Energy 84 (2015) 563–574

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

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

Sven Killinger [a,*], Kai Mainzer [b], Russell McKenna [b], Niklas Kreifels [a], Wolf Fichtner [b]

[a] Division Smart Grids, Fraunhofer-Institute for Solar Energy Systems ISE, 79110 Freiburg, Germany
[b] Chair for Energy Economics, Karlsruhe Institute of Technology (KIT), 76187 Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form
19 February 2015
Accepted 5 March 2015
Available online 11 April 2015

Keywords:
Optimisation
Energy-political objectives
PV orientation
Wind turbines
Autarky
Regional context

ABSTRACT

Currently, most PV (photovoltaic) modules are aligned in a way that maximizes annual yields. With an increasing number of PV installations, this leads to significant power peaks and could threaten energy policy objectives. Apparently sub-optimal inclinations and azimuth angles of PV plants on building roofs could 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 regional mix of wind and PV installations with different mounting configurations in order to locally generate the annual electricity demand. It does so by adhering to three distinctive energy policy goals: economic efficiency, environmental sustainability and security of supply. The hourly yields of wind parks and nine PV orientations are simulated for four representative NUTS3-regions in Germany. These profiles are combined with regional electricity demand profiles and fed into an optimisation model. 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 obtained. The results indicate that the optimal mix differs significantly for each of the chosen goals, depending on regional conditions, but also shows a high transferability of general statements.

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 PV (photovoltaic) capacities in Germany. From total installed electricity generation capacities for PV and onshore wind of 2.1 and 18.4 GW respectively at the end of 2005, the latest statistics report 35.9 and 34.7 GW respectively at the end of 2013 [1]. Despite a short-term drop in the expansion rate in 2013, further progress towards national renewable energy goals means that this trend is very likely to continue in the near and medium term future. 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 [2]), compared to current electricity generation costs of around 12 €ct/kWh [3] for new PV plants in Germany, the economic attractiveness of generating PV-electricity for self-consumption has drastically improved.

From a plant operator's perspective, the LCOEs (levelised costs of electricity) are the conventional economic yardstick with which to assess generation technologies like PV-systems and wind turbines [4]. 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 irradiance, average wind speed), applied technology and orientation/hub height. 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 as has been shown by Ueckerdt et al. [5].

* Corresponding author.
E-mail address: sven.killinger@ise.fraunhofer.de (S. Killinger).

http://dx.doi.org/10.1016/j.energy.2015.03.050
0360-5442/© 2015 Elsevier Ltd. All rights reserved.

Hence an orientation of PV-systems and combination with wind turbines, which appears economically suboptimal from an investor's point of view, 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, and the associated trade-offs, are discussed by Østergaard [6]. He mentions several criteria, including renewable energy shares, primary energy consumption, economic and social costs, carbon dioxide emissions, as well as 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. The different optimisation criteria yield quite different results. A crucial aspect seems to be whether or not the region is considered in island or connected mode, or a combination of the two; in the former case large expansions in renewables generators are not feasible unless spatial (networks) and temporal (storage) relocation infrastructure are also developed.

The complementarity of solar and wind resources can be exploited to smooth the generation curve, as these two resources generally exhibit quite different availabilities [7–9]. Budischak et al. [7] developed a model to analyse the total system costs of providing almost 100% of electricity from renewables to the PJM (Pennsylvania-New Jersey–Maryland) Interconnection system in the USA. Their model minimizes total system costs for electricity supply, based on a parameterisation for the years 2008 and 2030, and treating 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 and Rowlands [8] 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 when two resources and locations are considered. There is no additional benefit (but neither a necessary disadvantage) in terms of further residual load smoothing from a geographic dispersal of the plants, i.e. wind and solar in different locations, although electricity networks were not explicitly considered in the contribution, so this conclusion should be treated with caution.

