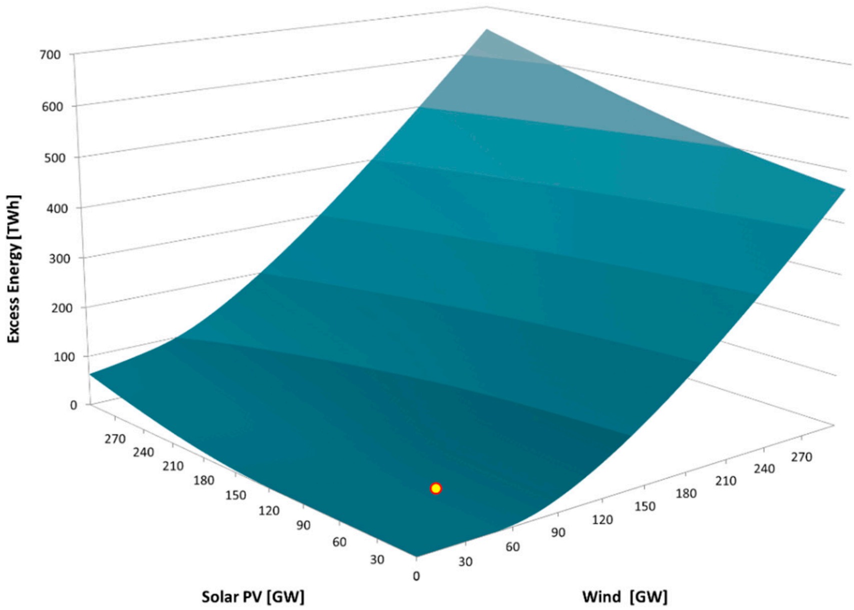
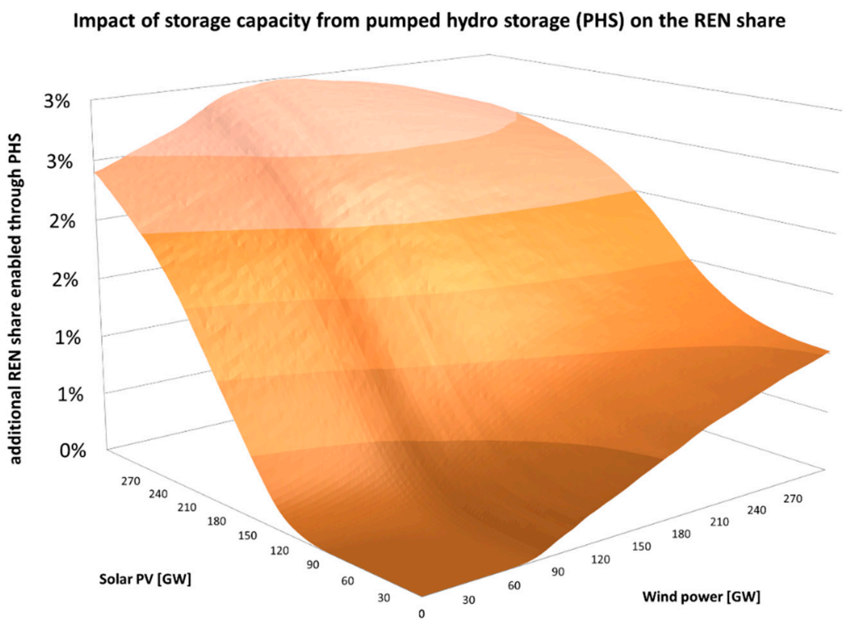


Figure 7. EE surface plot Case A including the 2017 capacities from wind and solar PV (point marking).

4.3. Cases BS and AS Including Electric Energy Storage from PHS

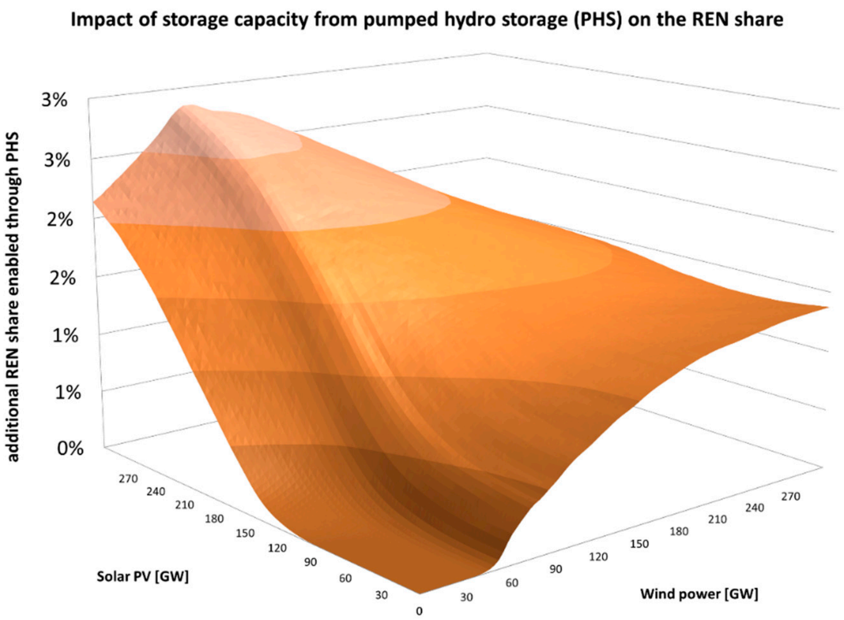
As described in Section 2.3, we modeled electric energy storage from PHS to identify its impact. The modeled storage enables the recovery of some of the EE from vRES, thus achieving higher REN shares from a given vRES capacity.

To visualize the results, we have chosen a surface plot showing only the differences in REN share between the cases with and without storage by subtracting the non-storage case from the storage case (and thus not providing any information about the absolute increase in REN share). The resulting differences surface plot (Figure 8) shows how storage boosts REN shares at different combinations of wind and solar PV capacities.



(**a**)

Figure 8. *Cont.*



(**b**)

Figure 8. Differences surface plot for REN share illustrating the additional REN share enabled by electric energy storage from pumped hydro storage (PHS); (**a**) for the differences between the baseline cases and (**b**) for the differences between the advanced technology cases.

Comparison with Cases Including Storage

For wind and solar PV capacities below the already identified threshold of 20 GW, no EE is produced and thus there is no effect from electric energy storage. For higher vRES capacities, the overall REN share increase from the modeled storage reaches up to 2.9% in the baseline case (BS) compared to the non-storage case B (Figure 8a). For high solar PV capacities, the addition of electric energy storage enables higher relative gains in REN share compared to the gains enabled for the same amount of wind capacities.

For the advanced technology case AS, a quite similar overall characteristic of the differences surface plot is obtained (Figure 8b). The higher productivity of advanced WEC leads to an earlier stabilization of the additional REN share.

The maximum additional improvement in REN share through PHS is about 2.9% at a 63% REN share provided by a wind capacity of 135 GW and a solar PV capacity of 300 GW (for the advanced technology case it is 2.8% additional REN share at 62% from 63 GW wind and 300 GW from solar PV). For lower and higher overall REN shares, this additional improvement is reduced as either less EE is available for storage or too much EE cannot be stored, either because of the limitations in installed power from PHS or storage capacity from PHS. This peak in additional improvement in REN share is therefore specific for each combination of power and storage capacity of PHS.

4.4. Efficient Pathways

Applying the algorithm for efficient pathways (see Section 3.2), the efficient capacity expansion from wind and solar can be identified and illustrated as pathways on the REN share surface plot. Efficient pathways starting from a zero wind and solar PV capacity combination are represented by the dashed red line in Figures 9 and 10, and the pathway starting at the 2017 capacities in Germany (yellow dot) is represented by the yellow dotted line. Figures 9 and 10 illustrate the identified pathways for cases BS and AS. Cases B and A without electric energy storage show only minor deviations below 3% in REN share (see Figure 9) and are therefore not depicted.

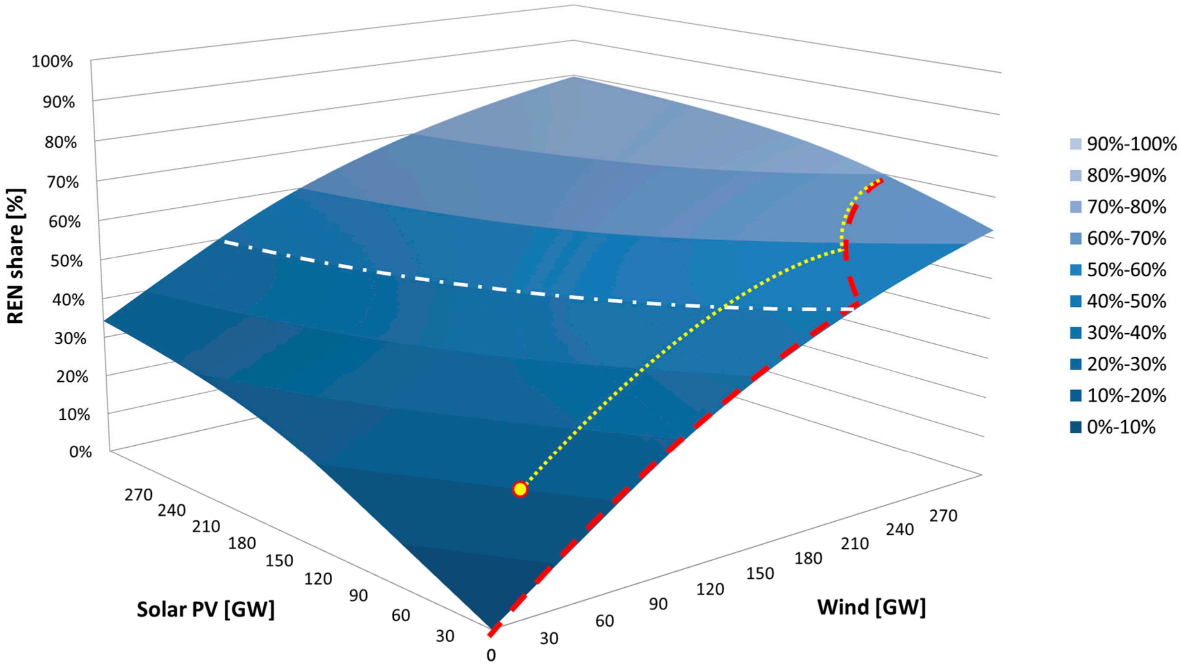


Figure 9. REN share surface plot and efficient pathway for Case BS, including the efficient pathway starting at 0 GW wind and solar PV deployment (dashed line), the efficient pathway starting at the 2017 capacities from wind and solar PV (dotted line), and the 50% REN share marking for various combinations resulting in a 50% REN share (mixed dotted-dashed line).

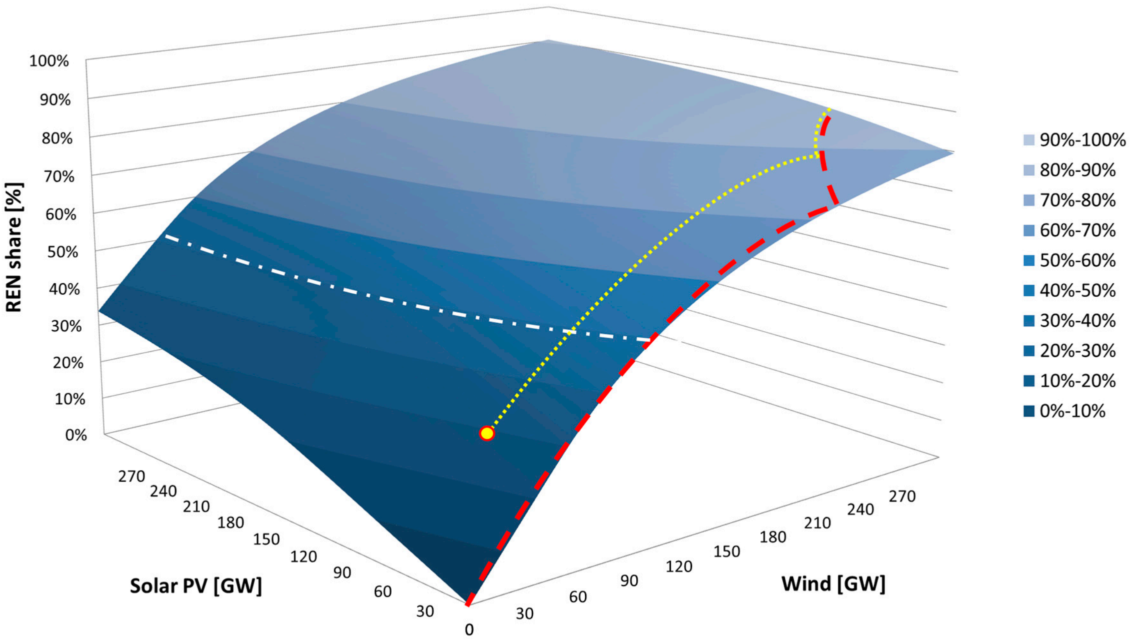


Figure 10. REN share surface plot and efficient pathway for Case AS, including the efficient pathway starting at 0 GW wind and solar PV deployment (dashed line), the efficient pathway starting at the 2017 capacities for wind and solar PV (dotted line), and the 50% REN share marking for various combinations resulting in a 50% REN share (mixed dotted-dashed line).

As apparent from Figure 9, for Case BS wind power was solely prioritized for REN share levels up to 47%. Solar PV capacity was added only before this threshold, after which an alteration of additional solar PV and wind forms the efficient pathway. When reaching the boundaries of the 100 × 100 array, the pathway for Case BS reaches 76% REN share, with wind power clearly dominating the capacity mix.

The same characteristics can be registered in Figure 10 for Case AS including advanced technology, although the first deployment of solar PV is pushed back to 76% of REN. When reaching the boundaries of the 100 × 100 array, the pathway calculated surpassed 87% REN share.

As shown in Table 2, the higher efficiency of wind power regarding the REN share per installed capacity is significant and is responsible for the initial dominance of wind power along the pathways. Efficient pathways do not include solar PV for REN shares below 47%. A comparison of Cases B and BS with Cases A and AS for a 50% REN share clearly shows that PHS can reduce the capacity requirement slightly but pushes the introduction of solar PV even further back along the efficient pathways. Interestingly, comparing baseline cases against advanced technology cases reveals that advanced wind allows for a reduction of almost 50% in required wind capacity.

Table 2. Overview of selected results from the calculated pathways.

	Case B	Case BS	Case A	Case AS
Initial Δ REN share/Δ 3 GW wind Solar PV	0.89% 0.56%	0.89% 0.56%	1.68% 0.51%	1.68% 0.51%
REN share at which solar PV is first introduced to complement wind	47% @ 186 GW wind	49% @ 192 GW wind	74% @ 234 GW wind	76% @ 240 GW wind
Minimum capacity requirement to attain 50% in REN share	186 GW wind + 15 GW solar PV	192 GW wind + 6 GW solar PV	105 GW wind + 0 GW solar PV	102 GW wind + 0 GW solar PV

To complement the findings on pathways, we provide residual load duration curves (RLDC) in Figure 11 to add one additional aspect associated with efficient pathways and capacity mixes for vRES. The RLDC presented are directly derived from Equation (2) for three different wind and solar PV capacity combinations, each enabling a 50% REN share in Case B. The duration curves are created by ordering all hourly RL values in a descending order [14,29]. The highest RL value is located on the very left of the graph and the lowest value on the right side. Values below 0 GW indicate negative RL and the connected enclosed area between the RLDC and the zero line is equivalent to the EE produced.

On the right side of the duration curve, where excess power is located below the 0 GW RL level, significant differences become apparent. For both solar PV and wind-dominated mixes (like the case for 60 GW wind and 300 GW of solar PV in a solar PV-dominated mix or 186 GW of wind and 15 GW of solar PV in a wind-dominated mix that is also part of the efficient pathway in Case B, see Table 2), higher maximum excess power can be identified and the enclosed area under the curve (equivalent to EE) is significantly enlarged compared to a balanced mix from wind and solar PV (108 GW wind and 114 GW solar PV). Especially for the solar PV-dominated capacity mix, high EE is generated with a three-fold higher maximum excess power.

As indicated by Ueckerdt [10], the RLDC continuously becomes steeper on the right hand side of the RLDC for high shares of wind and solar PV. Wind slightly covers peak load and increasingly contributes to cover mid and base load, but also contributes to EE production, whereas a solar PV-dominated capacity mix increases excess power and EE significantly.

The examination of RLDCs makes clear that different pathways have a huge impact on the magnitude and volume of the EE produced. It is possible to deduce the energetic and temporal structure of EE from the RLDC and identify how integration options like storage, demand side management or interconnectors have to be developed in order to make use of EE from vRES.

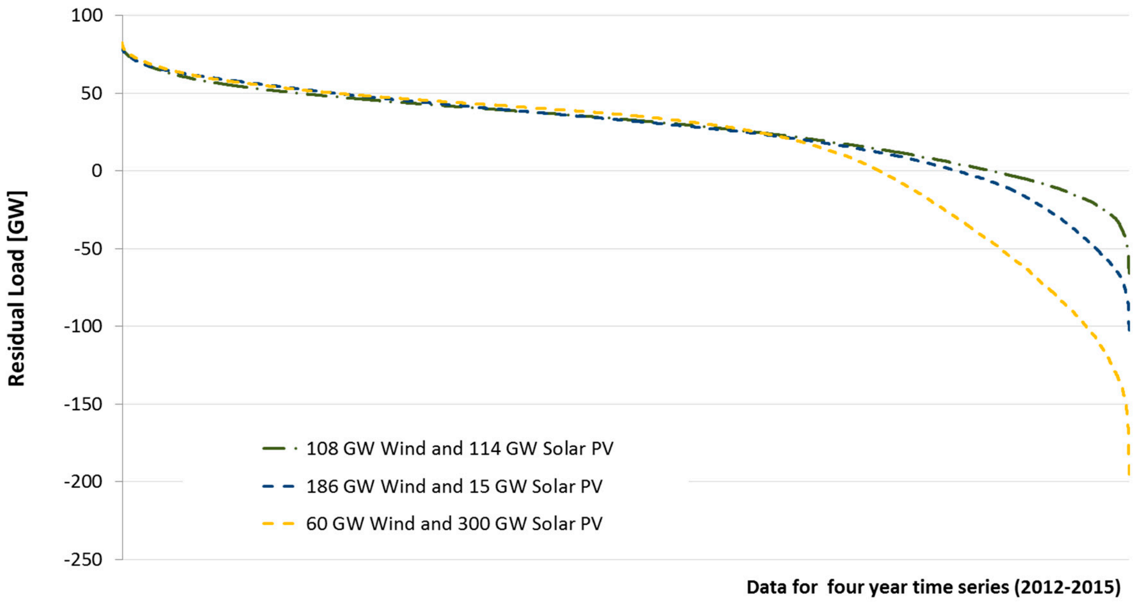


Figure 11. Residual load duration curve (RLDC) of different combinations of wind and solar PV all achieving a 50% REN share in Case B.

5. Discussion

The results provide a broader perspective on the interplay of wind, solar PV and power demand, the effect of electric energy storage form PHS, as well as pathways towards high REN shares in a case study for Germany. For power systems with a low initial REN penetration, wind power boosts REN share per installed capacity more than solar PV. This is primarily due to the higher productivity (full load hours) of wind compared to solar in the German case. Up to levels of installed wind capacity equivalent to more than 47% in REN share, wind power is more efficient from a required capacity perspective than solar PV, although significantly more EE is produced. Above this level, a mix from additional solar PV and wind shows a better performance regarding the boosting of REN shares compared to the sole addition of wind capacities. This is due to solar PV's different temporal production profile, which complements wind power to better match temporal demand patterns [20,31,32,46,71]. An indicator for this complementariness is the two-fold bend (bi-directional) concave surface of all the REN share plots, as neither wind nor solar PV alone reaches very high values for REN share (e.g., >62% in Case B), so that a combination of both sources is required. Additional renewable sources, enlarged electric energy storage, and DSM are key requirements for a fully renewable power supply.

5.1. Impact of Advanced Technology

Advanced wind power allows a significant increase of REN shares compared to the baseline technology, as apparent from the sharp gradient of the REN share surface plot in Case A (Figure 5) compared to Case B (Figure 7). In contrast, advanced solar PV, although allowing for a better coverage of daily load profiles, falls short of delivering equal benefits regarding its contribution to REN shares. Consequently, advanced solar PV is pushed back even further along the efficient pathways compared to the baseline setups and is only effective after high REN share levels of 74% are reached in Case A. Even considering the fact that EE production from advanced wind is increased, advanced wind performs better than solar PV.

Advanced wind has been identified as the most effective measure for achieving high REN shares from vRES. However, it comes at a trade-off of higher EE for REN shares at high penetration rates (Figures 6 and 8).

5.2. Effect of Electric Energy Storage

By adding storage capacities from PHS, EE from vRES can be recovered, which allows for higher REN shares compared to a progressive curtailment in the non-storage cases. The REN share differences plots showed a distinct effect of the modeled storage from PHS and that the interplay of PHS with solar PV performed better than in combination with wind power. The specific power-to-capacity ratio of the modeled PHS can be characterized as short-term electric energy storage, which is capable of integrating EE with a high frequency (several hours for a storage cycle) and high number of storage cycles but limited storage capacity. This characteristic of the existing PHS is ideal for the integration of the daily production pattern of solar PV. However, contrary to our expectation, PHS does not shift efficient pathways towards an earlier introduction of solar PV, as the generation from wind power also benefits from electric energy storage. Therefore, for all cases calculated, wind power dominated in the optimal pathways, especially in the advanced technology Cases A and AS.

