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Currently, most PV modules are aligned in a way that maximizes the overall yearly yields. Therefore, with an increasing number of PV installations, this leads to significant peaks in electricity production and could threaten energy policy objectives such as security of supply as well as ecological efficiency. Can the exploitation of the large remaining PV potentials on (seemingly) sub-optimal inclination and azimuth angle building roofs counteract such tendencies by achieving significant temporal shifts in the electricity production? This paper addresses the potential of these counter-measures by evaluating the optimal mix of wind and PV installations with different inclination and azimuth angles for a regional context. It does so by adhering to three distinctive energy policy goals: economic efficiency, sustainability and security of supply. It is further assumed that the examined regions aim for energetic autarky.

The hourly yields of wind parks and PV installations with different mounting configurations are simulated for four representative NUTS3-regions in Germany, based on specific weather conditions. These profiles are combined with standardized regional electricity demand profiles and fed into an optimization model. It is run three times, each time maximizing for one of the three energy policy goals. As a result we obtain the optimal installed capacity for PV for every possible configuration – determined by inclination and azimuth angles – and the optimal installed capacity of wind power.

The results indicate that the optimal mix differs significantly for each of the chosen goals and depends on regional conditions, but shows a high transferability on general statements. In terms of economic efficiency – the first of the three goals – a focus on a high share of wind power and southern oriented PV-systems is feasible for all German regions. When sustainability is chosen as the energy policy goal, results depend largely on the conventional power plant utilization and its CO_2-equivalent emissions leading to a high share of PV-systems in ratio to wind power. When maximizing the third goal, the security of supply, PV plants facing east and west as well as wind turbines are preferred, since this homogenizes the daily combined PV production.

A regional simulation and optimisation of renewable energy supply from wind and photovoltaics with respect to three key energy-political objectives

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Abstract

Currently, most photovoltaic (PV) modules are aligned in a way that maximizes the overall annual yields, which leads to significant peaks in electricity production and could threaten energy policy objectives such as security of supply as well as environmental sustainability. The exploitation of remaining PV potentials at seemingly economically sub-optimal inclinations and azimuth angles could partly counteract this trend by achieving significant temporal shifts in the electricity production. This paper addresses the potential of these counter-measures by evaluating the optimal mix of wind and PV installations with different inclination and azimuth angles in a regional context. It does so by adhering to three distinctive energy policy goals: economic efficiency, sustainability and security of supply. It is further assumed that the examined regions aim for energetic autarky.

The hourly yields of wind parks and PV installations with different mounting configurations are simulated for four representative NUTS3-regions in Germany, based on assumed installed capacities and specific weather conditions. These profiles are combined with standardized regional electricity demand profiles and fed into an optimization model, which is employed to maximise each of the three energy policy goals independently. As a result the optimal installed capacity for PV for every possible configuration – determined by inclination and azimuth angles – and the optimal installed capacity of wind power are determined.

The results indicate that the optimal mix differs significantly for each of the chosen goals and depends on regional conditions, but shows a high transferability in terms of general conclusions. For economic efficiency – the first of the three goals – a focus on a high share of wind power and south-oriented PV-systems is feasible for all German regions. When sustainability is chosen as the energy policy goal, results depend largely on the conventional power plant utilization and its CO_2-equivalent emissions leading to a high share of PV-systems in ratio to wind power. When maximizing the third goal, the security of supply, PV plants facing east and west as well as wind turbines are preferred, since this homogenizes the daily combined PV production. The developed methodology is found to be robust with regard to the relative conclusions, whilst the absolute magnitude of the results is sensitive to the

input data. Further work should focus on refining the representativeness of the four model regions and on quantifying the three considered criteria more holistically.

1 Introduction

1.1 Motivation

A combination of ambitious European and national goals alongside strong economic support policies have led to a rapid expansion of onshore wind and photovoltaic (PV) capacities in Germany. From total installed electricity generation capacities for PV and wind of 6 and 24 GW respectively at the end of 2008, the latest statistics report 36 and 34 GW respectively [1,2]. Despite a short-term drop in the expansion rate in 2013, this is a trend that is very likely to continue in the near and medium term future as progress towards national renewable energy goals continues. The rapid development of decentralized PV systems, in Germany, fuelled by the Renewable Energy Law, has led to drastic cost reductions and associated adjustments to the feed-in tariffs in Germany in recent years. In countries (such as Germany) where grid parity has been achieved for residential electricity customers (who pay around 31€ct/kWh for their electricity [3], compared to current electricity generation costs of around 12 €ct/kWh [4] for new PV plants, the economic attractiveness of generating PV-electricity for self-consumption has drastically improved.

From a plant operator’s perspective, the levelised costs of electricity (LCOEs) are the conventional economic yardstick with which to assess generation technologies like PV-systems and wind turbines. However, from a macro-economic and/or societal perspective, it should be not just the generation costs, but the overall system costs, i.e. including electricity supply costs, that matter.

One key determining factor for the LCOEs of PV and wind, as well as the investment and running costs, is the absolute electricity generated over a year, which depends largely on the location (annual solar irradiation, average wind speed), applied technology and orientation/hub height. Hence whilst previously the focus has been on the minimization of LCOEs based on reducing costs and maximizing the (specific) system output, there are increasingly more reasons why this approach might not be satisfactory. For example, the electricity network may not be able to cope with the generation profile (peak power and power gradients) in its present condition - in other words the system costs are actually much higher, when the necessity of network expansion and balancing power are considered.

Hence an apparently economically suboptimal orientation of PV-systems and combination with wind turbines may lead to lower overall system costs and/or greenhouse gas emissions, and/or a higher level of energy security, when all aspects are considered.

1.2 Literature review

The diverse and in some respects contradictory criteria with which to optimise energy systems are discussed by Østergaard [5]. He mentions several criteria, including renewable energy shares, primary energy consumption, economic and social costs, carbon dioxide emissions, and several aspects directly relating to the integration of renewable energies, namely whether a region is operated in island or connected mode, or a mixture, and the associated imports/exports and requirements for reserve power plant capacities. These criteria are applied to an energy system model for Western Denmark, and a multi-criteria decision analysis is then used to evaluate the three scenarios. In spite of this simplicity, the author concludes that the different optimisation criteria yield quite different results. A crucial aspect seems to be whether or not the region is considered as in island or connected mode, or a combination of the two; in the former case large expansions in renewables generators are not feasible unless relocation (networks and storage) infrastructure are also developed. Hence the approach emphasises the fact that there will ultimately always be (more) trade-offs involved between and depending on the (more) employed optimisation criteria.

The complementarity of solar and wind resources can be exploited to smooth the generation curve, as these two resources generally exhibit quite different availabilities [6,7]. Budischak et al. [6] have developed a model to analyse the total system costs of providing almost 100% of electricity to the PJM system in the USA from renewables. Their model minimizes total system costs for electricity supply, based on a parameterisation for the years 2008 and 2030. Importantly, they do not consider storage capacities for matching supply and demand, and they treat the electricity network as a “copper plate”. The main result is that the least-cost system has excessive renewable generation capacities - enough to generate three times the total demand due to the reduced storage requirement and thus lower total system costs - which would be used to meet some of the thermal loads (not considered in the article). Hoicka et al. [7] employ non-dimensionalised electricity production indices for four locations in Ontario, Canada and assess various technology and location combinations. They conclude that the combination of these two technologies in one location does indeed smooth production, which is further improved once more when two resources and locations are considered. There is no additional benefit (but neither a necessary disadvantage) from a geographic dispersal of the plants, although electricity networks were not explicitly considered in the contribution.