5.3. Efficient Pathways

Efficient pathways for the capacity expansion of wind and solar PV show significant differences in their required overall capacities of wind and solar compared to all other possible pathways presented. The higher productivity of wind in terms of FLH in the case study region leads to wind-dominated pathways in the presented cases, regardless of whether PHS was included or not. Storage and especially advanced wind technology reduce the capacity requirement to achieve a 50% REN share, with an almost 50% reduction in overall required capacity from vRES (Table 2). As far as overall installed capacities are a criterion from an economic or technical point of view, wind power is identified as a preferable vRES source until substantial REN shares of at least 47% are reached, although it comes at the cost of increased EE production.

5.4. Transferability and Uncertainties

The presented findings cannot be fully generalized and directly transferred to other regions, as load and vRES complementarities are specific to individual regions [29,72]. For instance, the findings of Solomon [20] for the California state power system are affected by significant differences in demand and vRES production profiles. This makes it necessary to identify efficient combinations and pathways specifically for each region.

Since no field data for future cases of higher vRES shares in Germany are available, no direct comparison of the calculated outcomes is possible, but results are in line with the findings of relevant publications in the field regarding the effect of high vRES shares and the impact of electric energy storage [3,15,24,29,40,45]. Input time series data have likewise been checked by the authors, as well as by the scientific community using the data source [48]. To the best of our observation, all presented calculations are reproducible as expected due to their deterministic nature. Selected results were successfully checked based on alternative spreadsheet calculations of the modeling. Furthermore, published studies for selected elements of the approach underline the validity of the presented approach [11,25,31,40,45,59,73].

Clearly, the presented model is a simplified model in relation to the actual power system and many other relevant aspects are not considered. Consequently, the results only highlight the temporal integration aspects of vRES and do not cover other relevant aspects like economic costs, land availability, acceptance etc.

6. Conclusions

This case study for the German power system widens the existing systems analysis approaches with regard to the discourse of vRES integration in electricity systems and adds additional criteria for the transition towards a vRES-based power supply system.

The main objectives of this paper were to (i) provide a broad picture of how wind and solar PV can be combined to achieve efficient pathways in capacity expansion to fulfill future REN share targets in a storage-restricted energy system, (ii) compare the impact of advanced technologies from wind and solar PV against baseline technology, (iii) and study the impact of electric energy storage from PHS to make use of EE production from wind and solar PV. With these objectives in mind, our results indicate the following conclusions.

The results show that the higher power production from wind energy per installed capacity leads to a higher effectiveness of wind power, and effective pathways all depend on wind power in the first place, with solar PV added only after a certain REN share provided by wind is surpassed.

The positive impact of advanced technologies was confirmed for the case of wind power, as less capacity is required to achieve set REN share targets. For solar PV in a mixed setup of south, east and west-oriented systems, the lower productivity of these setups is not compensated by their better temporal matching with the demand profile from a REN share point of view.

Existing electric energy storage from PHS enables a better integration of wind and solar PV into the power system and allows for a faster achievement of REN share goals in the modeled cases. However, PHS does not result in an earlier introduction of solar PV along the efficient pathways. For all different cases calculated, wind power dominated the efficient pathways, especially in the advanced technology case, regardless of whether PHS was included or not.

To sum up: taking efficient pathways as a criterion for the future capacity expansion of vRES in the investigated case, a wind-based capacity expansion provides a faster transition towards high REN shares, even considering existing electric energy storage infrastructure from PHS in the region. Per unit of installed capacity, a considerably larger fraction of renewable energy can be provided from wind than from solar PV. Advanced wind power in particular provides higher productivity and effectiveness along with benefits regarding system integration [39,40].

Support schemes and especially tenders for renewable generation capacities should therefore ensure a steady capacity expansion of wind power, especially in the form of advanced system-friendly wind turbines. The reduced overall capacity requirement additionally offers substantial potential to reduce land use conflicts and environmental impacts, so that the results provide various connecting points for an analysis of land use implications [74], environmental impacts and economic comparison.

Specifically for the case of Germany, which has an almost equal proportion of existing wind and solar PV installations, the results underline the importance of wind power expansion in the coming years to reach the governmental goals for 2030 and beyond.

7. Outlook

The assessment of advanced technology is the focus of ongoing research [16,40,42,52,65] and an economic evaluation of the combined perspective of advanced technology and efficient pathways will be helpful to prioritize renewable policies. With specific investment costs and levelized cost of energy for wind and solar PV currently in the same order of magnitude in Europe [10,75–80], non-economic aspects are likewise relevant to decide on future capacity expansion pathways. The possibility for a quick capacity expansion of solar PV, contested public acceptance, as well as availability of sites for wind power and environmental impacts, are additional aspects to be considered. Given the mid- to long-term perspective that was taken in this case study, further advancements in technology and innovations in vRES technologies and electric energy storage will influence the outcome of efficient pathways as well.

Furthermore, a successful and fast transition to a fully renewable power supply system also depends on the extent to which other renewable sources such as bioenergy, hydro and geothermal can complement vRES in order to contribute to a secure power supply. Without additional contributions from these non-vRES sources and at current consumption levels [47], wind and solar PV have to provide more than 85% of the power supply in Germany. Therefore, additional integration options like new storage technologies, demand side management or a better coupling of the sectors for electricity, heat and mobility are key factors for integrating high shares of vRES on power supply systems.

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Abbreviations

The following abbreviations are used in this manuscript:

Case A	advanced technology study case
Case AS	advanced technology + electric energy storage study case
Case B	baseline (non-advanced) technology study case
Case BS	baseline (non-advanced) technology + electric energy storage study case
DSM	demand side management
EE	excess energy (equivalent to the cumulated negative residual load)
FLH	full load hours, equivalent to the capacity factor of a power converter
GW	gigawatt
GWh	gigawatt hour
MW	megawatt
RL	residual load (power demand minus renewable feed-in; renewable feed-in is limited to wind and solar PV in the modeling)
REN	renewable energy
REN share	renewable share on power demand
solar PV	solar photovoltaics
vRES	variable renewable energy sources (primarily wind and solar PV)
WEC	wind energy converter

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Publication Three

Integration of wind power — Challenges and options for market integration and its impact on future cross-sectorial use.

Tafarte, P., Buck, P.

14th International Conference on the European Energy Market (EEM), Dresden, Germany, 2017

Integration of wind power – challenges and options for market integration and its impact on future cross-sectorial use

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***Abstract* — The decarbonisation of the economy calls for an increase in demand from renewable power supply, that in many countries has to be provided by variable renewable energy source (vRES) like wind and solar. In this article, we will give an outlook on how system friendly wind turbines can contribute to mitigate this challenge today and improve future cross-sectorial use. Therefore we use various time series data to model the market value of wind turbines and provide scenarios for the German power system in 2035 to assess the potential of system friendly wind energy.**

***Index Terms*— power systems, renewable energy sources, wind energy integration, power system,**

I. Introduction

The technical and economic integration of significant shares of vRES poses major challenges; especially in power systems with little flexibility options (storage, demand side management, interconnectors) and a rigid conventional power supply system [1-4]. Progressively increased variability in power supply from vRES, increased Residual Load (RL) fluctuations, excess energy and even curtailment of power production from vRES can be the result.

Among the economic challenges, the value prop of wind and solar energy with increasing shares of power supplied by these vRES reflect the challenges for the future market integration as these sources are not demand driven but rather producing depending on weather conditions [5-8]. The development and broad introduction of system friendly renewables, especially advanced onshore-wind turbines or system friendly wind turbines (SFWT), can mitigate some of the problems associated with power systems with high shares of vRES [9]. These SFWT are characterized by low specific rated power per rotor swept area (typically below 350 W/m²) and hub heights of more than 100m compared to legacy standard wind turbines (STWT) with higher specific power ratings and lower hub heights. But regional wind resources as well as future technological developments in wind turbine technology are also factors that determine the characterization of a WT regarding its system friendliness.

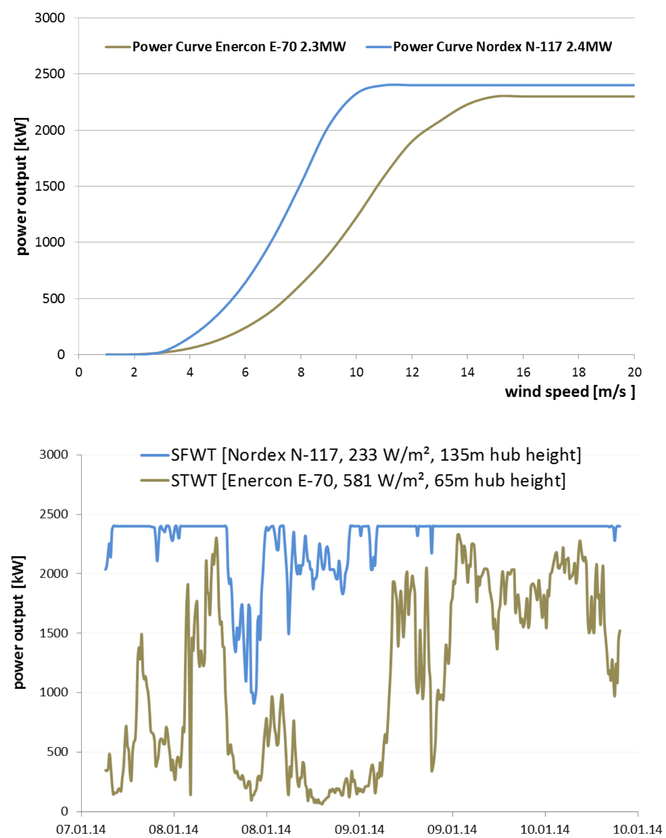

Figure 1: exemplary power curves and production time series of STWT and SFWT registered and calculated in a wind farm located in Germany.

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SFWT where developed for sites which provide only low-to-medium wind resources and are gaining relevance due to their specific advantages in terms of productivity (measured in full load hours (FHL) but also due to the temporal characteristics of their power production. Figure 1 provides an impression of the significant differences in temporal production characteristics of STWT and SFWT in an existing wind park in Saxony (Germany).

Although both wind turbines have almost similar installed capacities of 2.3 and 2.4 MW, their rotor swept area as well as the hub heights fall well into the different categories of SFWT and STWT. The SFWT are not only more productive, they also operate on average at a higher power output with less variability compared to a STWT. SFWT are capable to achieve up to 4.000 FLH at standard reference wind conditions [6, 9-11] compared to the average of 2.007 FLH assumed for the national average in 2035 according to the 2035 B 1 scenario published in the network development plan (NEP) in 2015 for Germany [12].

To assess the impact of system friendly wind turbines (SFWT) on future power systems, we are using a range of indicators like the wind value factor, excess power and connected excess energy production, installed capacities and renewable shares. Compared to existing studies and reports including renewable excess energy for cross sectorial use [12-16], we identified considerable potential to improve the integration of excess energy form vRES using SFWT.

II. Methods

A: To assess the effects of system friendly onshore wind power on market integration of vRES in the near term, we analyzed production time series of existing wind turbines in 2015 to assess the impact of system friendly wind turbine layouts on market value as an economic indicator [17]. In 2015, Germany had produced 70.9 TWh from onshore wind energy that provided a 11.9% share of the gross electricity consumption [18].

For this comparison, we have selected production time series of existing STWT in Germany and the registered wind speed time series on site to derive production time series of SFWT as an alternative. Together with hourly day-ahead EPEX market prizes for Germany we can perform an economic evaluation of the revenue potential to evaluate ex-post the 2015 performance of different STWT and SFWT, applying the market value approach according to [6, 17] given in (1),

$$\text{wind value factor} = T \cdot \frac{\sum w_t \cdot p_t}{\sum w_t \cdot \sum p_t} \tag{1}$$

where w_t is the electricity generated from a wind turbine and p_t is the hourly spot market price.

Formula (1) gives a relative market value factor for a specific generation time series of a WT (STWT or SFWT) in relation to base load value in a given period (in this assessment the year 2015).

B: Furthermore, we developed a model using historic feed-in from vRES as well as power consumption time series [8] to assess the future impact of system friendly wind turbines on excess energy for sector coupling for the year 2035. It includes the modelling of system friendly wind turbines and their feed-in characteristics to analyze the effects compared to STWT. Here we use a 4 year time series from 2012 to 2015 with normalized wind power and solar PV production as well as power consumption for Germany provided by the OPEN power system data platform [19] to cover temporal variability of vRES production and power consumption as the Total Load (TL). In line with the NEP 2035 B1 scenario published in 2016 [12] we have scaled the feed-in time series from wind and solar PV to simulate the expansion of future installed capacities, as wind and solar PV are variable renewable sources which are primarily responsible for negative residual loads or simply excess power. The RL is calculated in (2),

$$RL_t = TL_t - (wind_t + solarPV_t) \tag{2}$$

where RL_t is the residual load, TL_t the total load and $wind_t$ and solar PV_t the feed-in from wind and solar PV of the time step $_t$ of the four year time series.

The basic methodology for the modelling of SFWT and the scaling of time series to cover the expansion of installed capacities has been described in [9, 20] as well as by [6], however, applying a different methodology. This approach focuses on the primary characteristics of the temporal feed-in from vRES and power consumption. Within the scenarios, the feed-in time series for solar PV remains unchanged at the 59.9 GW projected for 2035. Important factors like demand side management, power storage and especially Must-Run power production to maintain power system stability are not included, due to the fact that they are subject to significant uncertainties regarding their development for the time frame until 2035. Likewise, other power generation sources are not included, so that the calculated time series is the primary RL after vRES feed-in from wind and solar PV has been subtracted from the TL time series.

Apart from the baseline NEP 2035 B1 scenario for Germany we added two scenarios denominated System Friendly Wind SFW I and SFW II as alternative scenarios (see table 1).

TABLE 1: SCENARIO FRAMEWORK TAKEN FROM [12], SOLAR PV CAPACITIES REMAIN AT 59.9 GW AS WELL AS TOTAL POWER DEMAND OF 535.4 TWH.

	Scenario framework		
	Installed capacity wind-onshore[GW]	***AEP [TWh]***	***Full Load Hours [h]***
Baseline			
NEP 2035 B1	88.8	178.2	2,007
System friendly wind scenarios			
SFW I	59.4	178.2	3,000
SFW II	88.8	266.4	3,000

The SFW I and SWT 2 scenarios include higher full load hours (FLH) from system friendly wind with an projected 3,000 h per year against the 2.007 h per year of the baseline NEP 2035 B scenario. The 3,000 h have been selected as an estimate that falls in between todays 4,000 h of SFWT at the German reference site wind conditions excluding losses, and the projected 2,007 h in the NEP 2035 B scenario that includes losses. In [21] we also confirmed that even based on power curves of today's SFWT and spatially resolved wind resource data, there are sufficient potential sites with wind resources enabling a minimum of 3,000 h including 10% losses in annual energy production.

In SFW I we scale the feed-in from system friendly wind turbines up to achieve the same annual energy production as in the baseline NEP 2035 B scenario applying a methodology described in [9]. In other words in the SFW I scenario the higher productivity of system friendly wind turbines is used to reduce the installed capacities in wind power while still achieving the set annual energy production target of 178.2 TWh from wind energy in 2035, equivalent of 33% of the annual power consumption of 535.4 TWh. Whereas in scenario SWF 2 we assume the same 88.8 GW of onshore wind capacity as in NEP 2035 B scenario, but again using time series for system friendly wind turbines. This projection of time series data for future vRES capacity expansion extends the model to identify how future demand for power and other demand sectors (cross sectorial use for mobility, heat and materials) can be effectively supplied in the future.

The generated time series data of the three investigated scenarios are further aggregated to duration curves of negative RL, or in other words, negative values for RL are sorted in a descending order and plotted over the connected hours of the 4 year time series. The graphs presented in the results section give an impression of the magnitude and frequency of negative RL. Negative RL or simply excess power production from wind and solar PV can either be curtailed, stored of utilized for cross-sectorial use. The duration curves for the three different scenarios are providing useful information of the calculated future excess power production from vRES and the differences due to the introduction of system friendly wind turbines in the SFW I and SFW II scenarios.

III. RESULTS

A: The result from our ex-post evaluation of the market value of different wind turbine types for 2015 is presented in the following fig.2.

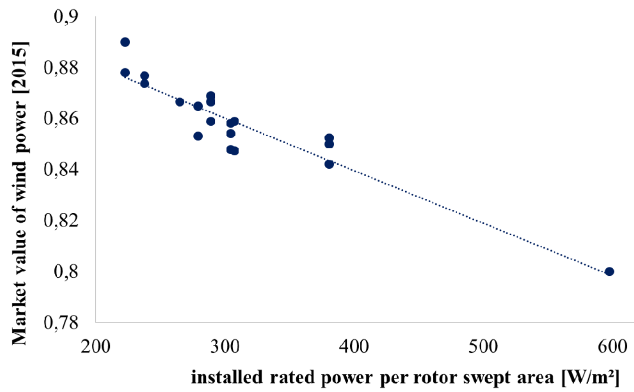

Figure 2: Relative market value factors for selected wind turbines in 2015 versus their specific rated power per rotor swept area.

The higher relative market value for wind energy from system friendly wind turbines with low specific power rating becomes apparent from fig.1. Although for all wind turbines studied, the market value is below the average base load value in 2015, lower specific power ratings allow for a higher relative market value than turbines with high ratings. For comparison, the legacy STWT model that has been selected in figure 1 with a high specific power rating of 581 W/m² and low hub height of 65m, which was state-of-the-art about 20 years ago and is still offered and produced today, is also included in the market value calculation in figure 2. Such STWT held a strong market presence 20 years ago and are due to be decommissioned in coming years and can be repowered by SFWT. These STWT have the lowest market value according to our market value calculation or 2015. This is primarily due to the temporal production patterns that provide wind energy on a less appropriate temporal spectrum (compare also figure 1) to cover consumption profiles. From an economic perspective, the produced wind energy from SFWT is of higher value on average as more wind energy is produced in times of higher prizes, which also helps to mitigate the value drop [6] associated with expanding vRES power production. For details of the market value investigation we refer to [12].

B: The results from the assessment of future excess energy for cross-sectorial use from vRES in 2035 are provided in duration curves for negative values of the RL and the following table 2.

TABLE 2: KEY INDICATORS FOR THE SELECTED SCENARIOS FOR 2035.

	Renewable share [%]	*Excess energy [TWh/a]*	*Max Excess power [GW]*	*Hours of excess [h/a]*
Baseline				
NEP 2035 B1	42.7	7.7	44.7	635
System friendly wind scenarios				
SFW I	43.3	4.3	36.9	543
SFW II	54.7	31.6	66.3	1,588

As given in table 2, system friendly wind turbines in the two provided scenarios SFW I and SFW II allow of an improvement in various key indicators compared to the baseline NEP 2035 B1 scenario. In SFW I, which provides the same amount of energy from onshore wind power using lesser installed capacities, an even slightly higher renewables share is achieved (43.3% against 42.7%). The maximum excess power in the basic NEP 2035 B1 scenario is 44.7 GW while for the SFW I scenario is lowered to 36.9 GW, a difference of 7.8 GW for which no additional infrastructure regarding power grids, storage or capacities in cross-sectorial applications is required. The connected excess energy is likewise lowered by 40%, from the 7.0 TWh in the NEP 2035 B scenario to 4.6 TWh of the SFW I scenario. The reduction in excess energy combined with the higher renewables share in SFW I is equivalent to a faster achievement in the energy transition in the power sector, as only 59.4 GW of system friendly wind power have to be installed compared to the 88.8 GW in the baseline case.

The temporal composition of the excess power in the different scenarios is provided in figure 3 and figure 4 in the form of duration curves of the negative RL (excess power).

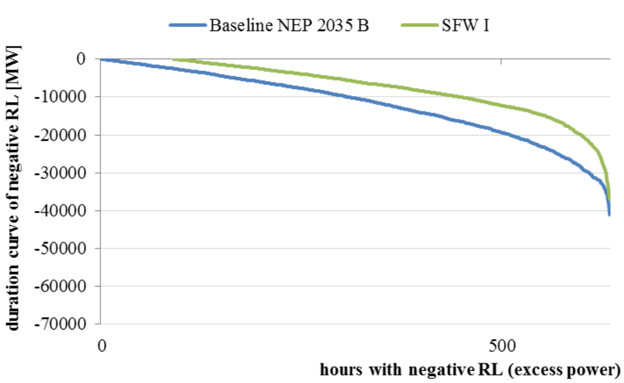

Figure 3: duration curves of negative residual load for baseline NEP 2035 B and SFW I scenario.

From figure 3 which provides the duration curves for the scenarios NEP 2035 B1 and SFW I, it becomes apparent that lesser excess power and excess energy is produced using system friendly wind turbines, while significantly lesser installed wind capacity is required to achieve an even slightly higher REN share.

In scenario SFW II, we were assuming the same 88.8 GW of onshore wind energy as in the NEP 2035 B scenario. Here the renewable share (54.7%), excess power (66,262 MW) and excess energy production (31.6 TWh/a) are all increased significantly (see table 2). Scenario SFW II enables a more than 4 fold increase in excess energy (31.6 TWh versus 7.7 TWh) while the maximum excess power is only increased by 50% (44.7 GW versus 66.3 GW). Accordingly, the yearly hours in which excess power from wind and solar PV is available, increases 2.5 fold (1,588 h/a versus 635 h/a). The composition of excess power and excess energy is provided in figure 4.

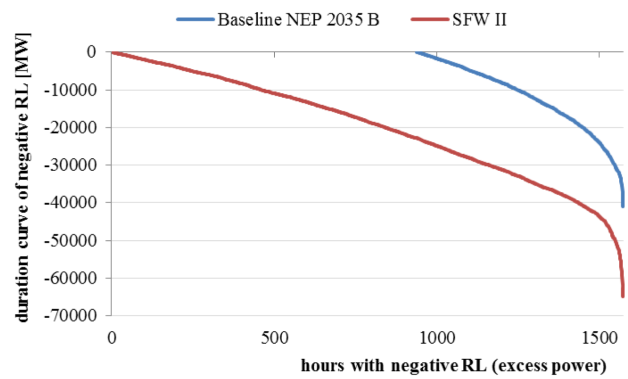

Figure 4: duration curves of negative residual load for baseline NEP 2035 B and SFW II scenario.

The substantial increase in excess energy in SFW II can be expected to provide a better potential for cross-sectorial use, as a significant amount of excess energy is provided on an increased temporal basis while infrastructural requirements are kept constant at 88.8 GW of installed wind capacity of the NEP 2035 B baseline scenario. So that for any costly infrastructure like installed power generation capacity, power transmission lines and P2X installations, the relation of energy [TWh] produced, transmitted or processed to the installed capacity [GW] is equal the yearly hours of full load operation. The broader temporal basis and increased hours of full load operation of these infrastructures in the SFW II scenario therefore indicates the potential for an improved specific utilization. Especially for P2X concepts with initially low operational hours based on progressively increased amounts of renewable excess energy in the process of expanding vRES capacities, SFWT can increase their operational potential in terms of yearly operational hours up to 2.5 fold as calculated in SFW II.

IV. CONCLUSION

From our analysis we conclude that system friendly wind turbines improve market integration as their power production achieves higher market value in the power market of up to 11% compared to legacy wind turbines in the year 2015. Furthermore, various benefits for future power systems with high shares from wind power are identified: the temporal feed-in patterns and higher FLH from system friendly wind turbines can reduce infrastructural requirements associated with power grids and future power storage.

For a mid-to-long term perspective on power system with high shares from vRES, we identified that system friendly wind turbines either allow of a quicker transition towards renewables in the power sector as fewer installed capacities are required to achieve set renewable targets. Or a substantial amount of excess power can be utilized more easily and transferred to new cross-sectorial demand sectors if system friendly wind turbines are deployed with the same amount of installed capacities as projected for 2035.

System friendly wind turbines are therefore identified as a “no regret” option as they already today improve market value and system integration for wind energy as well as they allow for a faster transition to high renewables shares and provide a better utilization of excess power for cross sectorial applications in the future. The huge potentials identified should therefore be fostered and implemented into energy system analysis and updated energy scenarios.

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Publication Four

Towards energy landscapes - Pathfinder for sustainable wind power locations.

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Towards energy landscapes – "Pathfinder for sustainable wind power locations"

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ABSTRACT

Land is a scarce resource, especially when its multiple demands for use are taken into consideration. With more than 25,000 wind turbines installed currently, wind power plays an integral role in the development of renewable energy technologies in Germany. In addition to the positive effects, e.g. reduction in greenhouse gas emissions, wind power also has negative effects on the environment and human well-being. With this in mind, it is important to identify most suitable locations for wind turbines that accounts for different aspects of sustainability. The approach suggested here is a practical method to identify sustainable sites at local to national scale. Additionally the paper compares emerging technology (system friendly wind turbines) with standard technology with respect to environmental concerns and assesses the current performance of wind power in a specific study region. The study finds that the approach enables sustainable locations to be identified in a feasible but scientifically robust manner, and that the system friendly technology outperforms the standard technology in each case. The current allocation of wind turbines is less efficient since repowering and reallocation means that more electricity can be generated by fewer turbines. Furthermore, the impact on the environment and human well-being can also be reduced.

1. Introduction

The transition of a power system, from fossil and nuclear resources towards renewable energy technologies, is characterised by a dramatic change in power provision infrastructure and affects different spatial and administrative scales. As the proportion of renewable power has to increase significantly by 2035 to 55–60% of gross power consumption, and to at least 80% of gross power consumption by 2050 [1], society faces a challenge that affects multiple interests and stakeholders. The overarching objective of such a transition process is represented by the energy policy triangle of security of supply, economic viability and environmental soundness [2]. It is often taken as the starting point for the assessment of possible transition pathways. Indeed, the dimensions of this triangle of objectives also form the framework for the assessment approach described in this paper.

Here, the focus is on environmental soundness in combination with high energy yields and infrastructure requirement reduction as one component of economic viability of the wind power based part of the energy system.

Several research activities are being conducted which investigate the reliability of supply and economic viability of the whole energy system [3–5]. A new challenge has emerged as part of these investigations. Maintaining a balance of supply and demand becomes increasingly difficult in a power system based on an increasing proportion of variable renewable energy sources (vRES) like wind power and photovoltaics. These vRES have generation characteristics that are weather and season dependent. This means that their power generation patterns are difficult to harmonize with the temporal demand patterns of a modern post-industrial society [6–8]. However, various approaches to improve the system integration of vRES into the existing power system have been developed [6,9–12]. There are various ways to improve the system integration of vRES, such as power storage, grid reinforcement and geographical smoothening of dispersed vRES installations, demand side management, and power to X concepts. Of the renewable energy sources, wind power is seen as a central pillar of future electricity provision in Germany because it is comparably cheap to

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Nomenclature

AEP	Annual energy production
AEP_{reclas}	Reclassified (0–1) annual energy production
D_{EP}	Distance wind turbine to protected areas in meters
$D_{EPreclas}$	Reclassified (0–1) distance to protected areas
D_{HW}	Distance wind turbine to settlement areas in meters
$D_{HWreclas}$	Reclassified (0–1) distance to settlement areas
GWh	Gigawatt hours
I_{EP}	Potential impact on environmental protection
I_{EPcum}	Cumulated impact on environmental protection
I_{HW}	Potential impact on human well-being
I_{HWcum}	Cumulated potential impact on human well-being
km^2	Square kilometer
m	meters
MW	Megawatt
m/s	Meter per second
SFWT	System friendly wind turbine
STWT	Standard wind turbine
vRES	Variable renewable energy sources
WT	Wind turbine
WTMA	Wind turbine minimal allocation
W/m^2	Watt per square meter

generate [7,13,14]. Wind turbines (WT) are crucial for future renewable based energy systems, but can also trigger higher spatial conflicts with regard to public acceptance and nature conservation, especially in densely populated countries like Germany. This means that identifying possible solutions in minimising the number and allocation of WTs is crucial. System friendly vRES technologies (also denoted as “advanced vRES” by other authors [7]) have been shown to improve integration of vRES by better adapting temporal production patterns to demand patterns and are more productive at most site conditions [7,14], so that a lower number of installations is necessary to achieve a certain energy yield and infrastructural requirements (power grids, power storage) are likewise reduced. Regardless the given improvement potentials, allocation issues for WT are under intense debate [15–19]. This becomes even more relevant since an increasing number of existing wind turbines will reach the end of their life span and will have to be decommissioned in the coming years [20,21]. This provides the opportunity for a reallocation of wind turbines.

A common way of identifying suitable sites for wind power developments are GIS-based Multi-Criteria-Decision-Making (MCDM) approaches [22–25]. In addition, a good overview of multi-criteria decision making applications established in different energy related thematic areas during the last 20 years, is given in a review paper by Mardani et al. [26]. Most of the GIS-based approaches consider multiple criteria, e.g. wind conditions, proximity to (supply and transportation) infrastructure or impairment of endangered species and result in a “maximum potential” identifying areas, suitable for wind power development. However, such potential areas can usually carry multiple WT locations that still differ in power generation capacity and potential impacts. Taking all of the different aspects of wind power provision and allocation into consideration, the main aim of this paper is to identify sustainable locations for WT to enhance the performance of WTs using a consistent methodology while accounting for the parameters of energy transition - energy yields and socio-environmental impacts. A second objective is to compare the performance and spatial patterns of standard and system friendly technologies to identify trade-offs between them. The third aim is to assess current allocation patterns with regard to sustainability aspects in order to provide reallocation recommendations.

The remainder of this paper is organized as follows. The study region and the input data are introduced in the methods section. This is followed by a detailed description of the technologies under consideration. Site selection and wind turbine allocation approach is explained next. Then, the criteria deduction and optimisation approaches are described. In Section 3 the Results are presented, followed by a discussion in Section 4. Finally, the paper concludes in Section 5.

2. Methods

Multi-criteria analysis (MCA) and optimisation were used to tackle the above-mentioned issues.

The basic assumption for the MCA and optimisation approach is that the negative potential impacts on threatened species and human well-being decrease with (i) increasing distance of a WT from protected areas or settlements and (ii) decreasing number of WTs. Furthermore, a low number of WTs needed to fulfil an energy objective indicates high WT specific power yields. To assess the performance of the currently installed WT in the study region, the optimally identified WT locations are compared with current allocations (see Section 3.1). Fig. 1 illustrates this general approach of multi-criteria optimisation. First, suitable sites, therefore, areas able to carry several wind turbines, for WT establishment have been identified and then individual WT have been allocated within these sites. Next the individual locations have been assessed and optimised and finally the necessary WTs have been selected according to the optimal ranking and the energy objective. Henceforth the term “sites” represents areas able to carry several wind turbines whereas the term “location” refers to an individual wind turbine location.

2.1. Study region

The study region corresponds to an area of 110,000 square kilometres that comprises the six German federal states of Brandenburg, Hamburg, Mecklenburg-Western Pomerania, Saxony, Saxony-

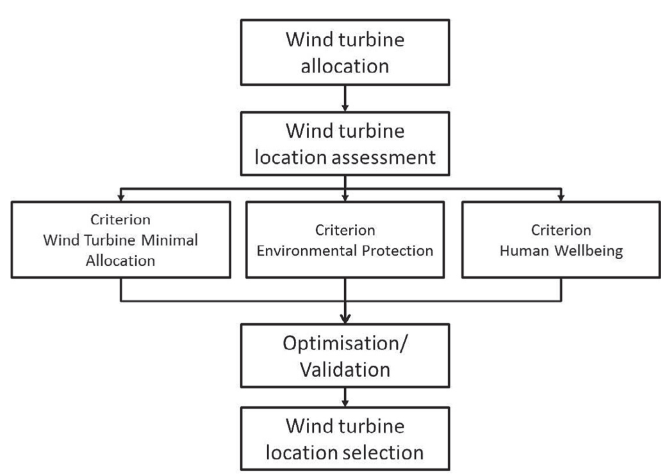

Fig. 1. Flowchart of the approach.

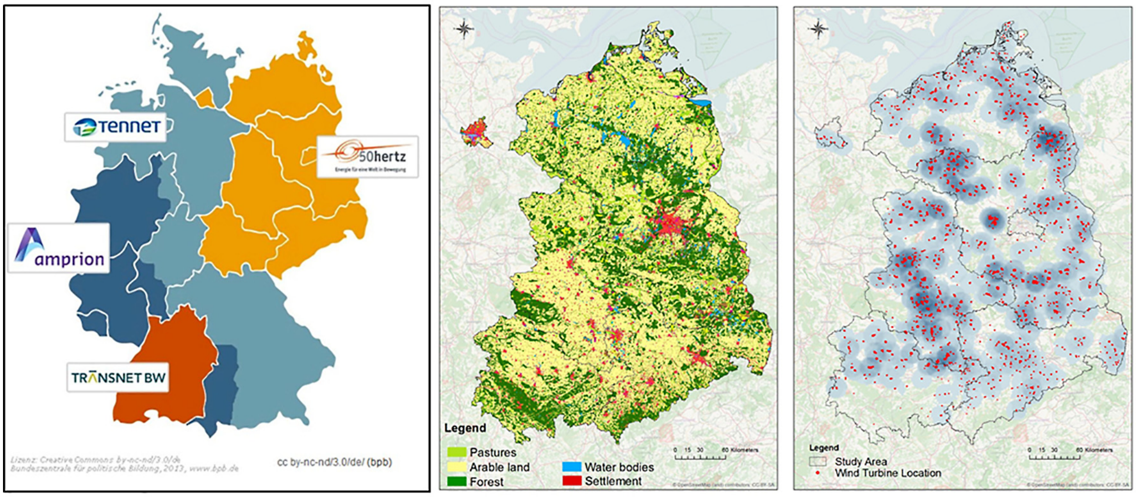

Fig. 2. Left panel: Network transmission area 50 Hz GmbH in orange (License: cc by-nc-nd/3.0/de/ (bpb). Centre panel: overview of the land use in the study area. Right panel: spatial distribution of the installed wind turbines in the study region. License for base map center and right panel: ©OpenStreetMap (and) contributors, CC-BY-SA.

Anhalt und Thuringia. This area is served by the transmission operator 50 Hz GmbH (see Fig. 2, left panel). It has a population of approximately 14 million people with an average population density of 122 people per square kilometer for the territorial states (min. 69 people per km^2 in Mecklenburg-Vorpommern max. 220 people per km^2 in Saxony), and 3109 people per km^2 for the city states (min. 2331 people per km^2 in Hamburg, max 3887 people per km^2 in Berlin).

According to the national classification of landscapes, the study area belongs to the regional landscape “North German Lowlands” and “Eastern Low Mountain Range” [27]. These regional landscapes are generally suitable for wind turbine installations. In terms of land use/land cover (including forested areas) around 90% of the study region can theoretically be used for wind turbines. However, not all restrictions have been considered, yet.

The region is characterised by average wind speeds of between 3.5 m/s and 14 m/s with an overall average of 6.7 m/s at 80 m height [28]. This provides sufficient kinetic energy for wind power applications.

In 2015, around 9634 wind turbines with a total of 15,736 MW (MW) of installed wind power capacity were located in the study region [21]. This is about one third of the overall installed capacity in Germany in 2015 (41,651 MW from 25,982 WTs). These wind turbines generate about 23 TWh/a in total. Many of these WTs originate from the first wind power expansion in the late 1990s and early 2000s. Thus a significant number will be reaching the end of their 20-year technical life span [13] in the next few years. This opens a window of opportunity to improve the allocation of WTs on a broader scale, to take advantage of new technological developments while taking into account human well-being and nature conservation.

2.2. Input data

The main data sources for this analysis are land-use maps, wind resource data, wind turbine operation parameters, wind turbine asset master data and the geo-data of protected areas. The input data are displayed in Table 1.

2.3. Technical specifications of wind turbines

Two types of wind turbines are investigated: standard (STWT) and system friendly (SFWT) wind turbines. The main difference between the types of technology is the ratio between rotor diameter and nominal generator capacity or, in other words, the specific power rating [W/m^2]. System friendly wind turbines are characterised by a lower specific power rating (223 W/m^2 for the selected SFWT) compared to standard wind turbines (375 W/m^2 for the selected STWT) under otherwise similar conditions (see Table 2).

The difference in the specific power rating of both technologies results in a better utilisation of lower wind speeds by SFWTs and hence a more continious electricity provision. However, the area demand per SFWT increases by a factor of 1.4 compared to STWT in order to mitigate efficiency losses of a wind turbine located in the slipstream of another one (so-called “park effect”). This leads to a reduction in suitable locations.

2.4. Wind turbine allocation procedure

In an initial step, suitable sites for WT allocation within the study area were identified [31,32]. Here the blank map approach was applied. This was done to estimate the full potential of suitable locations without excluding areas already occupied by wind turbines. First, all sites in the study region with land cover types physically suitable for the construction of WTs were identified. Sites that are not legally qualified for the construction of wind turbines were excluded [33] (see Table 3).

The use of forest and woodland is possible for wind power development, however this is a controversial issue [34–36]. Therefore, both land cover types are not considered further in this investigation.

Finally, individual locations were allocated for wind turbines within the suitable sites using a novel approach [37]. It takes into account minimal distances between wind turbines (six times the rotor diameter in the main wind direction and three times the rotor diameter in the secondary wind direction) in order to mitigate the park effect [38] and to allocate the maximum number of individual locations possible, also considering neighbourhood relationships between adjacent sites.

Finally a number of 69,919 candidate locations for STWTs and 23,105 candidate locations for SFWTs are obtained. Although this number of WTs would not be required to fulfil the current political targets for the study region [1,39], it demonstrates that there are abundant alternatives for allocating wind turbines in the landscape which makes it even more relevant to identify sustainable allocation solutions.

Table 1
Overview of input data.

Data type	Source
Land use data - Digital basis landscape model (basis DLM 2012)	Official Topographic-Cartographic Information System ATKIS Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany and Land cover database DLM-DE 2012. European Commission programme to COoRdinate INformation on the Environment (Corine)
Wind resource data [28] - Weibull parameters (form and scale parameters) - 200 m × 200 m spatial resolution	German Metrological Service Deutscher Wetterdienst Frankfurter Strasse 135 63067 Offenbach
Wind turbine parameters Power curve of - Nordex N131	Nordex SE Langenhorner Chaussee 600 D - 22,419 Hamburg
- Enercon E101 [29]	ENERCON GmbH Dreekamp 5, D-26605 Aurich
Wind turbine asset master data	Rauner et al., 2016 [30]
Geo-data of protected areas	Federal Agency for Nature Conservation (BfN) Nature conservation information, geo information

2.5. WT location assessment procedure

The main aim of this paper was to identify sustainable locations to enhance the performance of wind power in the study region. Therefore, the individual performance of wind turbines had to be assessed. Three assessment criteria were derived as described below. These were applied to both technology options.

2.5.1. Wind turbine minimal allocation (WTMA)

The criterion wind turbine minimal allocation refers to the resource consumption and potential impact of wind power generation. If the desired energy objective can be reached with lesser turbines, the possible conflicts as well as the resource consumption can be reduced. The criterion is measured by two variables: (1) The annual energy production (AEP) of an individual wind turbine (STWT and SFWT) and (2) the number of wind turbines needed to fulfil the respective energy target.

2.5.1.1. Annual energy production AEP. To calculate the annual energy production for a wind turbine (WT) at a given candidate location, we used the frequency distribution of the wind speed at hub height and the power curve. The frequency distribution $f_{(vm)}$ of the wind speed (v) is commonly described as a Weibull distribution [40,41], which is characterised by a scale and a shape parameter (denoted as A and k):

$$f(v_m) = \frac{k}{A} \times \left(\frac{v_m}{A}\right)^{(k-1)} \times exp^{-\left(\frac{v_m}{A}\right)^k} \quad (1)$$

The annual energy produced on a candidate site by the respective WT (baseline and advanced) in one year (E_a) is the sum of all energy production values $P(v_m)$ weighted by the frequency $f(v_m)$ by which the wind speed v_m is observed at the site under consideration, multiplied by the number of hours per year ($t_a = 8760$ h):

$$E_a = t_a \sum_{m=0}^{m_{max}} f(v_m) P(v_m) \quad (2)$$

Here, m_{max} represents the upper limits of the wind speed range within which the WT operates. It should be noted that this calculation is only valid for standalone wind turbines.

We obtained the values for the parameters A and k with a horizontal resolution of 200 by 200 m from the German National Weather Service. The annual energy production of each WT is determined according to Eq. (2) in gigawatt hours per year (GWh/a).

Since, for the calculation of the AEP of a candidate wind turbine, power curves and weather based wind speed distributions have been used, several “real world” losses in AEP due to wake effects in wind parks, non-availability for servicing and repairs, environmental shut down times (regarding bat activities) or curtailment are not considered so far. Several studies have discussed different losses to cover such aspects [42–44]. For this investigation, a reduction of the AEP of every candidate WT by ten percent was considered.

2.5.1.2. The number of WTs necessary to fulfil a certain energy target. Here the total number of WTs necessary to fulfil the respective energy target is estimated. The value of this variable depends on the selection process of WTs out of all possible WT locations. According to resource consumption and potential impacts, the performance of wind power is best with minimal number of WTs to be installed.

2.5.2. Environmental protection

Onshore Wind power generation is a source of diverse environmental impacts, mainly on birds and bats [45–49]. These impacts range from disturbance or displacement of birds [50,51] up to collision events causing individual death [50,52–54] which can lead to negative consequences on populations [47]. Several studies have suggested methods to assess such impacts. Promising assessment methods are based on the direct count and estimation of collision victims at windfarms [55,56] in post erection assessments, the distribution of focal species [57], a combination of the potential habitat analysis with the distribution [58] or different

Table 2
Key parameters of baseline and advanced wind power technology.

Parameter	Standard wind turbine	System friendly wind turbine
Hub height	135 m	135 m
Nominal generator capacity	3 MW	3 MW
Rotor diameter	101 m	131 m
Specific power rating	375 W/m^2	223 W/m^2

Table 3
Primary suitable land cover types (left column) and restriction criteria (right column).

Primary suitable land cover types	Restriction criteria
Cropland	Buffer distance to settlement area (800 m)
Grassland/pasture	Buffer distance to traffic infrastructure (up to 250 m)
Heath	Protected areas (nature conservation, …)
Scrubland	
Vegetation-free areas	
Acclivity/reclaimed land	

spatially explicit modelling techniques [59,60] in pre erection analysis. However, such investigations need comprehensive field work or specific data that is either missing or unavailable or is insufficient for analysis. Therefore, distance functions have been selected as a criterion, emerging from a compromise between significance and practicality. Using distance as an indicator for the severity of a conflict or as a means to avoid conflicts is a common approach. In Germany, the recommendations of the "Working Group of German State Bird Conservancies" (LAG VSW) are the most prominent in this context. The LAG VSW defines minimum distances to breeding areas and protected areas [61,62]. Similar recommendations also exist in eleven of the sixteen German federal states [63]. In this study a similar approach is selected. Instead of keeping a minimum distance buffer around known breeding habitats free of wind turbines, the distance of wind turbines to potential breeding/feeding areas has been maximised. However, detailed and exhaustive data of breeding/feeding areas are hardly available. For the sake of simplicity, it has been assumed that special protected area (SPA) of the European Union Natura 2000 framework cover valuable bird habitats [64,65]. Therefore maximising distances between wind turbines and SPA should reduce the risk of negative impacts. For bats, no such specific protection areas exist. However, some of the Flora-Fauna-Habitat protection areas of the European Union Natura 2000 framework are also designated for bat protection. Furthermore, "a protected area is a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values." (as defined by the International Union for Conservation of Nature and Natural Resources). Therefore, in this study, one aim was to maximise the distance of WT to most kinds of conservation areas to minimise potential impacts. Here, the distance (D_{EP}) between individual WT locations and the closest neighbouring protected area (as explained by the national nature conservation act) is measured (see Fig. 3).