Several authors have analysed the technical potential to optimize the sizing and setup of PV systems [8–11]. For example, Weniger et al. [10] optimise the sizing of residential PV and battery systems with a view to maximizing the self-consumption rate[1] and degree of self-sufficiency[2]. Widén et al. [8] focus on the technical potential for matching the electricity

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[1] Defined as the fraction of PV electricity that is used for own consumption.

[2] Defined as the fraction of the total (annual) electricity consumption delivered by the PV/battery system.

generation from PV with the load profile. As well as considering different sizing (both absolute capacity and PV panel to inverter ratios) and orientation (azimuth angle, inclination), the approach considers two other options for load matching, namely demand side management (DSM) and electricity storage. The authors apply the method to several typical load profiles for northern latitudes but suggest that the method could easily be employed elsewhere. The main findings are that storage is the most attractive option at higher penetration levels, whereas DSM is as effective or even superior at lower penetrations. Interestingly, the authors report that “although optimisation of the aggregate PV output profile through optimal orientation of subsystems suggests an east-west orientation at high penetration levels, the impact [...] is quite small compared to the other options”.

Mondol et al. [9] undertake a purely technical analysis by employing a developed TRNSYS simulation model to optimise the setup of grid-connected photovoltaic systems. The model accounts for the effect of surface inclination and orientation, as well as considering insolation, PV output and efficiency, inverter efficiency, system efficiency and performance ratio. The results indicate that, typically, the maximum electricity yield is obtained by facing directly south (azimuth angle of 90°) with and inclination of 30° and the minimum yields are obtained with east and west (0° and 180° respectively) facing plants on vertical surfaces (inclination of 90°). The study also shows that there are often regional and local deviations from these general results, such as for the location in Ireland where the optimal inclination was found to be 20°.

Other authors also consider economic aspects in their approach to setup optimization [12–14]. Mondol et al. [12] further develop their methodology from [7] to consider economic aspects of PV electricity generation and thus investigate the scope for matching the generation profile of the PV system to the load. In addition to the technical factors listed above, this contribution accounts for the impact of array size, orientation, inclination, PV/inverter sizing ratio and PV/inverter cost ratio on the economics. Based on location-specific electricity load profiles, irradiation and feed in tariffs as well as electricity prices, the model is applied to several European locations. The results demonstrate the sensitivity of PV-electricity generation costs to the setup of the system (especially the ratio of the PV module to the inverter) as well as suggesting that feed-in of this electricity should be avoided when the tariff lies below the electricity price. One limitation of the economic assessment is that it is based on feed-in tariffs and electricity prices which are assumed to be constant.

Hartner et al. [13] also investigate the effect of alternative approaches/orientations on the total system costs. The authors argue that an energetically sub-optimally oriented PV system (i.e. not south and 30° inclined) could still be environmentally favourable in terms of fuel costs and emissions, depending on the electricity from the system that it displaces. The authors thus equate the market value of PV-electricity with the marginal costs of the power plant park (that it displaces), hence neglecting system integration costs in the form of network expansion and balancing power. A further assumption is that the maximum market value of PV electricity corresponds to the minimum costs for the whole system. For this purpose an optimisation power plant dispatch model of the German-Austrian power plant park is developed. The basis data (RES feed in and load profile) is taken from 2012 and the two countries are disaggregated into 23 regions (about the size of a federal state). The results show that only with very large capacity additions (over 100 GW) of PV does the energetic optimum deviate from the market optimum. Furthermore, with an unlimited availability of storage and a completely uncongested electricity network, the energetic optimum would be the market optimum, but these two conditions are clearly not applicable in reality, which makes a similar consideration on a regional level necessary.

Finally, Waldmann et al. [14] investigate the economics of PV systems in open spaces with an east-west orientation. A simulation model is developed and employed to large open space (over 3 ha) plants in two locations, one with high irradiation (Freiburg) and one with lower irradiation (Hamburg), in order to determine the respective electricity production and associated balance of system (BOS) costs. The authors conclude that, whilst currently east-west plants are not economically attractive compared to south-facing plants, their profitability can be better (than south-facing plants) if their mounting system costs are lower and the grid connection costs as well as land rent are high. In addition, the profitability of east-west plants is typically better in regions with lower solar irradiation.

1.3 Objective, methodology and overview

The foregoing discussion has highlighted several previous studies concerned with the technical and economic optimization of the orientation of PV systems, for example to minimize overall costs or by matching supply and demand. Most applications have tended to focus on specific locations or large geographical areas and some have overlooked the local structure of the demand side. Finally, the implications for greenhouse gas emissions and security of supply appear to have been insufficiently considered.

Hence this paper has the objective of determining to what extent PV systems and wind turbines are able to contribute towards these criteria just through variations in the orientation of PV systems and of the ratio of PV to wind capacity.

In order to do this, a spatially resolved weather simulation model and an optimisation model are presented and applied to four example regions in Germany. The regions differ in terms of their potentials for electricity generation from wind and PV, their demand side structure and their size. They are therefore intended to be representative of diverse regions throughout the country. Oriented towards the energy policy triangle, which defines the three key goals of

German energy policy as economic efficiency, environmental sustainability and security of supply, the installed capacity and orientation of PV and wind systems are optimised. The results of these optimisations are then analysed in order to identify trade-offs between these three criteria. Whilst the results relate to the German situation, they are intended to be transferable to other contexts.

The paper is structured as follows. The next section (2) describes the methodology employed, whilst the subsequent section (3) presents the results. Section 4 discusses the results and the methodology in light of the objectives and section 5 concludes and summarizes.

2 Methodology

2.1 Construction of renewable power generation profiles

In this section a tool is presented, which is used to generate time series of PV and wind power for different systems and regions [15]. It consists of two main parts:

- *Weather Model:* Highly spatially and temporally resolved weather data from numeric weather model COSMO-DE of the German Weather Forecasting Service (Deutscher Wetterdienst DWD)
- *PV- and Wind-Model*: Simulation model of power generated by photovoltaic and wind turbines based on weather data

2.1.1 **Weather model**

The weather data is delivered by the German Weather Forecasting Service (DWD) and calculated by the numerical weather model COSMO-DE [16]. The weather data of COSMO-DE relates to single grid points with an average offset of 2.8 km and a timely interval of one hour. The model used in this paper is restricted to the NUTS3-level, a spatial resolution which involves 412 individual regions in Germany. To allocate weather data from each grid point to the surrounding NUTS3-regions, the geographic structure of the numerical weather model is needed, as described in [16]. For the allocation of the weather data to the NUTS3-regions, the average value of all grid points within a region is used. This methodology is applied for the following different parameters:

- Direct irradiation
- Diffuse irradiation
- Wind speed
- Roughness length of ground

- Temperature

In this paper, weather data from the year 2012 is used. The sum of direct and diffuse irradiation, known as global irradiation, is displayed in Figure 1. The roughness length is needed to calculate the wind speed for different hub heights from the wind speed at 10m with the logarithmic formula [17]. An overview of the average wind speed at 100m is given in Figure 2.