In the assessment, a potential impact value (I_{EP}) for every WT location was calculated according to the following Eq. (3). Although the impact value is based on distances measured in metres; the potential impact itself is a dimensionless value.

$$I_{EP} = 1 - \frac{(D_{EP} - D_{EPmin})}{(D_{EPmax} - D_{EPmin})} \tag{3}$$

2.5.3. Human well-being

The criterion is measured as the closest distance (D_{HW}) between individual WT locations and the nearest neighbouring settlement area (see Fig. 4). Settlement areas that are located around the study area are also considered here to avoid boundary effects. Even if all legal requirements regarding emission protection are fulfilled (usually achieved by buffer zones [66–68]) most people prefer wind turbines to be farther way from their homes [69–71]. In order to assess the potential conflicts with human well-being, an impact value (I_{HB}) was calculated according to Eq. (4). As above, the impact is a dimensionless value.

$$I_{HW} = 1 - \frac{(D_{HW} - D_{HWmin})}{(D_{HWmax} - D_{HWmin})} \tag{4}$$

2.6. Multi criteria optimisation procedure

2.6.1. Framing conditions

In terms of framing conditions, it was assumed that the power

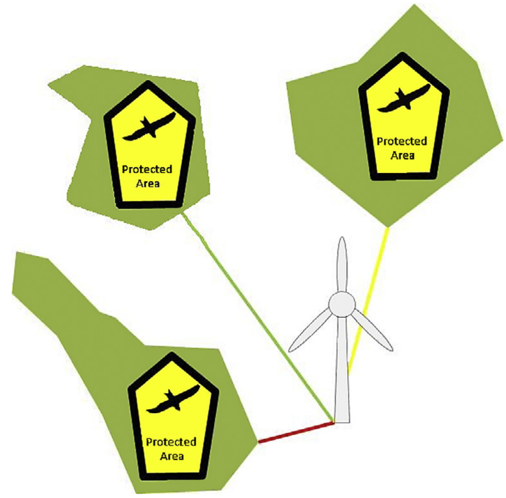

Fig. 3. Estimation of the criterion "environmental protection".

demand in the region will be constant at approximately 104 TW h (TWh) over the next decades in accordance with the 2012 German Net Development Plan [39]. This is substantiated by the trend that future energy savings are expected to be compensated for by economic growth and the expansion of electricity use, e.g. in transport. Of the several studies investigating the development of the German Energy System up to 2050 [3,72–74], the Network Development Plan for 2012 was selected because it has a more detailed spatial resolution (transmission network areas and Federal States) compared to the national studies. The 2012 Net Development Plan 2012 (NEP) assumes that onshore wind power will contribute more than 40% of the overall regional power demand in 2032. This defines our energy objective of 41 TW h per year (TWh/a) (i.e. 40% of the power demand). This framing condition is in line with governmental targets for renewables in 2030 [39].

2.6.2. Multi attributes value theory approach (MAVT)

The suggested approach was developed following the multi-attributes value theory [75,76]. With it, an optimal wind turbine location is characterised by a maximum distance to (1) protected areas, (2) a maximum distance to settlements and (3) the highest possible annual energy production compared to other turbines in

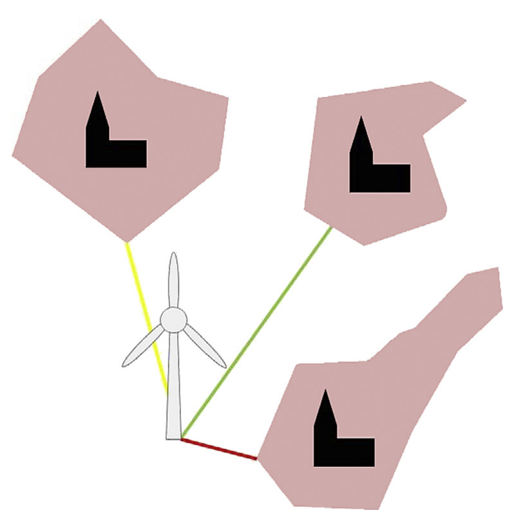

Fig. 4. Estimation of the criterion "human well-being".

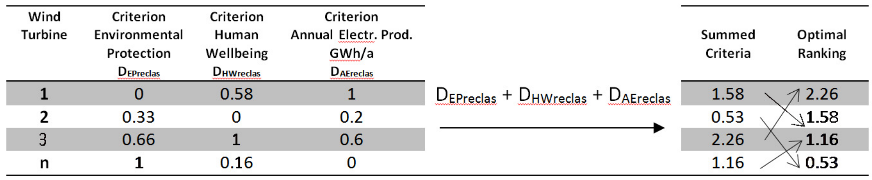

Fig. 5. Illustration of the multi-criteria optimisation approach.

the region. The weighted sum technique, as part of the MAVT was used to identify optimal WT locations.

An important step in the weighted sum method is the weighting of the criteria according to their importance in the overall objective. However, the weighting of the three objectives (environmental protection, human well-being and wind power generation) depends on individual preferences or political targets. This issue underlies the current controversial debate. It should not be determined independently from public discourse. Therefore, an equal weighting of all three factors is used in this case study to avoid preferring one objective over another.

However, a strength of this method is the way in which it is able to compare parameters/attributes of different scales as we are faced with the challenge of combining and comparing distances measured in meters and energy production measured in GWh. To overcome this problem, a reclassification of the three individual scales of between 0 and 1 was applied where 0 represents the closest distance or the lowest AEP, and 1 is the farthest distance away or the highest AEP.

To estimate the optimal WT locations, the individual scores of AEP, environmental protection and human well-being for one WT are added up on a cardinal scale. This can be done because a higher value is better than a lower one for every criterion. Then, the WT locations are ranked in descending order starting with the highest value which indicates the best location according to the assessment criteria. Fig. 5 illustrates the described process.

The entire approach was applied to both technology options so that there are two data sets with optimally ranked wind turbine locations for the study region.

2.7. Potential impact assessment and validation of optimised WT locations and the overall performance of wind power in the study region

To assess the performance of the optimisation approach and the overall performance of wind power in the study region, the energy objective of 41 TWh, as defined in Section 2.6.1, was taken as a framing condition. Hence, following the optimal ranking (see Section 2.6.2), wind turbines were selected by adding up their AEP until the cumulative value reached 41 TWh. Then the impact values were added up for the selected wind turbines (see Sections 2.5.2 and 2.5.3), producing a cumulative impact score for the criterion “environmental protection” and “human well-being” respectively.

This was applied for both technology options (STWT and SFWT) as well as for the currently installed wind turbines. This enables the respective performances to be compared.

2.7.1. Mono-criteria optimisation

Mono-criteria optimisation was applied for each of the three criteria to validate the results of the multi-criteria optimisation procedure and the overall performance. Here the optimisation objective was to minimise the potential impact on the respective criteria without taking the effects on the other criteria into consideration (see Table 4). Therefore, the wind turbine locations have been ranked in decreasing order, from highest to lowest, for each criterion ($D_{EPreclas}$, $D_{HWreclas}$ and AEP_{reclas}). Based on the estimated rank, wind turbines were selected until the energy objective of 41 TWh was reached. Then the cumulative impact values I_{EP} and I_{HW} were estimated as well as the total number of wind turbines. This approach is regarded as being similar to weighing each criterion separately, giving 100% importance to each. Thus, the respective vertices of the decision space are displayed. This procedure enables the consequences of different decisions to be shown e.g. how impacts change if one objective is prioritised over another. Table 4 summarises the described approaches.

3. Results

3.1. Wind turbine allocation procedure

The WT allocation procedure identifies a set of 69,919 WT locations for STWTs and 23,105 for SFWTs (see Table 5). This is the maximum technical potential that is physically and legally possible. If all locations were selected to erect a wind turbine, 482 TWh per year could be generated using the standard technology and 238 TWh per year using the system friendly technology. This presents 2 to 4.5 times the overall annual electricity demand (104 TWh per year) of the study region. The turbine-specific energy

Table 4
Summary of the optimisation and validation approach.

Criterion	Characteristic	Selection process
Multi-criteria optimisation	Minimal impact on both settlements and protected areas using a minimal number of WT	Ranking WT in descending order based on the sum of both the reclassified distances and reclassified AEP (WT with the highest value is the first to be used and so on until the energy objective is fulfilled), cumulated impacts (I_{EP}, I_{HW} and number of WTs) are determined.
Wind turbine minimal allocation	Minimal number of wind turbines	Ranking WT in descending order of their respective AEP (WT with highest electricity production is the first to be used and so on until the energy objective is fulfilled), cumulated impacts (I_{EP}, I_{HW} and number of WTs) are determined.
Environmental protection	Minimal impact on protected areas	Ranking WT in descending order by their reclassified distance to protected areas (WT with largest distance is the first to be used and so on until energy objective is fulfilled), cumulated impacts (I_{EP}, I_{HW} and number of WTs) are determined.
Human well-being	Minimal impact on settlement areas	Ranking WT in descending order by their reclassified distance to settlements (WT with the largest distance is the first to be used and so one until energy objective is fulfilled), cumulated impacts (I_{EP}, I_{HW} and number of WT) are determined.

Table 5
Overview of WT locations, existing and newly allocated wind turbines.

	Total area km^2	Suitable sites km^2	Number of existing WT 2015 [21]	Number of potential WT locations standard/system friendly	
Berlin	893	24	4	53	5
Brandenburg	29,698	9127	3463	22,209	6442
Hamburg	753	15	53	43	33
Mecklenburg Western-Pomerania	23,076	5635	1788	15,365	7952
Saxony	18,479	2207	880	5273	1577
Saxony-Anhalt	20,553	5874	2697	18,747	4179
Thuringia	16,195	2512	749	8229	2918
Total study region	**109,647**	**25,394**	**9634**	**69,919**	**23,105**

production ranges from 2.8 (STWTs) to 13.4 (SFWTs) GWh per year.

3.2. Multi-criteria optimisation procedure

Applying the multi-criteria optimisation approach identifies either 5669 STWT or 3910 SFWT locations necessary to fulfil the energy objective of 41 TWh in the study region.

For STWTs, the cumulative potential impact on environmental protection is 3625 [−]; for SFWTs it is 2935 [−]. The potential impact on human well-being for the standard technology is 3617 [−] and 2448 [−] for system friendly technology. Summarising the results shows that the advanced technology outperforms the baseline technology in terms of the number of necessary WT as well as total impact on environmental protection and human well-being (see Table 6).

3.3. Potential impact assessment and validation of optimised WT locations and the overall performance of wind power in the study region

To set the results of the multi-criteria optimisation approach into a broader context, and to assess the overall performance of wind power in the study region, the potential impact assessment was also applied to mono-criteria optimisation for the criteria "wind turbine minimal allocation", "environmental protection" and "human well-being" as well as to the currently installed wind turbines in the study region. The results are displayed in Table 6.

The lowest overall number of wind turbines needed to fulfil the energy objective (41 TWh) is the result of the option mono-criteria WTMA optimisation for system friendly technology. In contrast, the highest number of wind turbines is necessary if full weight is placed on the human well-being criterion for standard wind power technology. All three forms of mono-criteria optimisation perform best according to their objective functions. This means the respective impact is lowest when optimising with respect to the criterion. As displayed in Table 6 the following results were obtained for the assessment criteria: firstly, the number of necessary wind turbines ranges from 3754 WT (system friendly technology, WTMA criterion) to 6551 WT (standard technology, human well-being criterion), secondly, for the cumulative impact on protected areas the values range from 2849 (SFWTs, environmental protection criterion) to 5454 (STWTs, human well-being criterion), and thirdly, for the impact on human well-being the values range from 2325 (SFWTs, human well-being criterion) to 4638 (STWTs, environmental protection criterion). According to the average potential impact per WT, the outcomes for both technologies are similar. However, in terms of cumulative or total impact, system friendly technology options perform better for every criterion. A graphical representation of the results, given in Table 6, regarding the cumulated potential impacts I_{EPcum} and I_{HWcum} for the two respective optimisation criteria is provided in the following Fig. 6.

It becomes apparent that the cumulated impacts for environmental protection and human wellbeing are consistently lower in the case of system friendly WT, as it is likewise the case for the required number of WT.

3.3.1. Spatial WT distribution of the scenarios

In addition to analysing the trade-offs between the scenarios in terms of the assessment criteria (minimal number of WT, potential impact on human well-being and impact on nature conservation issues), the spatial consequences must also be taken into consideration. Fig. 7 illustrates the spatial distribution of the WTs as a result of the different objective functions. Within the mono-criteria optimisations of the WTMA criterion only wind-intensive sites were selected. These are concentrated in the coastal regions

Table 6
Results of the analysis.

Standard Wind Turbine Technology					
Optimisation Criteria	**Required WT [n]**	$\mathbf{I_{EPcum}}$ **[−]**	$\mathbf{I_{HWcum}}$ **[−]**	**Ø$\mathbf{I_{EP}}$ per WT [−]**	**Ø$\mathbf{I_{HW}}$ per WT [−]**
Wind turbine minimal allocation	4694	3980	3411	0.85	0.73
Environmental protection	6455	3712	4638	0.58	0.72
Human well-being	6551	5454	3513	0.83	0.54
Multi-criteria	5669	3625	3617	0.64	0.64
System Friendly Wind Turbine Technology					
Optimisation Criteria	**Required WT [n]**	$\mathbf{I_{EPcum}}$ **[−]**	$\mathbf{I_{HWcum}}$ **[−]**	**Ø$\mathbf{I_{EP}}$ per WT [−]**	**Ø$\mathbf{I_{HW}}$ per WT [−]**
Wind turbine minimal allocation	3754	3182	2572	0.85	0.69
Environmental protection	4486	2849	3074	0.64	0.69
Human well-being	4486	3788	2325	0.84	0.52
Multi-criteria	3910	2935	2448	0.75	0.63
Currently Installed Wind Turbines (2015)					
	Existing WT [n]	$\mathbf{I_{EPcum}}$ **[−]**	$\mathbf{I_{HWcum}}$ **[−]**	**Ø$\mathbf{I_{EP}}$ per WT [−]**	**Ø$\mathbf{I_{HW}}$ per WT [−]**
	9634	7788	6527	0,81	0,68

WT − wind turbine; I_{EPcum} − potential impact on environmental protection; I_{HWcum} − potential impact on human wellbeing; ØI_{EP} per WT − average potential impact on environmental protection per wind turbine; ØI_{HW} per WT− potential impact on human well-being per wind turbine.

(Mecklenburg-Western Pomerania) and the low mountain ranges of Saxony and Thuringia. For the human well-being and the environmental protection criteria optimisation, the patterns are more heterogeneously distributed over the study region. This is reasoned by the spatial distribution patterns of settlement and protected areas. Within the multi-criteria optimisation also primarily wind-intensive sites are selected but with a stronger scattering also in the inland federal states. The spatial patterns vary slightly between standard and system friendly technology. Strongest differences appear in the multi-criteria option (see Fig. 7). This is reasoned by the higher number of WT needed to fulfil the energy objective for STWT.

4. Discussion

Within this study a multi-criteria assessment methodology was introduced, that allows the identification of sustainable WT locations out of a set of legal and physical suitable sites regarding the potential impacts on environmental protection issues, human wellbeing and annual energy yield. The method was applied to the area of the 50 Hz transmission network (covering 6 federal states) for 2 selected types of wind turbines with differing specific power ratings - 223 W/m^2 (SFWT) and 375 W/m^2 (STWT).

Three main aspects for future wind expansion have become apparent:

1) System friendly wind power technology outperforms standard technology in every case. This means fewer turbines are needed overall, reducing the total impact compared to STWTs. Compared to the present number of WTs with lower overall AEP of 22.9 TWh/a, system friendly technology allows WT numbers to be kept below current levels, even though AEP increases to 41 TWh/a. This is mainly the result of higher productivity in terms of full load hours (flh) of SFWTs (Ø 3400 flh) compared to STWTs (Ø 2300 flh). However, the impact per turbine can be higher than the impact of standard technology.
2) Mono-criteria optimisation achieves the best results for the respective criteria, however the trade-offs regarding the performance of the other criteria in this case study are considerable. Multi-criteria optimisation consistently allowed for significant reductions in total impacts across all three criteria and came close to the lowest total impact calculated. Comparing the minimum number of turbines necessary for annual energy production resulting from a mono-criterial optimisation, about 1000 more STWTs and about 200 more SFWTs are required.
3) The spatial distribution of wind turbines varies widely, depending on the respective optimisation criteria and the underlying spatial distribution of the sites of these criteria. For instance, the mono-criteria selection of wind turbine candidate locations with the highest AEP will lead to a selection of WT locations in areas with the best wind resources. In general, these candidate locations are concentrated in certain regions of the study area, leading to a spatial clustering of wind turbines (see Fig. 7a and e). When distance maximisation is applied to settlement areas as an optimisation criterion, for example, it results in a more disperse distribution of the WTs given the existing structure of settlements in the study region (see Fig. 7c und g).

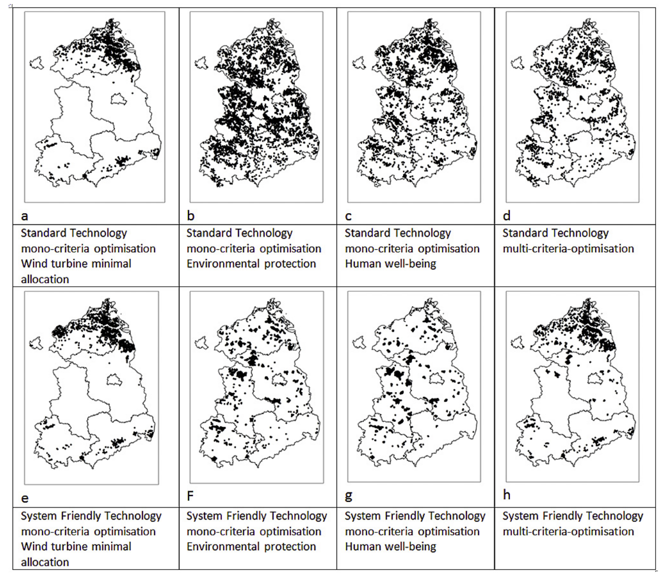

Fig. 7. Spatial allocation of selected WT candidate locations in 2032 [39] as a result of the different scenarios.

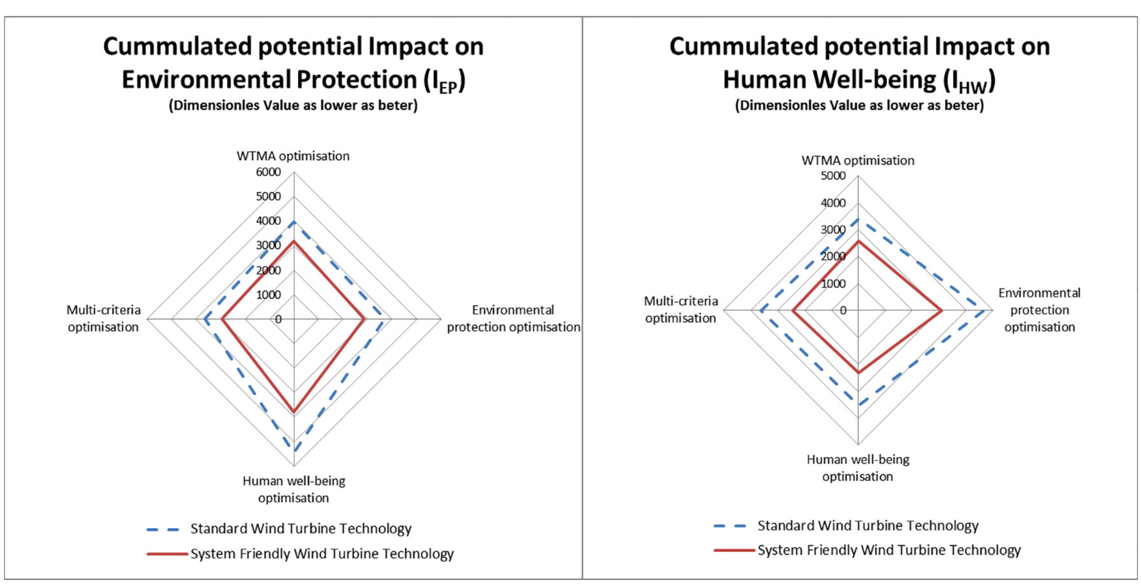

Fig. 6. Cumulated potential impact on environmental protection and human well-being from different optimisation approaches for STWT and SFWT.

The spatial allocation pattern resulting from multi-criteria optimisation is not an intermediate between dispersed distribution and clustered distribution; instead it is more clustered than dispersed (see Fig. 7d and h).

As mentioned above there is currently an ongoing political and social debate about prioritising individual objectives. The approach described here can be regarded as a tool for fostering this discussion process by showing the consequences of different decisions.

Compared to the current allocation of existing WT, the optimised allocation of wind turbines could improve the overall performance of wind power in the study region. All tested forms of optimisation (mono and multi-criteria), perform better in terms of wind turbine minimal allocation, environmental protection and human well-being. The total number of wind turbines in the study region could be reduced by at least 3000 with a doubling of the AEP. Also, comparing the worst optimisation results against the current status, the cumulative potential environmental impact was observed to be 30% lower in the case of optimised human wellbeing for STWT (at 5454 from 7788) and the cumulative potential impact on human well-being 29% lower in the case of optimised environmental protection for STWT (at 4638 from 6527) (see Table 6).

The approach as presented here can easily be adapted to different wind power technologies. An increase in size, modification of the power rating and feed-in characteristics is to be expected for future WT generations and can be implemented into the approach. Likewise, it allows manifold testing of different development preferences e.g. by respective weighting or mono criterial optimisation and shows the potential consequences and trade-offs. Particularly the potential consequences are measured dimensionless by “better as” or “worse as” and this approach can support developing energy scenarios that provide information on the potential consequences on a spatially explicit scale. Further it can be used by regional or state development planers during the search process in identifying locations for wind turbines and providing arguments why to dedicate a certain site for WTs and not another one.

Distances form the basis of the potential impact assessment of two of the three criteria in this study. This is sufficient for the purpose of this study of estimating trade-offs for different development options. However, thresholds for the severity of possible conflicts have not been applied. For example, threshold distances for certain species have been estimated based on collision probability functions [77]. This would enable a quantitative impact value to be given to a certain distance between a WT and a protected good instead of normative value as is performed in this approach. Furthermore, not all threatened species are covered by protected areas. Here more research is needed to extend the approach by methods that consider even such aspects. This shall be incorporated in a next step.

5. Conclusions

Taking all the different aspects of wind power provision into consideration, the main aim of this paper was to identify optimal locations to enhance the performance of wind energy using a consistent methodology and taking into account the national goals of the energy transition. Thedeveloped approach was tested for a German study region for the timehorizon up to 2030.

- The approach is easy to apply and a powerful way to identify sustainable locations for wind turbines. It can also be used to assess the performance of wind power in a certain region. Number of necessary installations, possible impacts on environmental goods and human well-being are the criteria to be assessed. Emphasising annual energy production (AEP) using a minimal number of WT (WTMA) leads to a concentration of WT in wind intensive areas. Mono-criteria environmental protection optimisation and human well-being optimisation show a much stronger distribution of wind turbines across the study area. The reason therefore is the spatial distribution and density of the protective goods. It is not surprising that in a multi-criteria (MC) optimisation the spatial diversity depends on the weighting of the different criteria. Nevertheless some regions have been identified as target regions under all different criteria, such as the “Mecklenburg Region” in north Germany and several smaller locations. They were selected simultaneously for at least three of the four tested optimisation approaches, underlining the robustness of these locations.
- A second objective was to compare the performance and spatial patterns of standard and system friendly technologies to identify the trade-offs between both technologies. The clearly evaluated result is that system friendly technologies outperform STWTs in every case (see Table 6), which underlines the need for dedicated support to install SFWTs. This is not only an issue for new wind turbine locations but also for repowering of WT on already existing locations (see Section 4).

However, the suggested approach has also limitations regarding the comprehensiveness of the assessment criteria and the applied data which need to be overcome in further research (see Section 4). With this approach many different options regarding the allocation of WT can be tested (weighting) and can provide material (numbers and maps) for incorporating stakeholders. This could support the acceptance process when expanding renewable energies, particularly wind power. Due to the ongoing discussion on the “how and where” of wind turbines in Germany, the developed approach could also support the classical energy system modelling. Since in addition to economic and energy system aspects, this approach also incorporates environmental consequences and with it, it provides the potential to improve future energy scenarios. This is an aspect that is currently weak or missing in national energy system analysis.

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Publication Five

Impact of flexible bioenergy provision on residual load fluctuation: a case study for the TransnetBW transmission system in 2022.

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Impact of flexible bioenergy provision on residual load fluctuation: a case study for the TransnetBW transmission system in 2022

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Abstract

Background: The transition towards a renewable based power system in Germany largely depends on variable renewable energy sources (vRES) like wind power and solar PV. Their high variability over time poses new challenges for power system stability. Bioenergy as a renewable source has already been established in recent years and has the capability to offset fluctuations from wind and solar PV and can therefore play a new role in coming years.

Methods: This paper describes how existing bioenergy plants can be operated in order to offset fluctuations in power systems, performing a power system modelling based on time series data. As sample transmission system (TS), TransnetBW has been chosen, one of the four German transmission systems. We modelled two different types of bioenergy plant clusters, one including solid biomass plants and the other cluster covering biogas plants and other plants with comparable characteristics. For the modelling of the operation of these clusters, we used registered time series of the years 2011 and 2012 for a total load and feed-in from wind and solar PV, which were projected for the year 2022. The flexible bioenergy clusters are operated in order to minimize fluctuations in residual load (RL). This approach served as the basis to assess how concepts for flexible bioenergy provision can contribute to the task of balancing future power systems based on vRES.

Results: Bioenergy plays an important role in the renewable power supply of the TransnetBW TS, as it holds a share of 23.3% among the renewables projected for 2022. A flexible bioenergy (BE) provision allows for a reduction in daily residual load fluctuations by 30% compared to the non-flexible power generation from BE. Flexible BE effectively offsets high fluctuations originated from the feed-in of the substantial solar PV installations in the TS and also contributes to serve the peak load. But in contrast to regions with higher renewable shares from vRES, the amount of avoided BE power production in times of negative RL (excess power from renewables) is still negligible for the 2022 time frame investigated and thus reducing the immanent requirement for flexible BE.
(Continued on next page)

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Conclusions: In line with existing studies, the results show that bioenergy is already a valuable asset to achieve the targeted REN shares and can support the integration of the large vRES capacities in coming years, if produced flexibly. Operating biomass installations in a flexible manner effectively reduce daily fluctuations in RL, allow for a better integration of vRES and contribute to cover peak power demand. But from the findings of this case study, we conclude that the focus in the near-term should be on the efficient utilization of BE as the top priority until the demand for flexible BE provision is progressively increased with rising shares of vRES. Giving the regional differences, it should be stressed that the regional context, the relative share of wind and solar PV in the power system and therefore the investigated time horizon are important for defining the role of flexible bioenergy in the years to come.

Keywords: Bioenergy, Flexible energy provision, Wind energy, Solar PV, Residual load

Background

The shift from a fossil fuel energy system to a low-carbon renewable energy system is vital for a sustainable development in the future. This transformation of our energy system requires a rethinking and redesign of how energy shall be produced and supplied in the future. Within the European Union, a renewable target of 20% in the final energy consumption by 2020 has been set by the Renewable Energy Directive 2009/28/EC as cornerstone [1]. Recently, the European Commission has stated a new target of at least 27% of the final energy consumption from renewables (at least 45% share in the electricity sector) by 2030 as part of the climate and energy goals for 2030 [2]. With an increasing share of renewables in the power sector, a demand for a new energy system design integrating and replacing the different emerging and existing energy sources in an efficient way occurs. Especially, the market integration of intermittent electricity provision by wind and solar power asks for flexible means in the power system in order to facilitate a secure and sustainable energy supply [3].

Strategies, which are currently being discussed for addressing this challenge and thus offsetting the temporal and spatial discrepancy of energy supply and demand, are manifold. The considered flexibility options cover the development of power storage and Power-to-X technologies, expansion of the electricity grid and interconnectors for import and export as well as enabling smart electricity supply (flexible fossil and renewable power plants) and demand side management (DSM). Referring to the latter option, this research focuses on the opportunities and challenges of a flexible power supply based on biomass conversion technologies. The intention is to reveal whether a flexible power generation based on biomass can be an appropriate approach for the system integration of the increasing share of vRES.

Therefore, this study addresses the following research question:

- What impact does a flexible operation of biomass installations has on the integration of renewables in a future solar PV-dominated power system?

To answer this question, we will assess (i) the impact of flexible bioenergy provision on daily variability in residual load (RL) (total load minus feed-in from renewables) as an indicator for system integration of renewables and (ii) the ability of a flexible operation of biomass plants to avoid power production in times of negative residual load (when renewables already cover the power demand).

Scope

The scope of this paper is the assessment of the role of flexible biomass installations in one of the four German transmission systems (TS) by 2022. Germany has been chosen as case study since it has an ambitious midterm goal of 40 to 45% by 2025 and a long-term goal of at least 80% renewables within the electricity system by 2050 [4], starting from a current share of 32.6% (195.9 billion kWh) in 2015 [5]. Thus, Germany is going to be affected by the stated problem. The intention is to show the impact of flexible bioenergy provision for balancing vRES in Germany in the midterm. This assists in identifying significant aspects and challenges for the electricity system on the road towards an energy supply based on 100% renewable energy sources.

Moreover, reflecting on the midterm perspective is of particular importance as the role of bioenergy (BE) in the German power system is highly disputed and existing BE installations as well as future investments in the sector are subject to uncertainty in the national energy policy. The year under consideration (2022) has been chosen in correspondence to the time horizon of the reference scenario considered within the “Network development plan electricity 2012 (NEP 2012)” [6]. The NEP 2012 includes a very comprehensive record on the scenario design for the midterm development of the electricity production in Germany, including a scenario for 2022 which was used for this case study. By choosing the year 2022, we focus on already available technologies and existing plant infrastructure.

Furthermore, the operation of flexible bioenergy facilities can mainly be found in Germany at the moment. This development has been particularly stimulated by favourable legislative conditions. Since 2012, the German feed-in tariff system (EEG) provides a bonus payment for a flexible operation of biogas installations. Here, investments in additional infrastructure are promoted which are allowing a demand-oriented electricity production. This policy environment facilitated the development and establishment of flexible biomass conversion facilities. Therefore, the German electricity system has comparatively great wealth of experience in a flexible electricity supply.

Within the German electricity market, we focused on the TransnetBW transmission system as the case study region. As Germany is divided into four transmission systems, the reflection of the transmission system as a whole is rather challenging. Therefore, the TransnetBW transmission system has been chosen as the study area since it shows a high share of solar PV posing specific challenges for balancing RL.

Review of previous studies

Studies reflecting options for balancing fluctuating electricity feed-in from renewable energy sources have mainly emerged in the last few years. Especially, since the impact of an increasing share of vRES within the European electricity system is being felt, the issue is on the political and research agenda. Although limited in volume, excess power generation from wind and solar has already led to their curtailment what is associated with significant economic losses.

A sound overview of the overall options for vRES integration is provided by the IEA report published in 2014 [7], ranging from system friendly vRES deployment, improved system and market operation and finally new infrastructure like flexible BE.

Many individual studies analyze and discuss the future challenges of large shares of vRES within the future European electricity system [8–11] (overall system approach).

Albrecht et al. [8] investigate the challenge of different instruments to stimulate the long term capacity building of renewable energy installations. They address that there is a need for pull-(RD&D) as well as for push -factors (production subsidies). A second large topic is that renewable electricity generation will be dominated in the future by solar and wind power [6, 9]. Subsequently, the most challenging issue is balancing these large vRES capacities because their stochastically feed-in characteristic does not necessarily match the demand patterns [10–13].

Other studies reflect on the various technology options for a smart integration of vRES [14–18] or they present specific case studies on applying several technologies for balancing variable renewable energy sources in a certain region [19–22]. For example in [18] the possibilities of combined heat and power (CHP) production for balancing large amounts of wind power in Finland were investigated. It was shown that CHPs can contribute to the balancing of vRES, while maintaining high overall efficiency, using adequate amounts of thermal storage capacities to uncouple electrical and thermal generation. Another example is given by [19] where the potential for balancing wind by demand-driven biogas plants for Latvia was investigated. On the level of market and system integration, [20] shows the potential to reshape the recent market design for a better integration of wind power to provide regulating power to balance fluctuations in electricity systems.

The study on hand picks up this last group of specific technological options that facilitate the integration of vRES in a defined transmission system. Here, it particularly relates to the investigations of flexible BE [16, 17] and intends to draw a comparison to the research results of flexible biomass installations in another transmission system [22]. This approach shall assist in deriving general conclusions on the contribution of flexible biomass provision for balancing variable power generation from solar and wind power in the midterm. Compared to most other studies, we are aiming at modelling the specific challenges of flexible BE in a power system with a higher degree of differentiation between BE conversion technologies (clusters). Here, we focus on the near-to-midterm which limits the technical options for flexible BE but allows us to answer the question of the effectiveness as well as the requirement for flexible BE in the midterm.

The analysis is based on three different scenarios, which are described in the "Scenario overview" section; the corresponding modelling is presented in the "Methods" section and the modelling results in the "Results and discussion" summarizing section.

Scenario overview

We define three different scenarios in order to assess the role of bioenergy on the provision of power in the TransnetBW transmission grid in the year 2022. Table 1 gives an overview of the considered scenarios.

As a reference, we use a no bioenergy (NO-BE) scenario, which excludes BE from the energy mix, assisting

Table 1 Overview of the different scenarios in 2022

	NO-BE no bioenergy at all	NON-Flex-BE non-flexible bioenergy	Flex-BE flexible bioenergy
Installed power from bioenergy plants	–	639 MW	985 MW (+346 MW)
Annual energy production (AEP) from bioenergy	–	5.6 TWh/a	5.6 TWh/a

in evaluating the impact of bioenergy supply on the investigated transmission system. Among the two bioenergy scenarios, one includes BE in the form of a non-flexible bioenergy (NON-Flex-BE) provision. Here, a quasi-constant power feed-in of 639 MW from BE is modelled. Based on [23, 24], we derived annual full load hours and installed capacities and assumed that the 639 MW of installed capacity is operated at rated capacity throughout the whole year. This non-flexible operation has been the predominant type of BE power provision until the introduction of the bonus payment for a flexible operation of biogas installations in the year 2012. The other scenario covers a flexible BE (Flex-BE) provision. Here, we assume a certain kind of installation of extra power capacity, although the overall BE power production of 5.6 TWh/a remains unchanged in comparison to the NON-Flex-BE scenario to maintain the comparability of the results (see Table 1). The additional 346 MW resulting in a number of assumptions in the way BE plants becomes flexible. First of all, we assume that only some of the existing plants (see shares for the Cluster 1 and Cluster 2 in Table 2) will be upgraded and extended in installed capacity, for example for small plants, the effort would not worth the required investments. For the plants which are upgraded to be operated flexibly, we assume that they double their installed capacity.

For modelling purposes, the portfolio of biomass installations has been grouped into two clusters representing each the dominating bioenergy technologies within Germany. The intention is to reflect on these substantially different technologies in terms of their ability to serve demand-driven electricity supply. Cluster 1 covers wood-based heat and power plants based on condensing technology using steam as well as the organic rankine cycle process. Cluster 2 represents biogas plants and other plants with comparable technologies like CHP units driven by biomethane or vegetable oils.

Based on typical biogas and wood-fired combined heat and power plant (WCHPP), assumptions for the flexible operation for both clusters were made. Here, especially the expansion of the installed capacities as well as storage capacities for intermediate energy, enabling plants to control their feed-in for several hours, was taken into consideration. Hereby, we focused on already available technologies for retrofitting existing plants, as the level of the current incentives of the feed-in tariff system is expected to result in a rather small increase in the total installed capacities in the years to come [23, 25]. Hence, innovative technologies, like multi-stage biogas plant concepts [26–28] or gasification CHPs for solid biomass [29] with larger bandwidth for load changes or spread between minimal and maximal load, are more likely to be realized after the year 2022.

Cluster 1 is represented by an average WCHPP. These types of plants are to a large extent integrated into combined heat and power (CHP) systems and mostly operated in a heat-driven mode. Nevertheless, these plants also provide a certain kind of flexibility. Even with a non-flexible mode of operation, the installed capacity is significantly larger than the rated power. However, in contrast to biogas installations, these plants are only able to adjust their power output slowly, due to the thermal inertia, caused by the steam generation in a large boiler.

Cluster 2 is represented by an average agricultural biogas plant (ABP). In case of the flexible operation, the installed capacity is more than two times the amount of the rated capacity. This means the plant can run for less than 11 h in a full load operation each day. Biogas plants are characterized by a high daily flexibility, resting upon an easy to control power output of generator sets and a relatively constant gas production. The constant gas production leads to an inflexibility related to seasonal adaptations in contrast to daily adaptations [30–32]. Table 2 provides an overview on the characteristics of the two clusters.

As the scenario for 2022 depends largely on the non-bioenergy-related elements of the power system, key scenario assumptions are given in Table 3. Here, the key capacities and energy figures for the different renewable power sources in the TransnetBW grid are given according to the scenario of the NEP for Germany by 2022 [6]. The NEP describes the measures that are required in

Table 2 Overview of typical characteristics and parameters for plants of the bioenergy clusters 1 and 2

Sample plant characteristics	Unit	Cluster 1	Cluster 2
Plant type	–	Wood-fired combined heat and power plant (solid biomass)	Biogas plant (biogas)
Rated capacity	[kW]	2500	330
Installed capacity (inflexible design)	[kW]	4750	430
Installed capacity (flexible design)	[kW]	6000	700
Share of flexible capacity (flexible design)	[%]	40	75

the next decade for designing a German electricity grid that can efficiently integrate the emerging renewable energy sources. Thus, a safe and reliable grid operation can be ensured.

The data of the NEP is chosen as reference for modelling the future development of RES, based on a 2-year time series data (2011/2012, see "Methods" section).

Specific to the TransnetBW transmission grid is the high share of solar PV regarding the projected capacity mix from renewables. sixty-eight percent of the overall projected installed capacity of renewables comes from solar PV, which is expected to provide a 36% share of the total energy produced from renewables in 2022. River hydro (25%), bioenergy (23.3%), wind power (12.1%) and other renewables (3.7%) contribute with minor shares to the overall renewable share of 35% in the region in 2022.

Methods

This paper is a follow-up on the publication of the 2015 book chapter [22] where a comparable approach was developed and applied to investigate the effects of flexible power generation from bioenergy for the 50Hertz transmission system in Germany for the years 2011 and 2030. Compared to the book publication, some minor refinements within the modelling have been included. BE technologies are now aggregated into two clusters. Moreover, the input data for the investigated TS differs in the investigated time horizon (2022 instead of 2011 and 2030). These differences may lead to limitations in the comparability of the results, which will be explained in greater detail in the "Discussion" section.

Table 3 Scenario framework for the case study including the three scenarios

Energy source	Year 2022	
	Capacity (CAP)	Annual energy production
	[MW]	[TWh/a]
Wind	1900	2.9
Solar PV	8900	8.6
River hydro	1000	6.0
Other renewables	200	0.9
Bioenergy		
Scenario NO-BE	0	0
Scenario NON-Flex-BE	639	5.6
Scenario Flex-BE		–
- Flexible solid biomass (cluster 1)	102	0.5
- Flexible biogas, liquid biofuel CHP (cluster 2)	530	2.2
- Remaining BE must run	333	2.9
Total		24[a]

[a]Based on the average demand from 2011 to 2012 of 68.4 TWh, capacity for 2011 from NEP 2012 2022B scenario [6], resulting in a REN Share of 27% in scenario NO-BE and 35% for NON-Flex-BE and Flex-BE

Modelling

The RL is calculated based on time series data (2011–2012) and the installed capacities for 2022, which are provided in Table 3. RL is defined as the total load minus feed-in from wind, solar, hydro and other renewables except of bioenergy. The use of historical feed-in and total load data with its variability over two climate periods (years 2011 and 2012) builds the basis for an extrapolation for RL of the modelling year 2022. This is done by using a normalizing and scaling approach of the feed-in from wind [33] and solar PV [34] that covers the build-up of new wind and solar PV capacities projected for 2022 (see Tafarte 2014 [35]). For river hydro and the category "other renewables", we assume a constant power production over time. The total load data of the TS is likewise provided by the transmission system operator [36].

For the scenario NO-BE, no modelling is applied, as we simply analyze the RL without any feed-in from bioenergy. The key figures of this scenario are presented in Table 5 in the "Results and discussion" section.

For the scenario NON-Flex BE, a constant feed-in of bioenergy (639 MW) is subtracted from the RL of scenario NO-BE, which is equivalent to an AEP from BE (5.6 TWh/a) over the course of 1 year (Eq. 1). No further modelling is applied.

$$\mathrm{RLB}_{(t)\text{NON-Flex}} = \mathrm{RL}_{(t)} - 639\,\mathrm{MW} \tag{1}$$

In the case of the Flex-BE scenario, the power production from the bioenergy plants is modulated in order to offset RL fluctuations. Therefore, an optimization algorithm that minimizes daily RL fluctuations is used [22, 37] which is implemented by the modulation factors m added to Eq. 1. Hence, the installed power generation capacity of the two bioenergy clusters is modulated in power output by the optimization algorithm in order to minimize daily variances in RL [22, 37, 38]. The algorithm enables bioenergy plants to contribute to use their flexibility in the Flex-BE scenario by shifting power generation from times of lower RL to times of higher RL, thus contributing to the balancing of power supply.