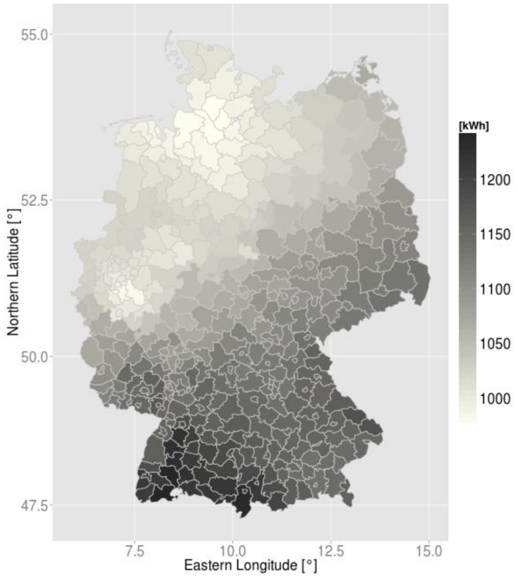


Figure 1: Global irradiation on surface 2012.

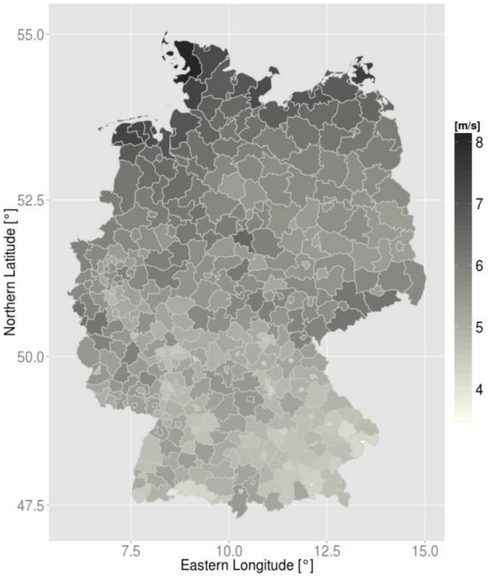


Figure 2: Wind speed in 100m height 2012.

2.1.2 **PV and wind model**

The basis for the PV- and Wind-Model is the weather data of the formerly described weather model and an individual methodology for each technology, as described in this section.

In order to simulate the generated power for individual PV-systems, the points in Figure 3 have to be completed step by step. Meteorological input is displayed on the left, technical specifications are on the right and important results of the simulation in the centre.

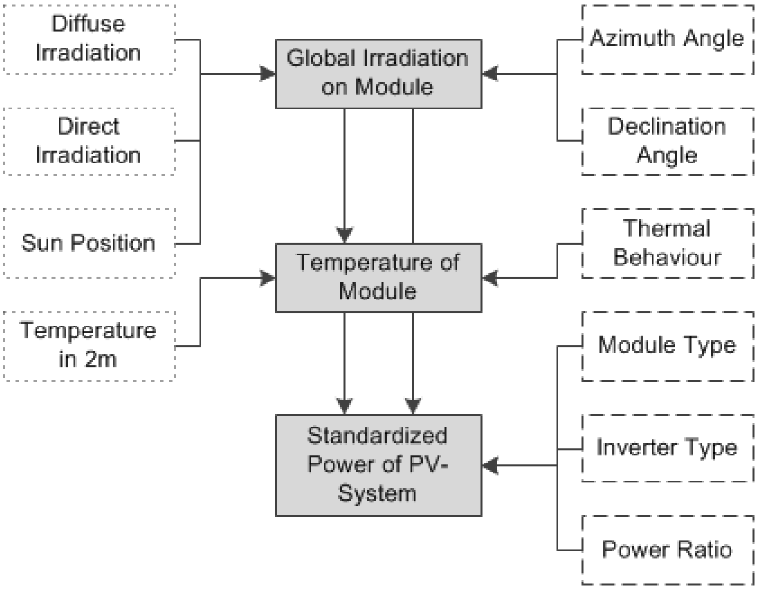


Figure 3: Methodology to simulate standardized PV power [18–21].

To simulate the power generated by wind turbines, the procedure is different and must include the steps in Figure 4.

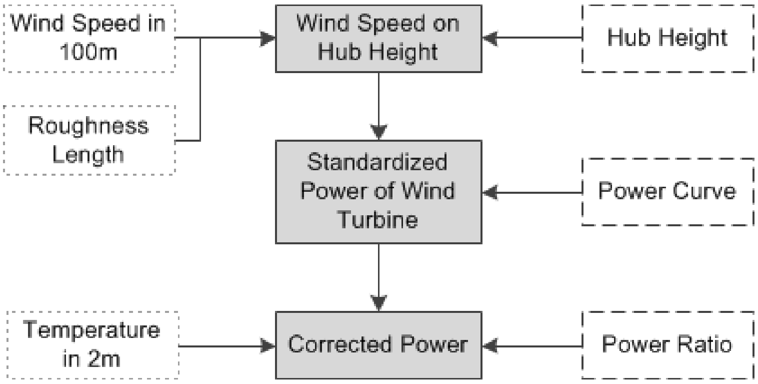


Figure 4: Methodology to simulate standardized wind power [17,21].

On basis of weather data from 2012, the standardized generated power of each technology and a mixture of different PV systems and wind turbines are calculated. The resulting full load hours are shown in Figure 5 and Figure 6.

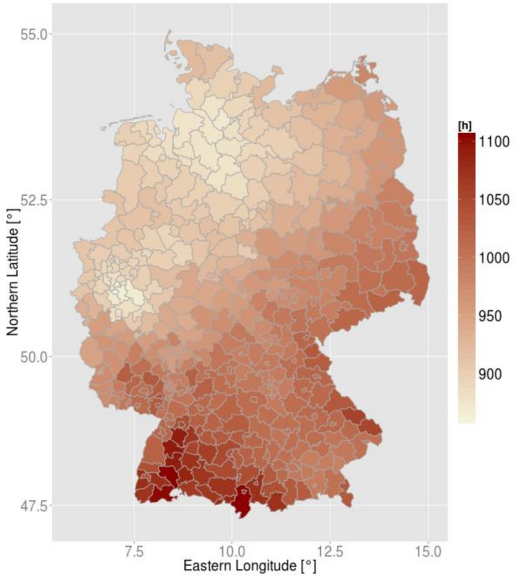


Figure 5: Cumulated standardized PV power in NUTS3 regions show full load hours 2012.

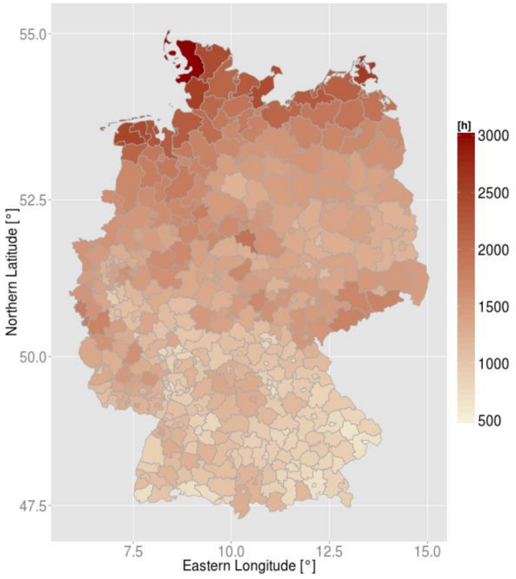


Figure 6: Cumulated standardized wind power in NUTS3 regions show full load hours 2012

A statistical and graphical analysis comparing the obtained model results with actual data shows both a high temporal correlation and a similar dimension of the investigated values.