The operation of cluster 1 and cluster 2 is performed in sequence so that the resulting RL in the Flex-BE scenario is $\mathrm{RLBE}_{\text{flex combined}}$, calculated from $\mathrm{RLBE}_{\text{flex cluster 1}}$ and $\mathrm{RLBE}_{\text{flex cluster 2}}$:

$$\mathrm{RLBE}_{(t)\text{flex cluster 1}} = \mathrm{RL}_{(t)} - m_{(t)\text{cluster 1}} * \mathrm{CAP}_{\text{cluster 1}} \tag{2}$$

$$\mathrm{RLBE}_{(t)\text{flex combined}} = \mathrm{RLBE}_{(t)\text{flex cluster 1}} - m_{(t)\text{cluster 2}} * \mathrm{CAP}_{\text{cluster 2}} \tag{3}$$

$$\min \text{variances}\left(m_{(t)\text{cluster 1}};\, m_{(t)\text{cluster 2}}\right) = \sum_{t=1}^{24} \mathrm{RLBE}_{(t)\text{flex combined}} \tag{4}$$

The daily "variances" as a function of the two modulation factors "$m(t)$ cluster 1" and "$m(t)$ cluster 2" (Eqs. 2 and 3) are subject to minimization (Eq. 4) so that the modulation of power output of the two clusters is optimized in order to reduce the observed daily variances in RL. Key technical parameters of the two different clusters are provided in Table 4.

The parameterization of the bioenergy plant clusters, in particular, the annual electricity production and initially installed capacities, is derived from the current inventory of bioenergy facilities installed in Germany.

The operation of the two bioenergy technology clusters is performed in sequence so that the temporal more dynamic technologies of cluster 2 (biogas, liquid biofuel CHP) come second after the less dynamic cluster 1 (solid biomass). This is done to ensure that both clusters with their specific characteristic are not operated in a conflicting way but rather complementary. The parameterization and operation of both technology clusters are explained in the following:

Cluster 1 (solid biomass plants): Firstly, the combined installed capacity from solid biomass plants is modulated from 0.5 to 1.2 in 2-h time steps for each day of the 2-year time series, meaning that the combined installed capacity from cluster 1 is multiplied by the modulation factor m and subtracted from the RL time series. The modulation factor of 0.5 is applied as the minimum modulation factor of the combined installed capacities, as the current heat demand from CHP production and the conversion technology do not allow for a power output below 0.5 or 50% of the rated power. Additionally, as there is a lower heat demand in summer, the daily energy production during the summer time is reduced by 66% compared to the operation during winter.

Cluster 2 (biogas, liquid biofuel CHP): The combined installed capacity from the plants of cluster 2 is modulated from 0 to 1 but on the basis of the RL remaining after the feed-in from cluster 1. The installed capacity of cluster 2 already includes the upgrading of the plant with additional installed power generation sets. Lower average power demand on weekends is taken into account so that daily power production is reduced by 38% accordingly. No seasonal adaptation of the plants is modelled in cluster 2.

Results and discussion

Table 5 gives an overview over key results from the modelling of flexible bioenergy in the TransnetBW transmission grid for the year 2022.

The modelling results show how flexible production of bioenergy contributes to reduce variability of RL on a daily basis and to what extent maximal and minimal RL was affected in the three scenarios throughout the 2-year time series.

Scenario "NO-BE", which excludes any use of bioenergy from the power system, provides the baseline for a comparison to the scenarios "NON-Flex-BE" as well as "Flex-BE".

The contribution of bioenergy (8%) to the overall power consumption in the considered transmission system is

Table 4 Technical parameters for the flexible operation from cluster 1 and cluster 2 bioenergy plants

	Bioenergy technologies	
	Cluster 1 (solid biomass)	Cluster 2 (biogas, liquid biofuel CHP)
Modulation of power output	$m_{(t)}$cluster 1 = 0.5–1.2 in 2-h time steps	$m_{(t)}$cluster 2 = 0–1.0 in 1-h time steps
Operational constraints	• Constant daily energy production	• Constant daily energy production
	• No storage limitations for input materials affecting operation	• On-site biogas storage equivalent to 12–24 h in biogas production
	• Reduced daily production (−66%) during summer from April to October	• Reduced bioenergy production (−38%) on weekends assuming feeding management
Energy production	Annual energy production (AEP) remains constant for either non-flexible or flexible operation. AEP from biomass in 2022 taken from [NEP 2022B]	

Table 5 Overview of key results from simulated flexible and non-flexible bioenergy power generation in the case study

	Year 2022		
	NO-BE	NON-Flex-BE	Flex-BE
Renewable share (REN share)	26.8% (other renewables)	34.9% (other renewables + non-flexible bioenergy)	35.0% (other renewables + flexible bioenergy)
Variance in daily residual load	–	100%	70% (reduced by 30%[a])
Maximum positive RL (deficit power)	10,440 MW	9801 MW (100%)	9458 MW (reduced by 4%[a])
Minimum negative RL (excess power)	- 1965 MW	- 2604 MW (100%)	- 2362 MW (reduced by 11%[a])
Hours of negative RL	42 h/a	98 h/a	70 h/a
BE power production in times of negative RL	–	44.1 GWh/a	26.5 GWh/a (reduced by 40%)
Avoided BE power production in times of negative RL	–	–	17.6 GWh/a

[a]Percentages compared to “non-flexible” values

significant and reflects the third major renewable energy source after solar PV (13%) and river hydro (9%). Without bioenergy at all, the overall REN share reaches only 26.8% in the NO-BE scenario compared to around 35% in the two scenarios including bioenergy: a drop of about one fourth of the overall renewable energy production in 2022.

The average daily variance of the RL is reduced by 30% in the Flex-BE scenario compared to that of the NON-Flex-BE scenario, which is the primary target of the flexible BE modelled in this study. Maximum RL was likewise reduced by 4% and minimal RL by 11% for the Flex-BE scenario.

The REN share for the NON-Flex-BE and the Flex-BE scenario shows hardly any differences. Only a small amount of energy is produced from bioenergy in times of negative RL. In the NO-BE scenario, only 42 h of negative RL is registered during the 2-year time series. In the NON-Flex-BE scenario, this number is increased to 98 h as, additionally, the constant feed-in of 639 MW from non-flexible BE is fed into the grid. With a flexible operation of BE, the number of hours is reduced to 70 h as power production had been shifted into times of positive RL. Any production of bioenergy in the Flex-BE scenario at times of negative RL is due to operational constraints forcing bioenergy plants even in the flexible operation to continue to produce power (see Table 5). This translates into a reduction of BE produced during times of negative RL of 40%, equivalent to 17.6 GWh/a. Compared to the overall BE of 5.6 TWh/a available in the study area, the avoided production of BE in times of negative RL is negligible with 0.3%.

A detailed analysis of the temporal operation pattern shows how the flexible bioenergy plants adapt to fluctuations in RL. With RL, the result of the total grid load minus feed-in from renewables, characteristic patterns of load and feed-in from renewables can be identified in the operational patterns of flexible bioenergy provision. Figure 1 gives an example of how flexible operation is affected by these patterns.

The high feed-in from solar PV during a typical summer time load and feed-in situation leads to a low utilization of flexible bioenergy power production around noon. Modest load and high feed-in from solar PV results in a situation, in which bioenergy plants stop producing electricity and production is instead shifted into morning and evening hours of the day, when higher load is not offset by solar PV production.

When averaging the modulation factors for each of the 24 h of the day over the course of the 2-year time series and differentiating in winter and summer time, the seasonal differences in the daily modulation pattern of power output from cluster 2 can be mapped to cover the full 2-year time series and empirically underline the typical patterns shown in Fig. 1. These seasonal differences in the daily modulation pattern in the power output of cluster 2 (biogas plants and liquid CHP plants) are depicted in Fig. 2. In both seasons, summer and winter, a two-peak daily modulation of the cluster is observed, with a primary peak in the evening and a smaller peak in morning hours. This is to a large extent caused by both patterns of load profiles as well as feed-in patterns from vRES, especially from solar PV. In summer time, the very low average modulation of flexible BE during noon and a distinct gradient towards the evening peak is a result of this interplay of load profiles and feed-in from solar PV in the study area.

A comparison of average daily profiles of the RL of the NO-BE and the Flex-BE scenario is shown in the following Fig. 3, again differentiated for winter and summer time. First, it can be identified that summer time RL is on average lower than in winter time. Furthermore, the minimum of average RL occurs during midday during summer time, which is again an indicator for a strong influence of the significant installations of solar PV capacities in the study area.

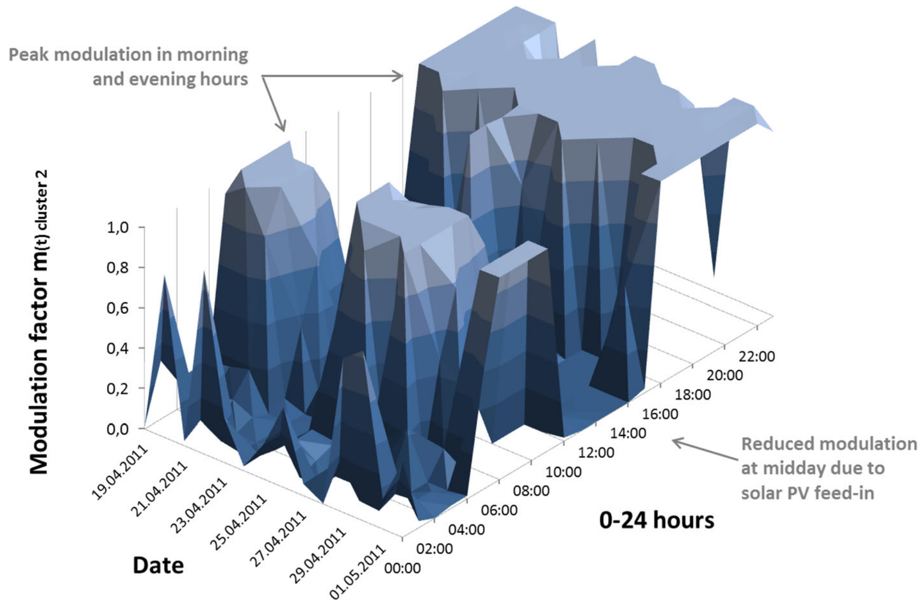

Fig. 1 Typical example for the modulation of power generation from cluster 2 during several days in spring time

In line with the modulation of flexible bioenergy generation shown in Fig. 3, the flexibility is used primarily in hours of high RL so that the daily variance of RL is minimized. The resulting average RL after flexible power generation (dashed line in Fig. 3) is therefore showing a reduction in the morning and evening peaks of the RL, whereas, for example during midday minimum RL situations, the lower average modulation leads to a comparably lower reduction in RL.

The following Fig. 4 depicts the residual load duration curve (RLDC) of the NO-BE, the NON-Flex-BE and the Flex-BE scenarios. Ordering the RL time series values of the 2-year time series in a descending order creates the duration curves. The highest RL value is located on the very left of the resulting graph and the lowest value on the right side.

Figure 4 shows the duration curves for the 2-year time series used for this study. For the NON-Flex-BE scenario, the duration curve is a simple parallel shift of the RL original duration curve, as a constant 639 MW is subtracted in every hour of the time series. This reduces the maximum RL as well as the minimum RL accordingly, as

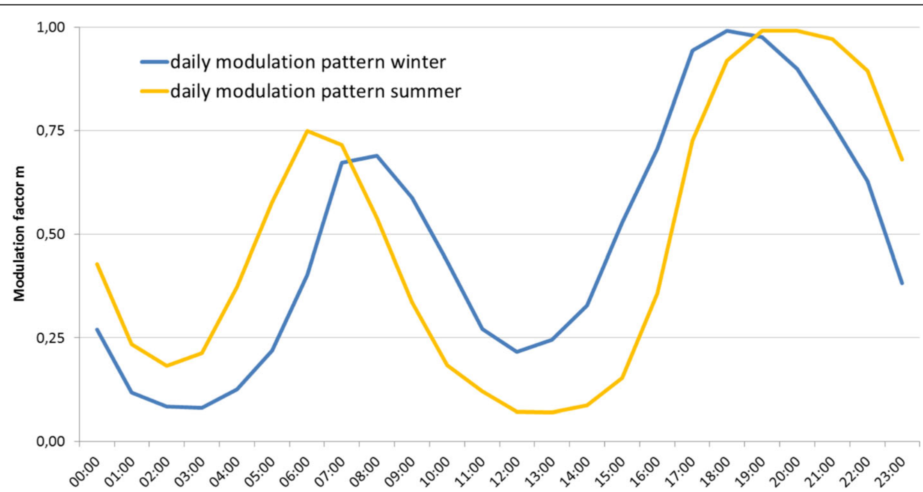

Fig. 2 Average modulation of cluster 2 (biogas plants and liquid CHP plants) over the course of the 24 h of the day, differentiated for winter and summer time. (Note the typical reduction of modulation at noon, especially pronounced in the graph depicting summer time modulation, caused by high solar PV feed-in; Additionally the earlier and later modulation peak during summer time compared to winter time)

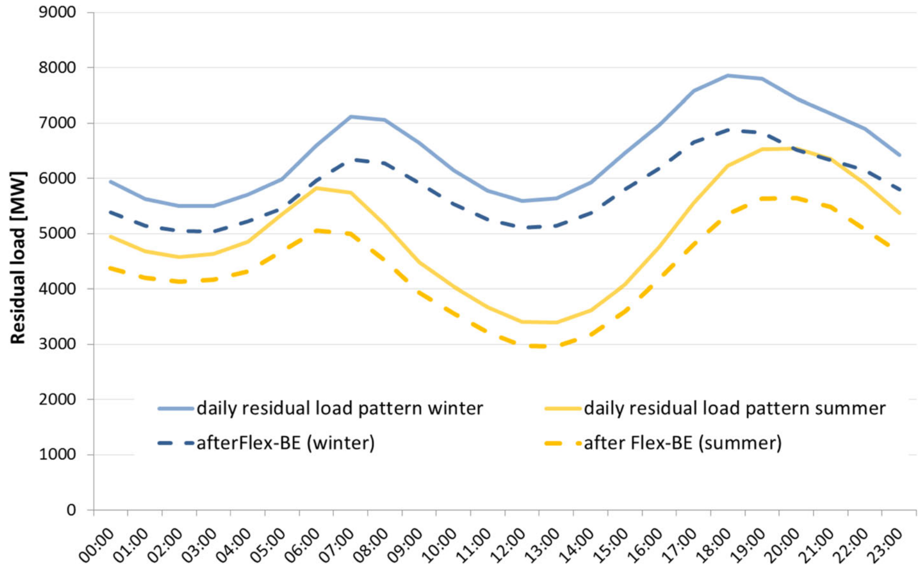

Fig. 3 Daily residual load before and after flexible power generation from biomass, differentiated for winter and summer time. (Note the reduced amplitude in average daily RL after flexible bioenergy power generation and the typical reduction of RL at noon in summer time which is partially caused by high solar PV feed-in)

already given in Table 5. The duration curve of the Flex-BE case is instead showing a slightly different form. As given in Table 5, the extreme values of maximum RL and minimum RL are improved with flexible operation of bioenergy plants in the modelled set-up. The reduction of the maximum RL is enabling a potential reduction in non-fluctuating plant capacity, which is currently mostly driven by fossil fuels and pumped hydro storage (PHS). The flexible operation mode enables a limited shift of power production (area between solid lines of the RL and shifting reflected by the arrow included in the figure) from times of low RL on the right side of the duration curve to times of high RL on the left. Furthermore, in the midrange of the RLDC, a slightly less pronounced declination of the curve can be identified (compare to [39]).

Apparent in the graphic as well as in Table 4 is the fact that RL in 2022 shows only marginal times in which RL for the grid area becomes negative (98 h/a in the NON-Flex BE scenario and 70 h/a in the Flex-BE scenario) or, in other words, times in which renewable production is greater than the total grid load. Accordingly, flexible operation of bioenergy can do little to avoid excess energy

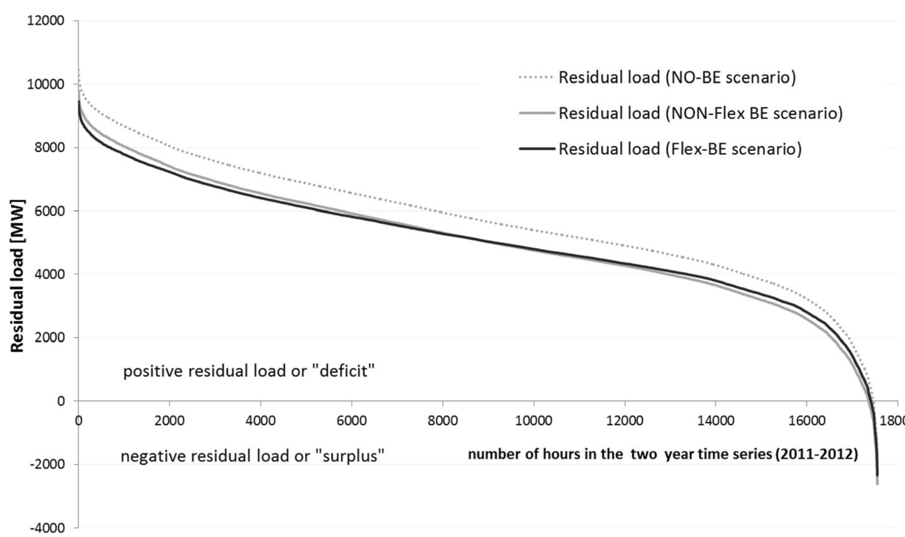

Fig. 4 Residual load duration curves (RLDC) for the TransnetBW grid network with flexible and non-flexible bioenergy (2022 installed capacities, 2-year reference period)

production by shifting bioenergy production into times of positive RL in this 2022 scenario, as basically the amount of vRES in 2022 and the REN share of only 35% are too low.

Discussion

In this study, we modelled flexible power provision from bioenergy (BE) for the year 2022 in the TransnetBW transmission system (TS) in Germany. Three scenarios were studied. The NO-BE scenario excluded the utilization of BE in the energy mix and served as a reference case. The NON-Flex-BE scenario investigated the effect of a constant production of BE as it has been the case for most BE power plants in recent years. The Flex-BE scenario included a modelling of a flexible BE provision. The BE plants in the Flex-BE scenario were grouped into two different technology clusters and these clusters were modelled in sequence using a rolling optimization of a 24-h time horizon with the objective function of a minimized daily variance of RL fluctuations.

In line with existing publications [15, 17, 22, 40], the results from this case study underline the principal usefulness and functionality of flexible BE in power systems with high shares of vRES. Compared to a similar study for a different transmission system 50Hz in Germany for the time horizon 2011 and 2030 [22], the results of the study on hand show similarities as well as some significant differences in the effect of a flexible operation of biomass installations on the power system. Due to the fact that the REN share in the TransnetBW TS for the year 2022 (35%) is comparable to the REN share in the 50Hz TS in 2011 (36%), these two time horizons allow for an adequate comparison of the two studies. The relative share of BE which is avoided to be produced in times of negative RL is similar in both cases, but the minimization of daily variances as the objective function of the modelling was achieved to a higher degree in the 50Hz TS (−56% relative to the NON-Flex scenario) compared to that in the TransnetBW TS (−30% relative to the NON-Flex scenario). Either it can be argued that this is the result of a higher relative share in installed power and generated energy from bioenergy for the 50Hz TS, which allows for a greater reduction in RL variances. Or it is likewise plausible that this is caused by the higher relative share of solar PV in the TransnetBW TS within the overall REN share, as the high variability of solar PV feed-in leads to a higher variability in RL that cannot be fully compensated by flexible BE provision. An in-depth investigation for an explanation of these findings is needed to identify how flexible BE adapts to different scenario settings.

Another indicator for the usefulness of flexible BE is the fact that the increased installed capacities from BE (343 MW) in the Flex-BE scenario were fully utilized to reduce the maximum RL over the course of the 2-year time series data.

The amount of avoided BE production (17.6 GWh/a or 0.3% of annual BE) in times of negative RL can almost be neglected for the 35% REN share in the Flex-BE scenario of the TransnetBW TS in 2022. So, although today's technical concepts for flexible BE allow for a good adaptation to the vRES feed-in patterns for 2022 in the TransnetBW TS, the limited overall amount of excess energy from renewables is indicating that there is little requirement for flexibility to avoid excess energy in the near-term. This is largely due to the modest REN share of the TransnetBW TS in 2022.

Conclusions

We conclude that operating biomass installations in a flexible manner effectively reduce the maximum RL values as well as RL fluctuations on a daily basis in a transmission system. The additionally installed capacities in the Flex-BE scenario have been fully utilized in the modelling to reduce maximum RL over the course of the 2-year time series. Hence, the technical concepts for a flexible power provision proved to be effective with regard to their contribution to one aspect of power system functionality and power supply security.

In contrast to the other German transmission systems, the overall REN share is fairly low within the investigated TransnetBW TS and the projections (35% in 2022) revealed that the REN share continues to lack behind the national REN targets for Germany. As a consequence, the effect on avoided BE power production in times of negative RL is negligible in the calculated scenario, as REN shares are too low to result in a significant share of BE being produced in times of negative RL. So, next to being a future flexibility option, the contribution of BE with a 23.3% share within the renewable mix remains a priority in the coming years for the TransnetBW TS in order to achieve the set renewable targets. Consequently, for regions with a low REN share in power supply and a reduced demand for flexibility options, we suggest that BE should primarily be utilized in the most efficient way in order to maximize its contribution to the REN share in these regions. Maintaining a high efficiency in BE power production and utilization, for example through a combined heat and power production mode, is therefore one crucial element for the BE utilization in the near-term.

Efficiency should be the top priority until the demand for flexible BE provision is progressively increased with rising overall REN shares and vRES shares in power supply. Giving the regional differences regarding this aspect, it should be stressed that the regional context, the relative share of wind and solar PV in the power system and therefore the investigated time horizon are important for defining the role of flexible BE in the years to come. So that for this case study region in the near-term outlook for 2022, the largely undebated potential for flexible BE as a flexible asset in future power systems with high shares of vRES [17, 41] is not immediately required on a regional perspective for a region with a low overall REN share as investigated in this case study.

The results of the study highlight that further research on the interplay of various integration options and scenario settings is crucial in order to assess the effect of flexible BE on future power supply systems with growing shares of fluctuating renewables. And it must be pointed out that the full set of flexibility options and their interplay has not been modelled and only the interplays of total load, feed-in from renewables and flexibility of BE in the modelled setup were investigated, what is certainly a limitation to the transferability of the presented results. Furthermore, must-run capacities from thermal power stations and interconnectors, which may significantly influence the effects of a flexible operation of biomass installations on the power system, have not been included in the presented modelling.

Abbreviations

ABP: Agricultural biogas plant; AEP: Annual energy production; BE: Bioenergy; CHP: Combined heat and power; Flex-BE: Flexible bioenergy provision; NO-BE: No bioenergy scenario; NON-Flex-BE: Non-flexible bioenergy provision; PHS: Pumped hydro storage; REN share: Renewable share; RL: Residual load; RLDC: Residual load duration curve; Solar PV: Solar photovoltaics; TS: Transmission system; TSO: Transmission system operator; WCHPP: Wood-fired combined heat and power plant

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Authors' contributions

PT carried out the data collection, preparation and processing and the major parts modelling and contributed to the results, discussion and conclusion section as well as to the overall study design. CH carried out the introduction section and contributed to the discussion and conclusion section as well as to the overall study design. MD provided the bioenergy plant clustering in the modelling section. DT contributed to the discussion and conclusion section as well as to the overall study design. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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Publication Six

Complementing Variable Renewable Energies with Flexible Bioenergy

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Chapter 9
The Potential of Flexible Power Generation from Biomass: A Case Study for a German Region

Philip Tafarte, Subhashree Das, Marcus Eichhorn, Martin Dotzauer, and Daniela Thrän

Abstract Energy scenarios and roadmaps indicate that intermittent renewable energy sources such as wind power and solar photovoltaic (PV) will be crucial to the power supply in the future. However, this increases the demand for flexible power generation, particularly under conditions of insufficient wind and/or solar irradiation. Among the renewable energy sources, bioenergy offers multiple end-use in the form of power, fuel or heat. Biomass-based power combines the advantages of being renewable, exceptionally CO_2 neutral and supporting demand-oriented production.

This chapter analyses four energy scenarios for Germany, focusing on the relevance of flexible bioenergy therein. Depending on how the scenarios are constructed, the range of biomass potential in the energy system is 1,180–1,700 PJ/a. The following sections of the chapter investigate the potential of flexible power generation from biomass on a regional scale (50 Hertz grid) starting with a description of the current state of bioenergy generation in the region and its potential for supplementary heat provision. We model the contribution of flexible biogas and solid biomass power using a minimization of daily residual load variance as a goal function. Two points in time are modeled – 2011 and 2030 to include the current and projected

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installed capacity from wind and solar PV. The results indicate that depending on the framework conditions, flexible bioenergy inclusion can reduce the daily variance in the residual load by >50 % compared to a non-flexible system. We conclude that flexible bioenergy has significant potential to contribute to balancing the power system with increasing shares of intermittent sources such as wind and solar PV.

9.1 Introduction

The previous chapters focused on the need for flexible bioenergy generation, resource availability, sustainability and environmental impact issues. This was extended by an overview of the available technologies and their potential for flexible energy generation from solid, liquid and gaseous biomass.

In this chapter, the potential for flexible power generation from biogas as well as solid biomass and its effect on the power supply system are demonstrated for a case study region – the area of the 50 Hertz transmission grid operator. The first section introduces some prominent examples of national energy scenarios. We focus on the role of bioenergy and the handling of fluctuations in the power supply within these roadmaps of energy transition. We demonstrate that there is still no silver bullet in sight at the moment and that several options remain possible. In Sect. 9.3 the study region with its current state of bioenergy use and its potential for supplementary heat use are illustrated. This forms the basis for the calculations in Sect. 9.4 which presents a numerical analysis of the contribution of biomass to flexible power generation in the study area followed by conclusions in Sect. 9.5.

9.2 Long-Term Potential for Flexible Bioenergy Generation

The biomass potential as discussed in previous chapters shows the upper limits for bioenergy provision. Further, it was explained that biomass is currently the only renewable source that contributes to all energy sectors e.g. power, heat and fuel and that bioenergy can be generated on demand with a short response time, enabling the balance of variable renewable sources (vRES) such as wind and solar photovoltaic (PV). However, from the scientific as well as the political perspective there is currently no consensus about the preferable end-use or function of biomass in the energy system.

Since the infrastructure of energy is fairly expensive and it is usually expected that it will serve for long time periods, e.g. up to 50 years for lignite or coal power plants, decision-makers usually base their decisions on sound scientific evidence. Scientific tools commonly used for the development and description of future energy systems are ‘Energy Scenarios’. Energy scenarios at the national and/or international level have been developed and published since the 1970s [8]. By content, energy scenarios cover the impacts of individual political decisions on regional

Table 9.1 Overview of energy scenarios

Study title	Year	Name/Abbreviation	Institutes
Klimaschutz: Plan B 2050 – Energiekonzept für Deutschland [4]	2009	Greenpeace	Eutech Energie und Management GmbH
Modell Deutschland Klimaschutz bis 2050: Vom Ziel her denken [9]	2009	WWF	Institut für angewandte Ökologie ÖKO-Institut e.V., Prognos AG
Energieszenarien für ein Energiekonzept der Bundesregierung [12]	2010	BMWI	Prognos AG
			Energiewirtschaftliches Institut an der Universität zu Köln (EWI)
			Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS)
Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global – Leitstudie 2011 [11]	**2012**	**Leitstudie**	Deutsches Zentrum für Luft- und Raumfahrt (DLR)
			Institut für Technische Thermodynamik, Abt. Systemanalyse und Technikbewertung
			Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES), Ingenieurbüro für neue Energien (IFNE)

and national energy systems up to changes and developments of the global energy supply system [8].

In order to get the full picture of the potential of bioenergy for flexible power generation, it is important to consider existing energy scenarios. Energy scenarios exist for Germany at the national scale [10, 14]. Some of them also consider a high share of fluctuating renewable resources; four of those recent and most prominent scenario studies (see Table 9.1) are briefly presented here.

9.2.1 Potential and Sector-Wise Distribution Under the Scenarios

Table 9.2 gives an overview of the expected sustainable primary energy potential of biomass under the scenarios. The results of the studies are relatively similar to one another in the range of 1,180–1,700 PJ/a, if import is excluded. This could be partially due to the fact that most of the scenarios (Leitstudie, Greenpeace and WWF) were basically based on the same fundamental literature [5].

The primary energy potential of bioenergy is distributed to different end-uses, separated into fuel for transportation, heat and the power supply. In 2010 about 30 % of the primary energy consumption was used for power, about 60 % for heat

Table 9.2 Sustainable bioenergy potential under the scenarios

	Leitstudie	BMWi	Greenpeace	WWF
Potential	[PJ/a]	[PJ/a]	[PJ/a]	[PJ/a]
Residue	800	NA	NA	700
Import	0	500	0	500
Others[a]	750	1,700	1,180	500
Total	**1,550**	**2,200**	**1,180**	**1,700**

NA not applicable
[a]E.g. energy crops, short rotation coppice, forest biomass

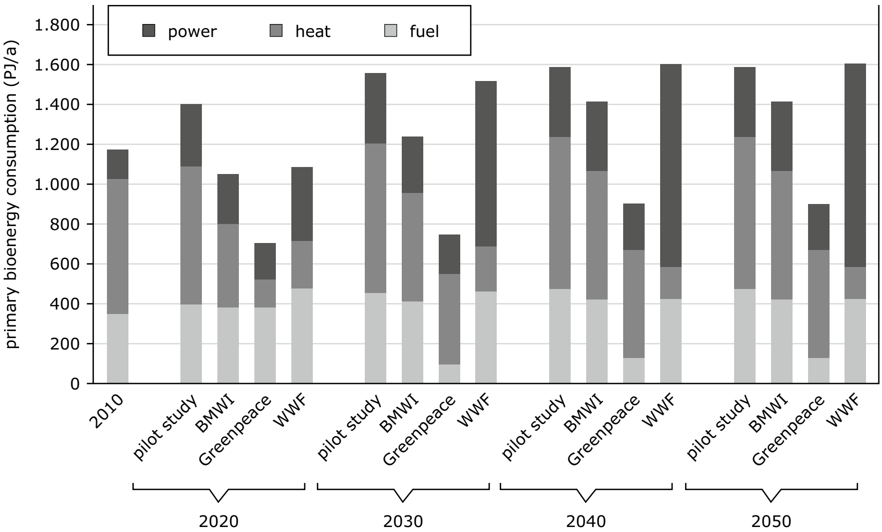

Fig. 9.1 Comparison of primary bioenergy consumption under relevant national scenarios (Based on personal communication with Julian Braun, DBFZ, 2013)

and 10 % for fuels [11]. However, under the scenarios, different development pathways with respect to the sectorial distributions of biomass are enumerated. This is basically due to a difference in the definitions of the sustainable application of biomass under framework conditions.

In Fig. 9.1, the contribution of primary bioenergy to the three sectors for a reference year 2010, as well as for the years 2020, 2030, 2040 and 2050 are displayed for comparison. Here, total and sectoral primary bioenergy consumption is compared under different scenarios. As it can be clearly seen in the figure, the scenarios differ with respect to power, heat and fuel consumption. The Greenpeace study which has a stronger focus on ecological aspects consistently allocates a lower (~ one-third) primary energy consumption of biomass compared to the other studies.

Against the above background, it can be concluded that only a small proportion of biomass is considered for power generation in the future. The following paragraphs clarify how the afore-mentioned studies deal with fluctuations and the specific role of bioenergy.

9.2.2 Flexible Power Generation Options Under the Scenarios

To compensate for fluctuations in feed-in from intermittent sources such as wind and photovoltaic, three options have been considered under the afore-mentioned scenarios: demand-side management, storage and instantaneous generation. Under the scenarios these options have been treated differently. In the following paragraphs, we discuss an instantaneous generation of power on demand, henceforth referred to as 'guaranteed capacity'.

Within the BMWI study, 50–70 GW guaranteed capacity has been calculated for the generation of balancing power. The largest contribution (~88–91 %) is provided by natural gas power plants and Carbon Capture and Storage (CCS) coal power plants. Biomass only contributes with 6 GW guaranteed capacity. However, full load hours of 6,500–6,800 h indicate that biomass plants operate in base load mode and are not managed for demand-oriented functioning.

As [11] shows, the expected guaranteed capacity is 68–77 GW. The main fraction of balancing power is foreseen to come from Combined Heat and Power (CHP) plants ─ both fossil-fuel driven as well as those fired by gaseous biofuels such as Biogas or Biomethane. Two pathways are considered in [11] with respect to the use of biogenic gaseous energy carriers. Firstly, the feed-in into the existing natural gas net for power and heat generation in large CHP plants and secondly the on-the-spot conversion to power whenever balancing power is required. For the latter option, modifications of existing bioenergy plants are necessary e.g. an increase in the installed capacity and storage capacity. The effects of a flexible on-the-spot conversion concept on the power system will be highlighted in the case study in Sect. 9.4.

The Greenpeace study mentions the challenges of tackling fluctuations in wind and solar PV, but it does not provide explicit quantifications. The WWF study calculates a guaranteed capacity of 59–61 GW depending on the scenario assumptions. This guaranteed capacity is separated into contributions from renewable sources plus imports (23–27 GW), conventional sources (mainly natural gas) and storage (34–36 GW). It does not explain however the exact contributions of the individual renewable energy sources.

Conclusively, a comparison of the studies on various scenarios shows that the role of biomass is more diverse than that of the other renewables but has not been discussed in detail along with its implications. The role of biomass in these studies is seen as ranging from base load operation mode for mainly heat and power production to a flexible source for balancing fluctuations in intermittent renewable sources (e.g. wind and solar). To use the specific advantages of bioenergy for balancing power grids, more information about the effect of flexible generation from biomass is needed. For such a smart bioenergy provision to be integrated into the overall energy system it is important to consider the regional framework condition, including the current state of bioenergy plants in operation, the demand for power and heat and the electricity grid situation. In the following (Sect. 9.3), we present a discussion of the current state of bioenergy plant distribution and the heat potential thereof followed by Sect. 9.4 which gives an example of the system effects of flexible power generation from biomass as a case study of the 50 Hertz Grid operator area in eastern Germany.

9.3 Regional Aspects of Bioenergy

This section introduces the study region for which flexible power generation from bioenergy has been modelled in the following sections. The study was conducted in eastern Germany. Geographically, the region covers seven German federal states (Hamburg, Berlin, Brandenburg, Saxony, Saxony-Anhalt, Thuringia, Mecklenburg-Western Pomerania) covering a total area of 109,340 km^2. The area is operated by 50 Hertz Transmission GmbH, which functions as the Transmission System Operator (TSO) serving about 21 % of the German population [15] (Fig.9.2).

In a classical energy supply chain, centralized systems played a major role. However, a high level of integration makes centralized systems vulnerable to changes within the supply chain. Decentralized systems, as a model of supply infrastructure, are less vulnerable to the availability of remote generation and transmission networks [6]. Furthermore, the demand for flexible power generation in a changing energy system with a high proportion of intermittent renewable sources (wind and solar PV) reaches the limits of possibilities offered by centralized fossil fuel power plants. Centralized systems are usually developed to operate at nominal capacity throughout the year which does not allow them to follow the high load gradients demanded by the feed-in of intermittent renewable sources. Flexible bioenergy is therefore emerging as a good option due to two main advantages (i) utility in decentralization mode and (ii) the ability to follow load gradients (e.g. power generation from biogas). However, the introduction of flexibility concepts to the bioenergy sector is also highly dependent upon regional or local aspects of energy production. Spatial aspects of current infrastructure are also crucial for establishing flexible energy systems at regional scales.

In the selected 50 Hertz region, the total number of plants (including biogas, solid biomass and biofuel plants) is 1,773 (2011). The total installed capacity in the region is ~1,365 MW with an average of 769 kW. The spatial distribution of these plants is shown in Fig. 9.3 while Table 9.3 shows the distribution of plants.

CHP plants primarily serve electricity production, however, heat, which is a by-product of the process may also be used e.g. for district heating. When introducing

Fig. 9.2 Transmission Network Operators in Germany

flexible options it is relevant to address the potential of district heating from biogas, since both flexibility and heat demands have temporal dimensions. Further, the spatio-temporal consideration of heat sinks in the design and implementation of flexible plants may be valuable in reducing storage requirements.

A further investigation into the biogas facilities installed in Saxony showed that currently these plants are driven by electricity demand and provide base load, thereby using only a minor proportion of the produced heat [7]. Results indicated that the total heat supply potential from biogas plants in the region is around 290 GWh (i.e. ~15 % of the heat demand in the region could be potentially fulfilled from bioenergy plants). The study identified a strong limitation due to a lack of demand centers around the plants with respect to housing infrastructure. About 40 % (194 GWh) of the heat that was theoretically available for supply faced geographical constraints for further use in district heating systems, because the plants are located too far away from the demand centers. However, in certain cases heat provision can act as a constraining factor for flexible power generation.

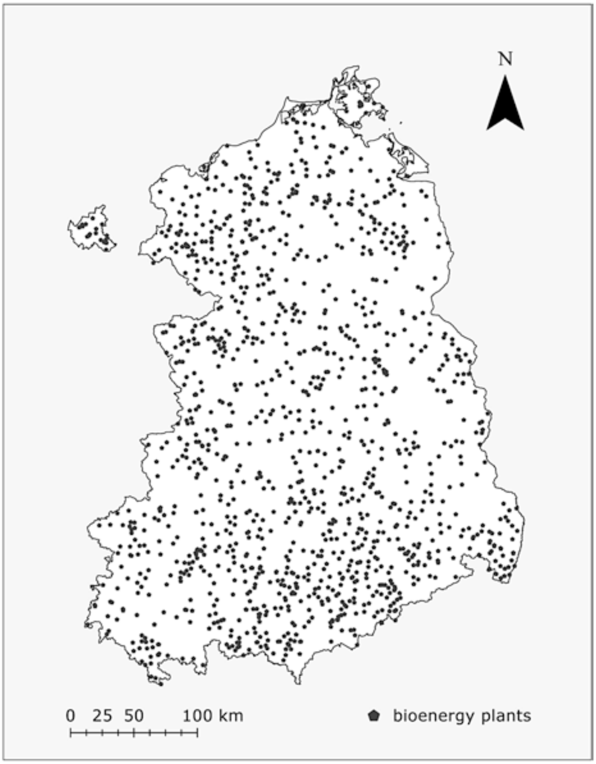

Fig. 9.3 Regional distribution of bioenergy plants

Table 9.3 Distribution of bioenergy plants in the 50Hertz grid region

Range of installed capacity (kW)	Number of plants	Total installed capacity (MW)
<500	1,006	307
501–1,000	643	391
1,001–3,500	81	137
3,501–45,000	10	46
5,001–10,000	17	108
>10,000	16	373
Total	**1,773**	**1,364**

Based on [1]

9.4 Complementing Variable Renewable Energies with Flexible Bioenergy

In the following paragraphs, the effect of flexible power generation from bioenergy to balance fluctuations in the electricity supply is demonstrated as a case study. To assess the balancing potential on fluctuations from variable renewable energy sources such as wind and solar photovoltaic (PV) as well as fluctuations of power demand, flexible bioenergy power generation is modelled for one of the four German power transmission grids, operated by 50HertzTransmission GmbH (50Hertz). Based on 3-year time series data for demand and feed-in from wind and solar, the effect of flexible bioenergy power production can be compared to current non-flexible bioenergy power generation. Residual Load (RL), calculated as the difference between the demand and supply from wind and photovoltaic forms the basis for modelling bioenergy power provision.

Since both demand and feed-in from wind and solar PV fluctuate, the compensation of the RL has to balance out these fluctuations for a stable power supply system. In contrast to non-flexible power production from bioenergy, flexible bioenergy generation is expected to contribute to the balancing of the power system, especially in cases of substantial shares of fluctuating renewable energy sources without any major power storages, e.g. large pumped hydro-storage systems.

Apart from assessing the effects of either flexible or non-flexible bioenergy power generation we also provide a scenario for the projected increase in installed capacities from wind and solar PV for 2030. The framing conditions for 2030 (installed capacities, annual energy power production and power demand) are adapted versions of [11]. Table 9.4 presents a comparison between 2011 and 2030 parameters. Two bioenergy technologies (biogas and solid biomass) are modelled, because they account for more than 90 % of the installed bioenergy capacity in the 50Hertz grid (see Sect. 9.3).

9.4.1 Model Description

Based on the time series data from 2009 to 2011 [3] the RL is calculated from the capacity given in Table 9.4 by a proportional scaling of the feed-in from wind and solar PV power plants. Feed-in from all bioenergy plants was simulated for two modes: (i) non-flexible power production and (ii) flexible power production. The

Table 9.4 Scenario conditions for the case study

	Year 2011		Year 2030	
	Capacity (CAP)	Annual energy production	Capacity (CAP)	Annual energy production
	[MW]	[TWh/a]	[MW]	[TWh/a]
Wind	11,719	18	17,979	41
Solar	4,070	3	10,005	9
Bioenergy	1,460[a]	9	2,435	15
Solid biomass	861[a]	5	1,552	9
Biogas	599[a]	4	883	6
Total	**17,249**	**30** (~36 % of demand[b])	**30,419**	**65** (~76 % of demand[b])

[a]Based on the average demand from 2009 to 2011 of 84 TWh, capacity for 2011 from 50Hertz plant data [2], capacity for 2030 derived from [11]

[b]Demand for 2030 falls by 10 % as projected by [11], 6.8 TWh of energy from wind and solar are considered to be excess energy in 2030

differences between non-flexible versus flexible power generation from bioenergy have been studied with a minimum temporal resolution of 1 h. The results from these simulations were compared to estimate the contribution of either mode to the reduction in fluctuations of RL.

To capture the effect of non-flexible bioenergy power production on RL, a constant feed-in of bioenergy is subtracted from the original RL resulting in a new RL after compensating for bioenergy ($RLB_{(t)non\ flex}$). In this case the value of "const" is equal to 1 so that no flexible operation of the bioenergy power generation capacity is possible.

$$RLB_{(t)nonflex} = RL_{(t)} - const * \left(CAP_{solid} + CAP_{biogas}\right) \tag{9.1}$$

CAP = installed capacity of either solid or biogas plants.

In the case of flexible power generation, the power production is enabled to adapt to RL fluctuations by allowing the optimization algorithm to modulate the power generation. This is realized by introducing the modulation factor "m" which scales the power generation of the capacity from bioenergy plants, so that a minimization of daily variances in RL is achieved [13]. This modulation forces power generation from bioenergy to contribute to the balancing of the power supply and demand by shifting flexible power generation from times of lower RL to times of higher RL.

On a daily basis, power from bioenergy is provided at times of high RL and reduced at times of relatively low RL throughout the time series from 2009 to 2011. As the flexible operation is modelled in sequence for the two different technologies (solid biomass and biogas), the resulting RL after the introduction of flexible bioenergy generation from $RLB_{flex\ solid}$ and $RLB_{flex\ biogas}$ is $RLB_{flex\ combined}$:

$$RLB_{(t)flexsolid} = RL_{(t)} - m_{(t)solid} * CAP_{solid} \tag{9.2}$$

$$RLB_{(t)flexcombined} = RLB_{(t)flexsolid} - m_{(t)biogas} * CAP_{biogas} \tag{9.3}$$

$$min\,variances\left(m_{(t)solid}; m_{(t)biogas}\right) = \sum_{t=1}^{24} RLB_{(t)flexcombined} \tag{9.4}$$

The "variances" as a function of the two modulation factors "m(t) solid" and "m(t) biogas" are subject to minimization in this modelling for the 24 h of each day throughout the time series.