It has to be considered that the potential for renewable energy production is limited by the available land, climatic factors, etc. To constrain the amount of installable capacity for wind and PV, the technical potentials for the study regions are estimated.

For PV, the methodology described in [22] is applied. This methodology makes use of the number and types of residential buildings in an area as well as some statistical figures to estimate the available roof area. Combined with the local global irradiation and assumptions on the technical characteristics of the PV systems, the technical potential is estimated. The method calculates the total technical roof-mounted PV potential, without differentiating between different module orientations.

For wind, the cost-potential results from [23] have been employed. The methodology for this potential estimation is based on an exclusion and application of minimum offset distances from unsuitable land use areas for wind energy. Suitability factors are then employed for the remaining areas and the turbine with the lowest generation costs (LCOEs) for a given land use category and wind speed is selected from a database containing technical and economical specifications of several turbines. For further details the reader is referred to the source.

2.2 Construction of regional load profiles

Depending on regional demand patterns, the electric load curves can be very distinctive for each study area. These patterns might lead to some regions correlating better than others with different PV generation profiles. For the method employed in this study, the matching of supply and demand is of great importance.

In order to represent the demand side, electric load profiles are generated by applying a method based on statistical values. It makes use of a number of regional variables measuring the size of each of the demand sectors: residential, industrial, service, agriculture and transport. Nationwide sector-specific demand profiles are then scaled using the relative size of each sector and combined to create an aggregated electricity load profile for the studied region. This method is explained in further detail by Mainzer et al [22].

Four different German regions are chosen as study areas in this paper. In order to capture heterogeneous conditions in Germany, the chosen regions vary in their location, with direct implications on available irradiation and windspeed potentials, as well as their sectorial composition, with direct implications on their electricity load profiles.

Two of the selected regions are located in northern Germany, with high potentials for wind generation. Of these two, one has a relatively strong industrial sector (Stormarn) and the other one has a stronger service sector (Nordfriesland). The other two regions are located in southern Germany, with better conditions for PV power generation. Again, one region has a stronger industrial sector (Südwestpfalz), the other a stronger service sector (Garmisch-Partenkirchen). Both regions also have strong agricultural sectors. Table 1 gives an overview of the regions. Full load hours (FLH) were simulated according to the methodology presented in chapter 2.1 for a mixture of different PV-system and wind turbines.

Table 1: Characterization of the four study areas.

	PV FLH 2012 [h]	Wind FLH 2012 [h]	Sectoral focus
Nordfriesland	*973*	*3,422*	*Service*
Stormarn	*940*	*2,037*	*Industrial*
Südwestpfalz	*1,068*	*1,283*	*Industrial*
Garmisch-Partenkirchen	*1,135*	*1,245*	*Service*

2.3 Greenhouse gas emissions for German electricity production

In order to assess the environmental value of the temporal distribution of renewable energy production, each produced kWh of electricity is rated by calculating the avoided emissions that conventional power plants would have produced.

The underlying assumption is that each kind of power plant causes emissions during operation, depending on its fuel type and efficiency. This leads to the insight that, depending on which power plants are producing power at each hour of the year (which is determined by the merit order curve), the emissions of the power plant mix can vary significantly over time. For example, large shares of coal power plants lead to greater average emissions than large shares of uranium power plants in the generation mix (cf. Figure 7).

Using technology-specific CO_2-equivalent emissions [24–26] combined with the information which power plants were in use during each hour [27], an hourly CO_2-equivalent emission curve of the German power plant mix has been constructed for the year 2012, as shown in Figure 7.

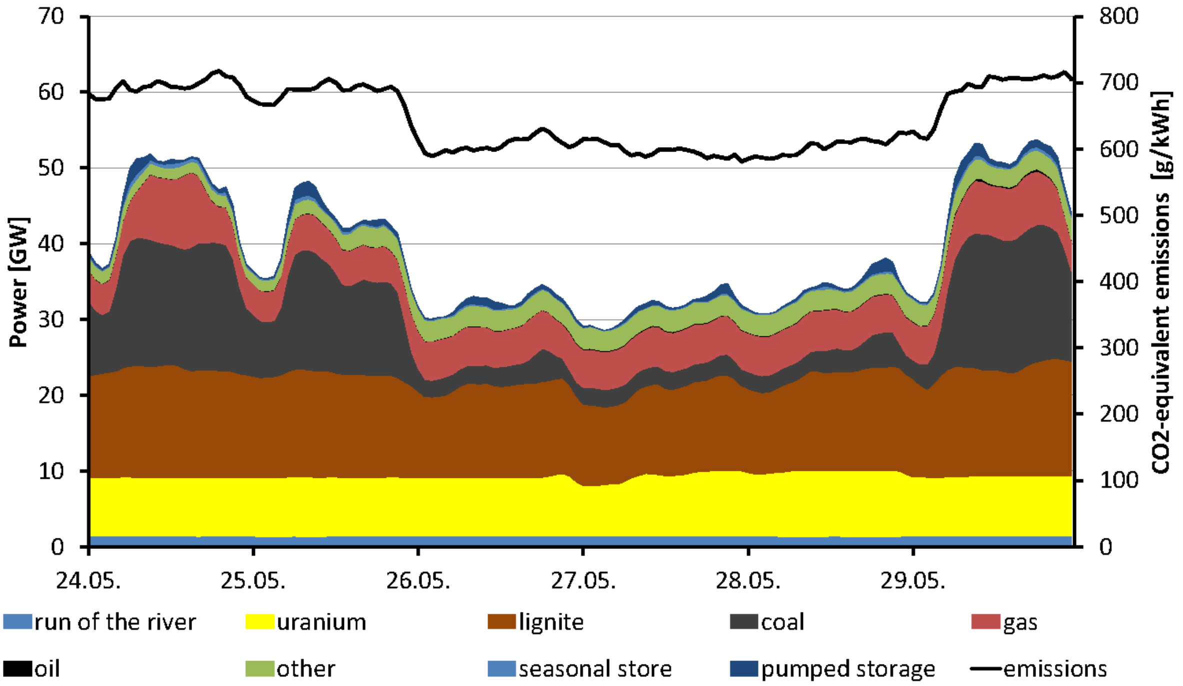


Figure 7: excerpt from conventional power plant production schedule and hourly CO_2-equivalent emissions curve for 2012

It becomes apparent that daily variations in demand, as well as special events such as holidays, influence power plant scheduling, which in turn influences emissions. Other observations from this analysis are that average emissions in summer are about 6% higher than in winter (partly due to nuclear power plant shutdowns during revision) and differ up to 20% between different months.

2.4 Optimisation procedure for adapting the generation profile

In this section the criteria, as well as the variables and constraints used for the optimization approach, are presented.