The details of the parameterization of the model are described in the following paragraphs. The key technical parameters are provided in Table 9.5.

The operation of solid biomass and biogas capacity is modelled in sequence to improve the combined effect of the different flexibility potential from both bioenergy technologies. Setting the more dynamic biogas capacities second after the less dynamic solid biomass capacities should ensure that the characteristics of both technologies are not operated in a conflicting way but rather in a complementary

Table 9.5 Technical parameters for the flexible operation of power generation from solid bioenergy and biogas plants

	Bioenergy technologies	
	Solid biomass	Biogas
Modulation of power output	0.5–1 in 2 h time steps (0.5–1.2 for 2030)	0–2 in 1 h time steps
Operational constraints	Constant daily energy production	Constant daily energy production
	No storage limitations for input materials affecting operation	On-site biogas storage equivalent to 12–24 h in biogas production
	Reduced daily production (−20 %) during summer from April to October	Reduced biogas production (−25 %) on weekends assuming feeding management
Energy production	Annual Energy Production (AEP) remains constant for either non-flexible or flexible operation. AEP from biomass in 2030 taken from [11]	

interplay. The parameterization and operation of either technology is explained in the following:

1. Solid Biomass Plants: The combined installed capacity from solid biomass plants is first modulated from 0.5 to 1 (0.5 to 1.2 in the 2030 case) for every 2 h time step of the time series, meaning that the combined installed capacity from solid biomass plants is multiplied by the modulation factor and subtracted from the RL time series. A modulation factor of 0.5 is applied as the minimum modulation factor as heat demand from CHP production and standard conversion technology currently does not allow for a power output below 0.5 or 50 % of the rated power. The lower heat demand in summer is taken into account by a reduction in daily energy production by 20 % compared to the operation during winter.
2. Biogas Plants: The combined installed capacity from biogas plants is modulated from 0 to 2 on the basis of the RL after the feed-in from solid biomass plants (as above). The maximum modulation factor of 2 points out that the installed capacity can provide twice the power output to allow for a more flexible production compared to the current almost constant modulation factor of 1. The constraint of a maintained overall daily production together with the modulation factors of 0 to 2 implies a maximum storage capacity on site for 12–24 h, although no detailed storage modelling is performed.

   On weekends with a generally lower power demand, the daily production of biogas and consequently power and heat production is reduced by 25 % assuming a feeding management of the biogas digester.

Since the most common operation mode in bioenergy plants is CHP, the given parameterization of the modeling allows for bioenergy plants to operate throughout the year to maintain a high utilization of heat without the necessity to deploy increased heat storage facilities.

9.4.2 Results

The results presented in this section correspond to the capacity provided in Table 9.4 (1,460 MW in 2011 and 2,435 MW in 2030 for bioenergy). The calculations were based on the time-series of 2009–2011 for RL and feed-in from wind and solar PV. The combined results from a flexible operation of solid bioenergy and biogas capacity are presented in Table 9.6.

The results demonstrate that flexible bioenergy production improves maximum and minimum RLs and variance in daily RL for both 2011 and 2030 cases. The flexible bioenergy generation enables a significant reduction of the variance in daily RL by 56 % for 2011 and 54 % for 2030 compared to the non-flexible reference. This leads to a significant reduction in load variations for the remaining non-renewable power generation system. It reduces the maximum RLs compared to a non-flexible operation by 7 % (2011) and 12 % (2030) compared to the 2011 level for non-flexible operation selected as the reference (100 %). As a result, this directly contributes to reductions in power plant capacity to provide the remaining residual power production. Likewise, the minimum RL or excess power is reduced, avoiding power production at times when power generated from wind and solar already completely meet the demand for power.

A closer look at the temporal operation patterns for the flexible bioenergy plants reveals that the modulation of power output adapts to the short-term production patterns of variable renewable energy sources as well as fluctuations in demand. As shown in Fig. 9.4, the power production of the solar PV installations

Table 9.6 Overview of the results from simulated flexible and non-flexible bioenergy power generation in the case study

	Year 2011		Year 2030	
	Non-flexible operation	Flexible operation	Non-flexible operation	Flexible operation
Variance in daily residual load	100 %	Reduced by 56 %[a]	100 %[a/**]	Reduced by 54 %[a]
Maximum residual load (deficit power)	12,499 MW (100 %)	11,651 MW (reduced by 7 %[a])	10,343 MW (100 %[a])	9,047 MW (reduced by 12 %[a])
Minimum residual load (excess power)	3,980 MW (100 %)	3,352 MW (reduced by 16 %[a])	13,536 MW (100 %[a])	12,538 MW (reduced by 7 %[a])
Bioenergy power production in times of excess power	176 GWh/a	118 GWh/a	11,010 GWh/a	10,021 GWh/a
Avoided bioenergy power production in times of excess power by flexible operation	–	58 GWh/a (reduced by 33 %)	–	990 GWh/a (reduced by 9 %)

[a]Percentages compared to "non-flexible" values
[**]The high levels for 2030 figures are caused by fluctuation from increased vRES capacities

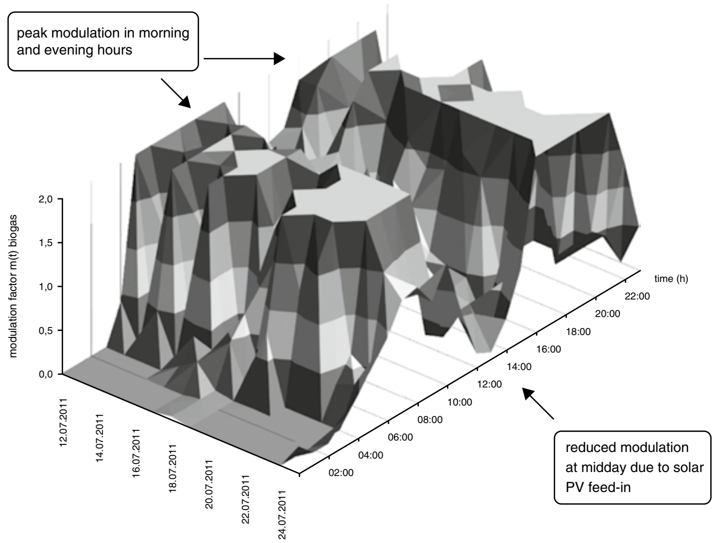

Fig. 9.4 Example for the modulation of biogas power generation in high insolation conditions

(4,070 MW/10,005 MW in 2011/2030) is responsible for the reduced RL at midday in high insolation conditions, leading to a low utilization of flexible bioenergy power production. Bioenergy power generation is instead shifted to provide maximum power production in morning hours and late evening hours when high demand cannot be met by solar PV.

Figure 9.5 depicts seasonal patterns of the effect of flexible bioenergy production on average daily RL before (solid lines) and after (dotted lines) the feed-in from flexible power production. The resulting RL shows a significant reduction in the average daily RL amplitude compared to the original RL.

Figures 9.6 and 9.7 show the duration curves for the simulated time series projected for 2011 and 2030. These duration curves are created by ordering all hourly RL values of the 3-year time series in a descending order, so that the highest RL value is located on the very left of the graph and the lowest value on the right side.

As shown by the duration curves, the flexible operation of bioenergy plants in the modelled set-up allows for a limited shift of power production (grey area between solid lines of the RL) from times of lower RL on the right side of the duration curve to times of higher RL on the left. This not only helps to reduce negative RL (excess power) from renewable energy, but also reduces maximum positive RL (deficit power), enabling a reduction in non-fluctuating plant capacity, which is currently mostly driven by fossil fuels.

The comparison of the duration curves of the RL in 2011 and 2030 reflects how a substantial increase in capacity for wind and solar power has an impact on the RL distribution. The overall duration curve shifts so that instead of a mere 120 h per year of negative RL (excess power) for 2011, over 2,000 h of negative RL per year are calculated for 2030. The maximum negative RL (excess power) over the 3 year

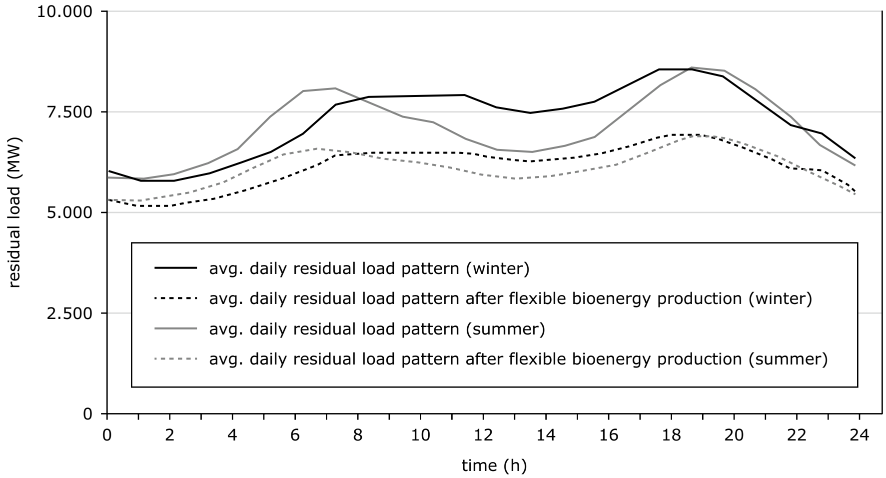

Fig. 9.5 Reduced amplitude in average daily RL after flexible bioenergy power generation, differentiated for winter and summer (2011 installed capacity) (Note: typical reduction of RL at noon in summer time, caused by high solar PV feed-in)

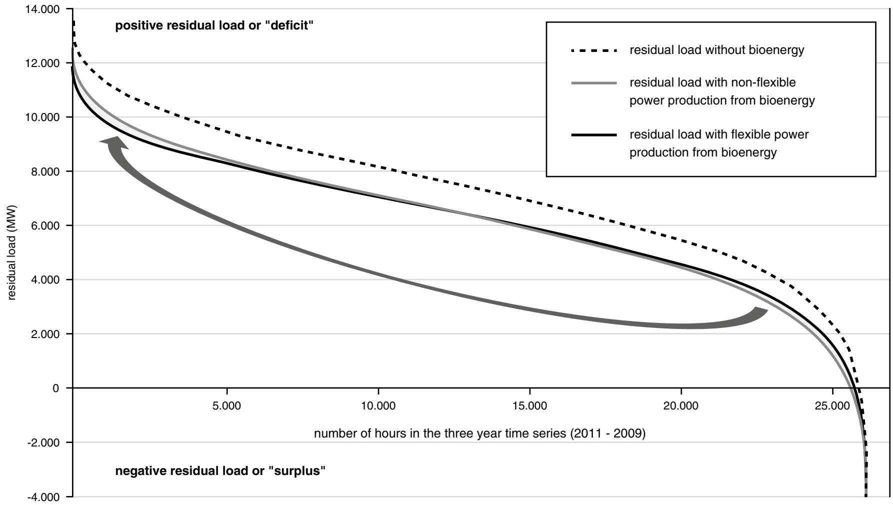

Fig. 9.6 RL curves for the 50Hertz grid network with flexible and non-flexible bioenergy (2011 installed capacity, 3-year reference period)

time-series increases from 3,980 MW (2011 capacities) to 13,536 MW (2030 capacities) (see also Table 9.6). This reflects an overall increase in capacity of variable power production from wind and solar PV. For flexible bioenergy, the consequence is that the demand for flexibility to complement these increased fluctuations will likewise increase. For example, power production from biomass has to be increasingly shifted over longer periods when prolonged periods of high power production from wind and solar are already serving the power demand.

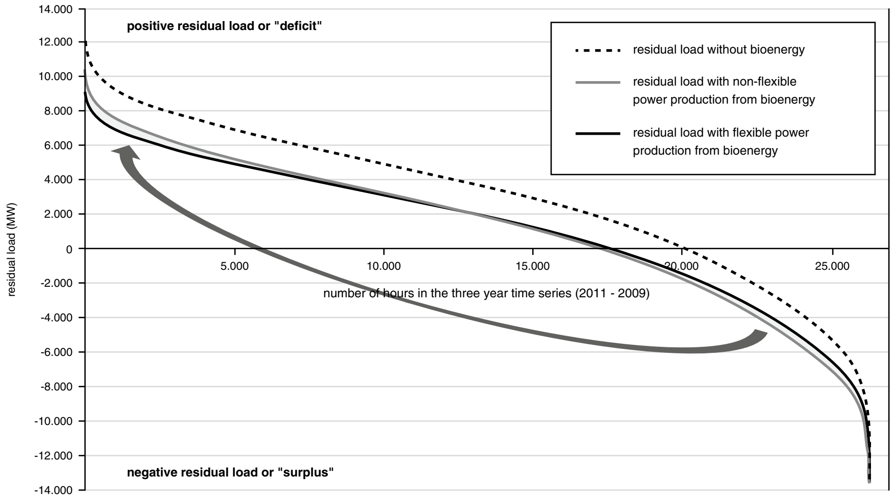

Fig. 9.7 RL curves for the 50Hertz grid network with flexible and non-flexible bioenergy (2030 installed capacity, 3-year reference period)

Of the 15,000 GWh/a of energy from biomass in 2030, about 3,500 GWh/a are shifted from times of low RL on the right side of the graph to times of high RL. Of these 3,500 GWh, about 990 GWh/a are shifted from times of negative RL so that bioenergy is not produced in times of fulfilled demand by wind and PV but shifted instead to times of positive RL. The remaining 2,510 GWh/a are produced even though wind and PV provide sufficient power to supply demand.

9.4.3 Discussion

This chapter investigated the potential of flexible bioenergy as an option for balancing fluctuations in the power grid resulting from load patterns and increasing vRES shares. The results from this regional case study indicate that flexible bioenergy can contribute positively towards balancing power grids.

Based on available renewable energy scenarios, an increase of vRES capacity (wind and PV) from 2011 to 2030 was modelled for the Eastern German region. The limited installed capacity of bioenergy in this case study (1,520 MW/2,435 MW from bioenergy in 2011/2030) is far too low to fully balance fluctuations of vRES capacity (15,789 MW/27,984 MW of Wind and solar PV in 2011/2030). However, the introduction and operation of flexible bioenergy capacity to balance fluctuations in RL (as shown in this case study) through the hourly modulation of capacity to minimize daily RL variance has been verified as an effective measure to balance short-term fluctuations. The simulation revealed a reduction in variability of more than 50 % compared to the reference case of non-flexible operation for both 2011

(56 %) and 2030 (54 %) (see Table 9.6). Modest improvements from flexible operation were identified in terms of maximum excess power and deficit power over the course of the 3-year simulation period, providing additional benefits for the power grid.

According to the simulations presented here, in 2011 the proportion of excess power or negative RL in the system was negligible (176 GWh/a). The modelling results indicate that 58 GWh/a of bioenergy generation could be shifted to compensate positive RL. By the year 2030 an increased share of vRES (see Table 9.4) and excess energy (11,010 GWh/a) in the system is expected. As for the modelling results, from the 3,500 GWh/a that would have been generated from biomass without a flexible operation in times of excess, 990 GWh/a could be shifted by flexible operation. To unlock the remaining 2,510 GWh/a and enable an additional shifting of bioenergy in 2030, greater flexibility is needed.

Therefore, these results indicate that flexible bioenergy provision in the short-term is an effective measure to balance a renewable system (with negligible excess energy), but that future (e.g. 2030) flexibility options will need to be complemented by additional flexibility options and further investments, i.e. in gas and heat storage.

Both, solid biomass power plants and biogas plants were taken into consideration, but with different assumptions about their flexibility. Solid biomass power plants are constrained in their modulation range (0.5–1.2). Although this limits their flexibility potential, power production may run at nominal capacity for long time periods as long as a sufficient stockpile of biomass is available for any addition to the base modulation factor of 1. By contrast, biogas plants with increased generator capacity can be modulated more dynamically than solid biomass plants (modulation factor 0–2). One of the factors that currently restricts flexible generation is the limited capacity to freely regulate biogas production as it is based on anaerobic digestion processes (see Chap. 5).

In general, flexible biogas plants with biogas storage on-site of 12–24 h are well suited to complement the daily production pattern of solar PV at times of high solar irradiance. As no such regular, semi-deterministic production pattern exists for wind power which has a greater dependence on high and low pressure weather systems over Germany prevailing typically for more than 12–24 h, the selected modelling setup is not sufficient to address the means of balancing long-term fluctuations from wind energy. One option to address this shortcoming is to link biogas plants to the natural gas grid to make use of the huge storage potential of the existing gas grid (see Chap. 5). This can overcome the limitations of on-site storage for biogas to cope with the long-term variability in RL.

While some inflexibility is presumably caused by restrictions of the modelling in this case study, as the applied optimization routine is restricted to daily load fluctuations and falls short of inter-daily shifting of power production from bioenergy. However, the flexibility of the biomass technologies which are used in the modelling as well as the operational constraints from combined heat and power operation limits the flexibility in the setup that was investigated.

It is worth mentioning here that this study used RL as a 'known input parameter (from the data)' which by contrast is only partially predictable in real-time plant operation. However, the above results for 2011 and 2030 are based on a set of ex-post data (measured/reported/calculated) specific to the 50Hertz region, implying that the optimization results and conclusions hold true for the set of input data used. The main benefit of using this approach is that it clearly illustrates the advantages of 'flex' bioenergy over using non-flexible bioenergy. Furthermore, results from the 3-year time-slice (RL and RES feed-in) and the applied modelling in this study provides a range of the calculated potential of bioenergy flexibility, allowing for a reduction in daily RL variance of up 56 %.

This case study strongly indicates that the adoption of flexible bioenergy has the potential of supporting the energy transition in Germany. In addition to demonstrating the technical options for flexible bioenergy as presented here, a detailed techno-economic feasibility assessment should be carried out to get the full picture. Innovations and/or adaptations to technologies need to be integrated into the current modelling process as and when required. Flexible bioenergy also needs to be adequately supported by policy, especially by specific incentives that promote flexible bioenergy and framed by sustainability requirements for the feedstock supply. In summary, flexible bioenergy does not necessitate additional bioenergy production but focusses on improving the use of bioenergy that has already been produced, while quantifying the future role of bioenergy in the energy sector can greatly benefit flexible bioenergy provision.

9.5 Conclusion

A transformation of bioenergy provision from a stand-alone provision to integrated systems can be realized on a regional level. A deeper analysis of the East German region showed that it is possible to start changing the existing installation to support the transition of the energy system in the immediate future. By enabling a flexible power provision from biomass, this will result in a higher value of the electricity provided, a reduction in the overall RL to be covered by fossil fuels, while neither the demand for biomass nor the combined heat supply are significantly altered.

For a description of future pathways towards a renewable energy supply, the options for flexible power provision from biomass should be included. So far, the available scenarios do not or not fully consider these and therefore assume higher RLs as well as more energy from fossil fuels. There is a need to adapt these scenarios –not only in terms of modified bioenergy provision but also in terms of economic effects: flexible bioenergy provision calls for much greater technical effort and leads to higher specific provision costs while the reduction of RL has a clear potential for cost reduction in the mid-term.

From the calculations in the case study, an increased negative RL can be expected while at the same time increasing the potential of bioenergy to reduce the fossil RL. Hence, in the long term, a flexible power generation from biomass has the potential of becoming a major contributor to the power supply. However, the results also show that the capacity of power provision from bioenergy is far too low to fully balance fluctuations of the vRES capacity. Consequently, if renewable power provision is to be directly integrated into the energy system, the optimization of power provision from bioenergy is only one aspect. Hence, this case study can be regarded as a starting point for a systematic optimization, which will inevitably lead to some additional potential and challenges for future developments:

1. Today the contribution of flexible power provision from solid biofuels is limited due to the currently installed technologies. Whereas new technologies will be available that support future flexibility –especially the provision of synthetic natural gas (SNG) and/or the power generation in gasification units –with the potential of a wider modulation. In this case, the flexibility of solid biofuels and biogas might be comparable in 2030. This has not been considered in the case study, because so far it cannot be estimated when and how those technologies will be in place on the market.
2. The case study focused on short term flexibility with a shift of electricity provision within 24 h (modulation rate of 0.5–2). Increasing this modulation and also including longer term flexibility might provide additional potential to balance fluctuations in the power system. The previous chapter showed how additional technical options are being developed to provide mid- and long-term flexible power.
3. Not only the electricity generation from biomass needs to be optimized with a view to system integration, but also the fluctuating energy carrier wind and solar PV can contribute to reduce fluctuations in RL, by taking into account spatio-temporal feed-in patterns and advancements in wind and solar PV technology [15]. Hence, the additional installation of renewable power capacity should be framed by integrated planning, considering those aspects as soon as possible.
4. Heat provision also has some additional effects on flexible power provision: on the one hand, CHP concepts require dedicated heat supply concepts for mid- and long-term flexible power provision. On the other hand, the availability of excess energy might lead to additional power-to-heat concepts as a second pillar for heat supply in an energy system mainly based on renewables. Both aspects have not been tackled here and need further investigation.

In terms of an efficient reduction of greenhouse gases, today's possible "no-regret-options" to reduce fossil-based power generation by adapting the existing biogas plants should be realized soon. Therefore, adjusted framework conditions are necessary to make investments in the additional power conversion unit (second CHP-engine) of the biogas plant feasible. This will be discussed in detail in Chap. 10.

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