2.4.1 Decision variables and indices

The decision variables are the installed PV capacity for each combination of azimuth and inclination angles and the installed wind capacity:

$$InstalledPV_{A,I} \quad \forall\, A, I$$
$$InstalledWind$$

For wind, a Vestas V90 turbine with a hub height of 80 m is used, whereas for PV, crystalline silicon systems are used, differing in the azimuth and inclination angle which are described by the following indices:

$$A = \{East; South; West\}$$
$$I = \{20°; 35°; 50°\}$$

For the nine PV-systems and one wind turbine an hourly standardized [W/Wp] time series t for each PV-system and wind turbine in the year 2012 was simulated by the methodology described in chapter 2.1. for each region.

2.4.2 Objectives

As described earlier, the optimization procedure is carried out three times for each study area, using each of the following criteria as objective function.

Economic efficiency

The idea of the criterion economic efficiency is not to follow a given subsidisation scheme which compensates each generated kWh with a fixed tariff. Instead, the criterion consists of three parts, which combined form the annual economic value of a given solution: annual investment (assuming a straight-line-depreciation), avoided power consumption costs and the economic value of feed in.

$$:= \frac{Investment}{DepreciationPeriod} + \sum_t AvoidedPowerConsumptionCost_t \\ - \sum_t EconomicValueOfFeedIn_t$$

The investment depends on specific costs [€/kW$_p$] and the installed capacity [kW$_p$] of each technology:

$$Investment := SpecificCostPV * \sum_{A,I} \left(InstalledPV_{A,I}\right) + SpecificCostWind \\ * InstalledWind$$

An important time series for all optimization criteria is the residual load, which is the difference between the regional load simulated by the methodology described in chapter 2.2 and the total power generated by all PV-systems and wind turbines:

$$ResidualLoad_t := Demand_t - Supply_t$$

$$\mathrm{Supply}_t := \sum_{A,I} \left(InstalledPV_{A,I} * GenerationPV_{A,I,t}\right) + \mathrm{InstalledWind} \\ * \mathrm{GenerationWind}_t$$

The avoided power consumption costs depend on the residual load as well as the consumer power price, which is parameterized with 31.7 €cent/kWh [3].

$$AvoidedPowerConsumptionCost_t := \begin{cases} ResidualLoad_t * ConsumerPowerPrice, & ResidualLoad_t \geq 0 \\ 0, & ResidualLoad_t < 0 \end{cases}$$

The economic value of feed-in on the other hand depends on the residual load and the German power price, given for each time step by the EEX-Transparency platform [27]:

$$EconomicValueOfFeedIn_t := \begin{cases} 0, & ResidualLoad_t \geq 0 \\ -ResidualLoad_t * GermanPowerPrice_t, & ResidualLoad_t < 0 \end{cases}$$

This objective function is nonlinear due to the case distinctions. It is solved using the GRG Nonlinear solver included in Microsoft Excel.

Sustainability

The second objective of the energy policy triangle, environmental sustainability, is interpreted in a way to avoid greenhouse gas emissions and hinder the environmental impact. Using the hourly CO_2-equivalents calculated by the methodology described in chapter 2.3, this objective function minimizes the overall emissions by incentivizing higher generation of renewable energies (thus lowering the residual load) in times of high CO_2-equivalents of conventional power generation.

$$:= \sum_t (ResidualLoad_t * GermanPowerMixCO_2Emissions_t)$$

This linear objective function is solved using Microsoft Excel’s Simplex LP solver.

Security of supply

The third objective of the energy policy triangle, security of supply, is an elusive goal, since it is not easily measurable. Extreme values in the demand-supply-balance can generally be considered as potential threats to the security of supply, however. In order to remedy these extreme values, this objective function minimizes the standard deviation of the residual load, which is a measure for its variation from the average value. This minimization thus yields a more constant residual load with lower peaks.

$$:= StandardDeviation(ResidualLoad) = \sqrt{\sum_t \frac{\left(ResidualLoad_t - \overline{ResidualLoad}\right)^2}{|ResidualLoad|}}$$

This objective again is of nonlinear form and is thus solved minimized using Microsoft Excel's GRG Nonlinear solver.

2.4.3 Constraints and exogenous data

One objective of this study is to research the possibility of autarky for the studied regions. Due to the fluctuations of renewable energy production, complete autarky at each hour of the year would not be possible without enormous storage capabilities, but at least a yearly balance of supply and demand is pursued:

$$\sum_t Supply_t = \sum_t Demand_t$$

The potentials described in chapter 2.1.2 are used to constrain the installed capacities and reflect a region's capabilities to exploit certain types of renewables:

$$\sum_{A,I} \left(InstalledPV_{A,I} \right) \leq PotentialPV$$

$$InstalledWind \leq PotentialWind$$

These constraints naturally lead to the conclusion that the optimization problem is only feasible for regions where the combined potentials for PV and wind are sufficient to supply the annual electricity demand.

Table 2 gives an overview of the exogenous data used. In the second column of this table a link to the methodology or the respective exact value is given.

Table 2: Overview of exogenous data used with respective sources.

Exogenous data	**Source**
$\boldsymbol{Demand_t \quad \forall\, t}$	*Chapter 2.2*
$\boldsymbol{GenerationPV_{A,I,t} \quad \forall\, A, I, t}$	*Chapter 2.1*
$\boldsymbol{GenerationWind_t \quad \forall\, t}$	*Chapter 2.1*
$\boldsymbol{GermanPowerMixCO_2Emissions_t \quad \forall\, t}$	*Chapter 2.3*
$\boldsymbol{GermanPowerPrice_t \quad \forall\, t}$	*EPEX Spot [1]*
$\boldsymbol{ConsumerPowerPrice}$	*31.7 € cent/kWh [3]*
$\boldsymbol{SpecificCostPV}$	*1400 € / kWp [4]*
$\boldsymbol{SpecificCostWind}$	*1400 € / kWp [4]*

PotentialPV	*Individual for each region [22]*
PotentialWind	*Individual for each region [23]*
DepreciationPeriod	*20a*

3 Results

3.1 Economic efficiency

In the following figures the results of the optimization are presented. Figure 8 shows the optimal regional allocation of different PV-systems and wind turbines in percentage of the overall installed capacity when optimizing for *economic efficiency*. Two aspects become apparent: First, wind turbines are preferred over PV systems resulting in larger shares of wind turbines, excerpt for Garmisch-Partenkirchen where the shares are equal. Second, PV systems facing south are obviously preferred when the economic efficiency is to be maximized.

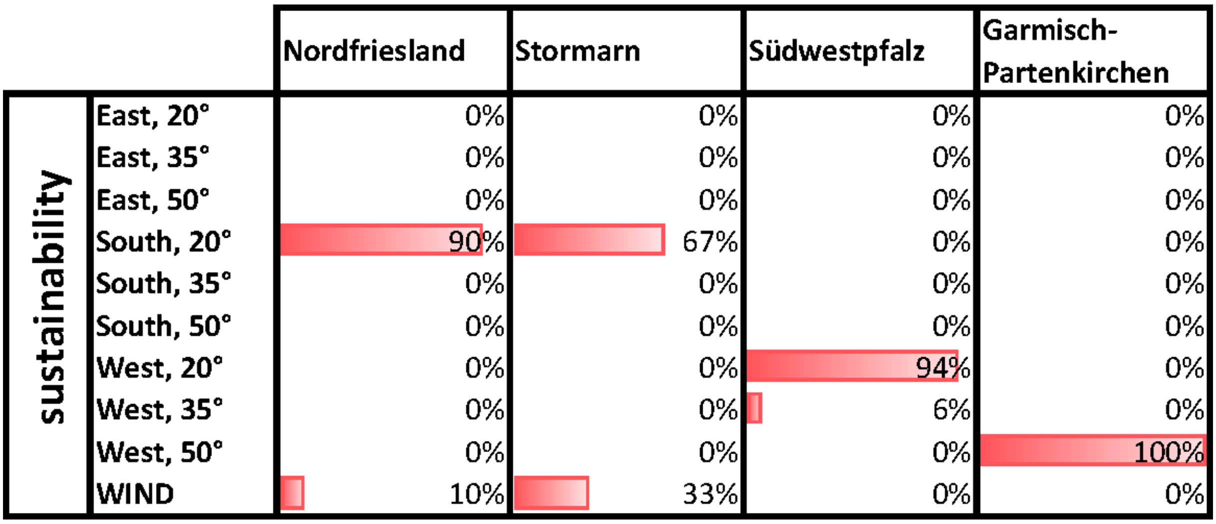
		Nordfriesland	Stormarn	Südwestpfalz	Garmisch-Partenkirchen
economic efficiency	East, 20°	0%	0%	0%	0%
	East, 35°	0%	0%	0%	0%
	East, 50°	0%	0%	0%	2%
	South, 20°	0%	0%	0%	31%
	South, 35°	32%	43%	37%	19%
	South, 50°	0%	0%	0%	0%
	West, 20°	0%	0%	0%	0%
	West, 35°	0%	0%	0%	0%
	West, 50°	0%	0%	0%	0%
	WIND	68%	57%	63%	49%

Figure 8: Composition for different PV-systems and wind turbines for criterion "Economic Efficiency".

3.2 Environmental sustainability

When optimizing for sustainability, the results are a bit more diversified. First, it can be noted that PV systems are generally preferred over wind turbines.

In the cases where the PV potential is sufficient to supply all the required electricity (which applies to the regions Südwestpfalz and Garmisch-Partenkirchen), PV systems facing west are favoured. For the cases where PV has to be supported by wind power to supply the required electricity (which applies to Nordfriesland and Stormarn), PV systems facing south are favoured.

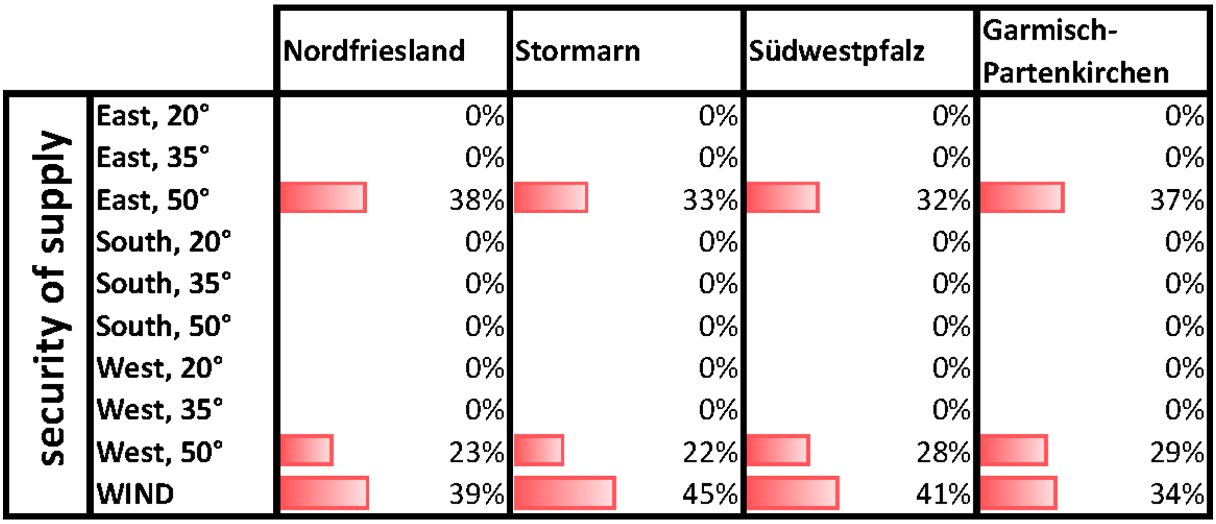


		Nordfriesland	Stormarn	Südwestpfalz	Garmisch-Partenkirchen
sustainability	East, 20°	0%	0%	0%	0%
	East, 35°	0%	0%	0%	0%
	East, 50°	0%	0%	0%	0%
	South, 20°	90%	67%	0%	0%
	South, 35°	0%	0%	0%	0%
	South, 50°	0%	0%	0%	0%
	West, 20°	0%	0%	94%	0%
	West, 35°	0%	0%	6%	0%
	West, 50°	0%	0%	0%	100%
	WIND	10%	33%	0%	0%

Figure 9: Composition for different PV-systems and wind turbines for criterion "Sustainability".

3.3 Security of supply

The third policy goal of *security of supply* is represented by maximizing the temporal match of renewable supply with demand as stated above. The results in Figure 10 show a very homogeneous picture for all four regions that differ from the results for the other two policy goals. In this case the optimal mix consists of PV-systems facing east and west with an inclination of 50°. Wind turbines have a significant part as well with a share below 50% though.



		Nordfriesland	Stormarn	Südwestpfalz	Garmisch-Partenkirchen
security of supply	East, 20°	0%	0%	0%	0%
	East, 35°	0%	0%	0%	0%
	East, 50°	38%	33%	32%	37%
	South, 20°	0%	0%	0%	0%
	South, 35°	0%	0%	0%	0%
	South, 50°	0%	0%	0%	0%
	West, 20°	0%	0%	0%	0%
	West, 35°	0%	0%	0%	0%
	West, 50°	23%	22%	28%	29%
	WIND	39%	45%	41%	34%

Figure 10: Composition for different PV-systems and wind turbines for criterion "Security of Supply".

3.4 Comparison of three objectives

In Table 3 different parameters of two criteria and their relative change compared to "Economic Efficiency" are displayed. These values were calculated by standardizing the regional parameters by the local amount of load generated and used. Thereby each region has the same weight and is regarded with the same influence. In the second step the average of all standardized, regional parameters was built and compared to the criterion “Economic Efficiency”.

Table 3: Selected parameters and their relative change compared to criteria "Economic Efficiency".

	Environmental Sustainability	*Security of Supply*
Min residual load change gradient	*41%*	*-9%*
Max residual load change gradient	*53%*	*-8%*
Min residual load	*35%*	*-4%*
Max residual load	*0%*	*0%*
Investment	*35%*	*9%*
Installed PV-systems	*212%*	*78%*
Installed wind turbines	*-78%*	*-16%*
FLH for PV plant mix	*-20%*	*-24%*

In the case of environmental sustainability, there is a significant increase in the total amount of installed PV capacity, leading to higher gradients, which indicate the temporal change, and a smaller minimum residual load due to a higher peak generation in summer. The high number of PV-systems creates higher investments, although fewer wind turbines are installed. The average full load hours of PV-systems are smaller, which is an effect of a shift to western oriented plants, as shown in Figure 9.

Taking a closer look at the criterion “Security of Supply” reveals smaller positive and negative gradients and a higher minimum residual load, which was the aim of the objective function itself. Investments are 9% higher because more renewables are built in total, with PV-systems being favoured. On a system level there might be economic advantages created by smaller gradients and a more constant residual load, regarding additional grid construction and the economic value of PV power [28]. The smaller gradients and a more constant residual load are a consequence of PV-systems facing east and west (Figure 10) leading on average to lower full load hours.

The maximal residual load is equal for all criteria, meaning that there will always be some hours when generation of renewables is zero and an energy grid needs alternative generation or storage systems to cover the load.

4 Discussion

In this chapter, the previously described results are further analysed and discussed, and the employed methodology is evaluated.

4.1 Results of optimization

In order to investigate the transferability of the results to other regions in Germany, the three optimization criteria are analysed in the following text sections including the results of Figure 8 - Figure 10. It is important to mention that the installed capacity is the value behind these figures and the basis for the discussion. Regionally different full load hours, as displayed in Table 1, lead to regional differences in the generated energy, which are high especially in the case of wind turbines.

4.1.1 Economic efficiency

The optimization criterion consists of two main parts which are responsible for the results. The investment is one factor and accounts for one third to one fourth of the target value. The more decisive parts are the (avoided) energy costs (when regional demand exceeds generation), or the economic value of the electricity fed back to the net (when generation exceeds demand).

On average, it is more lucrative to use electricity for self-consumption rather than to feed it into the local grid. Increasing self-consumption and matching load in peak times has therefore the biggest influence on this optimization criterion, which has to be realized with an efficient mixture and high full load hours of PV-systems and wind turbines. Therefore it is not surprising that there is a strong tendency towards south oriented PV-systems with an inclination of 35°, which generate on average the highest amount of energy in Germany [19], while also being most cost-efficient. Furthermore, wind turbines are attractive, which have the highest full load hours in all regions. The differences between all regions seem rather small and the message is clear: An energy system with high economic efficiency has to consist of a well-balanced mixture of PV-systems and wind turbines. The regional ratio depends on the individual generation profiles but small differences in the composition cause only rather small effects on the target value.

4.1.2 Environmental sustainability

The CO_2-equivalents of the German power plant mix (cf. 2.3) are the dominant factor and determine the time at which it is attractive to replace conventional power plants by PV-systems and wind turbines. Therefore it is mandatory to take a closer look at the emissions in Figure 11. The diurnal average of CO_2-equivalent emissions is displayed for a representative month in winter and summer. The figure shows clearly that the daily differences are rather small with a peak in the early evening, but the seasonal differences are more significant. In summer, emissions are larger due to a high percentage of coal powered plants in the energy system.

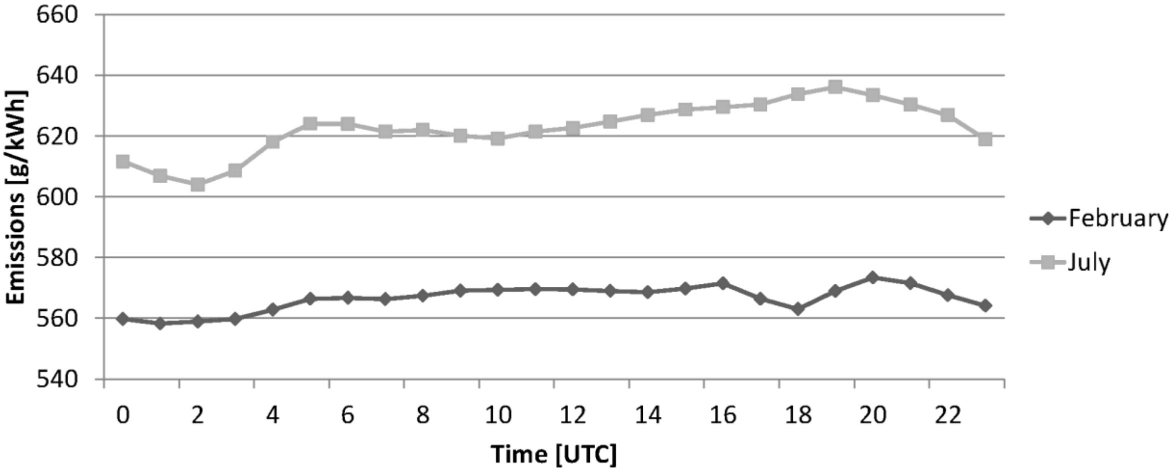


Figure 11: Diurnal average of CO_2-equivalent emissions for February and July 2012.

Therefore, renewables with a large energy yield in summer and early evening are most attractive from an environmental sustainability perspective. If the PV potential does not limit the optimization, western-oriented PV-systems are favoured like in the regions Südwestpfalz and Garmisch-Partenkirchen. In case of Nordfriesland and Stormarn the potential of PV-systems is reached, leading to more efficient and southern oriented PV-systems supported by wind turbines. The reason for this switch from western- to southern oriented PV systems is probably caused by a marginally worse fit to the emissions profile of the southern-oriented systems, which is compensated by their substantially larger yield.

It is also noteworthy that with a large share of PV-systems and fewer full load hours compared to wind turbines, this result leads to the highest investments for all of the objective functions.

4.1.3 Security of supply

The results in Figure 10 exhibit a very similar composition for all regions. The optimization matches the regional load with the generation by PV-systems and wind turbines by minimizing the quadratic offset between load and generation, known as residual load. The regional load has a daily variation between 60 and 120 MW in case of Nordfriesland, visualized in Figure 12. Two peaks are visible, one around 10:00 till 12:00 UTC and another in the late afternoon, but the seasonal variation of load is less pronounced. The seasonal differences between PV and wind-profiles are high, however: wind is on average higher and more constant in winter, PV-systems generate most of their yearly power in the summer months. This is why a well-balanced residual load needs both, PV-systems as well as wind turbines.

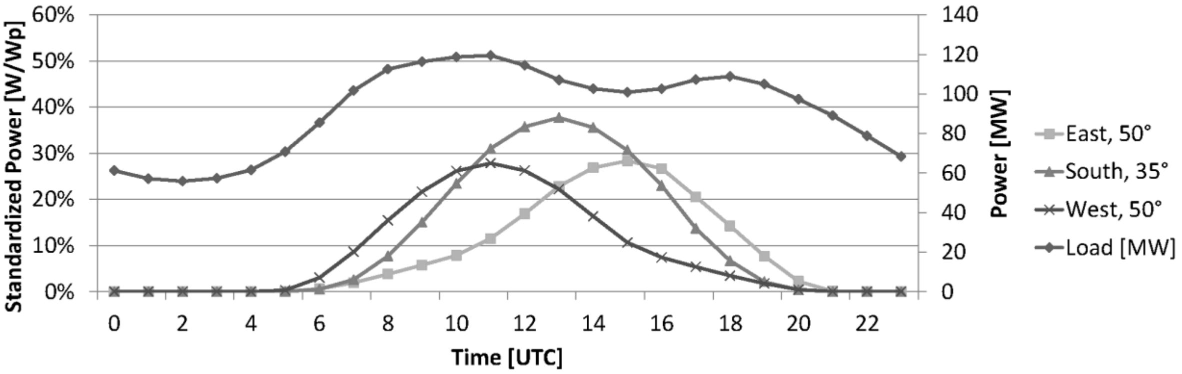


Figure 12: Diurnal average load and PV generation profiles for Nordfriesland.

Regarding PV-systems, a generation over most of the day is needed, matching the load peaks in a good way. Three PV-profiles are displayed in Figure 12: East-, south- and west-oriented PV-systems with an inclination of 35° and 50°. The diagram shows how east and west facing systems complement each other well, caused in particular by their contrasting profiles. Furthermore, these systems match the load peaks far better than south-oriented PV-systems.

In summary, the objective security of supply requires a broad generation portfolio, composited of dissimilar profiles, in order to generate power most of the time and minimize fluctuations of the residual load. Therefore, PV-systems facing east and west combined with wind turbines are most attractive.

In conclusion, the individual results depend on the regional load and the fluctuating production by PV and wind. Although results show regional differences, there are significant overall similarities, which allow drawing a general trend for each criterion, as it has been done in the previous section.

4.2 Critical reflections on the presented approach

This section presents a critical reflection on the approach and methodology. This critical reflection considers the shortcomings of the objective functions, the representativeness of the input data and the study regions. Finally, the sensitivities of the results to the input data are analysed.

4.2.1 The objective functions, input data and model regions

First, the goals of the policy triangle have to be addressed in the right way. In order to limit complexity, simplifications had to be made by choosing one objective criterion for each policy goal, which cannot represent the entire policy. Second, in the *Environmental sustainability* scenario, repercussions on the energy system if every region changed their generation patterns have not been considered. If that happens though, CO_2-factors would change, which were the basis for the objective function here. A third critical aspect during optimization is in the *Economic efficiency* scenario, where the spot market day-ahead price is used for economic compensation instead of guaranteed feed-in tariffs (which represents more of a macro-economic than an investor's point of view). Fourth, with *Security of supply,* one could argue that penalizing differences with a quadratic exponent is not enough. The basis for the layout of the grid is the expected extreme load peaks, e.g. Nordfriesland shows a higher maximum residual load for security of supply than for economic efficiency. The reason is a higher share of PV-systems. Although the residual load is more constant in average, the criterion could not avoid seldom but high spikes. The consideration of energy storage options could, however, remedy this problem.

The second aspect deals with the *exogenous data* used. A model is always a simplification of the reality. In the following table some relevant and limiting factors are presented:

Table 4: Critical assessment of exogenous data.

Exogenous data	Critique
$\boldsymbol{Demand_t \quad \forall\, t}$	*Synthetic, more variation and higher peaks are possible in reality*
$\boldsymbol{GenerationPV_{A,I,t} \quad \forall\, A, I, t}$	*Synthetic, one year, weather data of numeric weather model, more variation and higher peaks in reality*
$\boldsymbol{GenerationWind_t \quad \forall\, t}$	*Synthetic, one year, weather data of numeric weather model, more variation and higher peaks in reality*
$\boldsymbol{GermanPowerMixCO_2Emissions_t \quad \forall\, t}$	*Power mix will change when big regions change generation portfolio*
$\boldsymbol{GermanPowerPrice_t \quad \forall\, t}$	*Only one year, not necessarily relevant*
$\boldsymbol{ConsumerPowerPrice}$	*future changes (especially rises) are highly likely but not considered here*
$\boldsymbol{SpecificCostPV}$	*Different for individual PV-systems, further change expected*
$\boldsymbol{SpecificCostWind}$	*Different for individual wind turbines, further change expected*

To mitigate errors when transferring the conclusions, four different regions, which differ in demand, their potential regarding irradiation and wind speed and their capacity potential for renewables, have been considered. However, it is difficult to draw general conclusions out of regional results. Further research might consider more regions or employ a methodology which ensures the representativeness of the chosen regions.

4.2.2 Sensitivity analysis

A good way to evaluate the critical aspects of the exogenous data and the composition of the renewables is a sensitivity analysis.

Exogenous data and its influence on recommended composition: During the development of the optimization tool, different input values have been considered and were adjusted. The results showed a high robustness against variations leading only to small changes in the general trends. Different investments for PV-systems and wind turbines will change the recommended composition for example, but not the general statement that both renewables are needed for a wide scope of different cost assumptions. In case of sustainability, only the temporal matching of generation, load and emissions is relevant for the results, not so much the absolute height. For security of supply, the findings are similar. It can be stated, that the architecture of the objective functions creates strong incentives making the temporal characteristics of the time series important but not the exact values. This is encouraging for an optimization tool, building on simulated time series for generation and load as the absolute height is difficult to simulate but the temporal characteristics for a big region with aggregation effects better to resolve.

Composition of renewables and its influence on target value: Despite each criterion reaching an optimal composition of PV-systems and wind turbines, the target value still shows only small differences for a wide scope of different compositions. This also becomes obvious when comparing results of the criterion “economic efficiency” to “security of supply”. Optimizing for economic reasons leads to a higher share of wind turbines and PV-systems facing south, but the target value is only 4% - 8% higher. “Security of supply” in contrast needs less wind turbines and more PV-systems oriented west and east, which increases its target value 3% - 10% when compared to “economic efficiency”.

5 Summary, conclusions and outlook

Motivated by attempts to consider to full system costs as well as environmental and security of supply aspects of PV systems resulting from different system setups, this paper has investigated the extent to which PV systems and wind turbines are able to contribute towards the three objectives of the German energy policy triangle without causing additional investment in networks and storage. In particular this means the following research questions have been addressed:

- How can optimization criteria relating to economic, environmental and security of supply aspects be fulfilled through a varied inclination and azimuth angle of PV systems as well as overall PV and wind capacity for a given region?
- Can general trends be generalised from the examination of four representative regions?
- How robust are the results regarding changes in the composition of PV and wind power systems?

According to the national energy policy triangle three criteria - Economic efficiency, environmental sustainability and security of supply - have been developed and objective functions defined. Four representative German regions, which differ in their demand patterns as well as in their capabilities to exploit different renewable energies, were selected. The installed capacity for these regions was required to match 100% of the regional annual electricity demand. Hourly profiles for load and different mounting configurations of PV-systems and a wind turbine have been simulated. The optimization was solved for each criterion and region by varying the installed capacity for each PV-system configuration and the wind turbine, deciding which investments should be made.

The results depend on the regional load and the fluctuating production by PV and wind. Results show local differences but overall similarities, which allow drawing a general trend for each of the different criteria:

- *Economic efficiency*: South-oriented PV-systems and a high share of wind turbines are favoured.
- *Environmental sustainability*: A high share of PV-systems facing west is needed when PV-capacity potential is high. If PV-potential is a limiting factor, PV-systems facing south and additional wind turbines should be built.
- *Security of supply:* A broad generation portfolio of renewables is needed, leading to east- and west-oriented PV-systems and wind turbines.

The results are robust for changes in the composition, meaning the general trends can be used as a first recommendation for each criterion and region. However, for individual regions and to consider, for example, network constraints, further, more detailed research is necessary.

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