Lund [9] examines the large-scale integration of the RES (renewable energy sources) wind, PV and wave into the electricity supply system of Denmark. The energy simulation model EnergyPLAN is employed to determine the percentage of RES that could be integrated, by avoiding excess electricity production and considering requirements for additional ancillary services. He concludes that the optimal mixture is with onshore wind producing around 50% of the total, with the proportions of wind and PV depending on the total renewable fraction of electricity generation: lower overall RES fractions favour higher PV penetrations and vice versa. The approach is a purely technical one, i.e. it identifies optimal combinations of RES without considering costs and other environmental, social, and practical aspects.

Several authors have analysed the technical potential to optimise the sizing and configuration of PV systems [10–12]. For example, Weniger et al. [10] optimise the sizing of residential PV and battery systems with a view to maximizing the self-consumption rate (defined as the fraction of PV electricity that is used for own consumption) and degree of self-sufficiency (defined as the fraction of the total (annual) electricity consumption delivered by the PV/battery system). Widén et al. [11] focus on the technical potential for matching the electricity 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 DSM (demand side management) 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 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. [12] undertake a purely technical analysis by employing a developed TRNSYS simulation model to optimise the setup of grid-connected photovoltaic systems. The study also shows that there are often regional and local deviations from maximum yields by facing directly south (azimuth angle of 90°) and with an inclination angle of 30°, such as for a location in Ireland where the optimal inclination was found to be 20°. Finally, in their investigation of mismatch factors for ZEBs (zero-energy buildings), Lund et al. [13] find that the challenge of integrating large amounts of PV with battery storage is best addressed at the utility level.

In an unpublished study, Tröster and Schmidt [14] investigate the impact of PV module orientation on grid operation by analysing several discrete orientation configurations for the city of Aachen in Germany. They conclude that east-west facing plants (or similar) have capacity factors not much lower than south facing plants, as well as power gradients and peak power outputs significantly lower, which has advantages for the electricity network and the integration of PV electricity. The authors conclude that there is no obviously optimal system orientation as this depends on the priorities and the prevailing conditions in the specific location.

Other authors also consider economic aspects in their approach to setup optimisation [15–17]. Mondol et al. [15] further develop their methodology from Mondol et al. [12] 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. 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.

Hartner et al. [16] 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 displaced power plant park, hence neglecting system integration costs in the form of network expansion and balancing power. 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 and Bhandari [17] investigate the economics of PV systems in open spaces with an east-west orientation. A simulation model is developed and employed to large (over 3 ha) open space plants in two locations, one with high irradiance (Freiburg) and one with lower irradiance (Hamburg), in order to determine the respective electricity production and associated BOS (balance of system) 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 irradiance.

1.3. Objectives, methodology and overview

The foregoing discussion has highlighted several previous studies concerned with the technical and economic optimisation of the orientation of PV systems, for example to minimize overall costs 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, some studies are purely technical. Hence this paper has the primary 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 installed PV to wind capacity. A second objective is to determine the extent to which it is possible for a region to become (on balance, over the year) autark regarding electricity, and the extent to which supply can be adapted to demand through different system configurations.

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* [18], the installed capacity and orientation of PV and wind systems in these regions 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 summarizes and concludes.

2. Methods

2.1. Construction of renewable power generation profiles

For the construction of power generation profiles for PV and wind power, two different methods can be applied. Historical data is the basis for real and site-specific profiles and was applied by Lund [19]. Another method is the calculation of synthetic profiles from weather data. This method provides the advantage that profiles can be generated for arbitrary locations and orientations, which is why it was chosen for this study.

In this section a tool is presented, which is used to generate time series of PV and wind power for different systems and regions and firstly described in Ref. [20]. It consists of two main parts:

- *Weather Model*: Highly spatially and temporally resolved weather data from the 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 DWD (Deutscher Wetterdienst) and calculated by the numerical weather model COSMO-DE as described in Baldauf et al. [21]. The weather data of COSMO-DE relates to single grid points with an average offset of 2.8 km and a temporal interval of 1 h. The model used in this paper is restricted to the NUTS3-level (administrative districts), a spatial resolution which includes 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 [21]. 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 parameters:

- DNI (Direct Normal Irradiance) and DHI (Diffuse Horizontal Irradiance)
- Wind speed
- Roughness length of ground
- Temperature

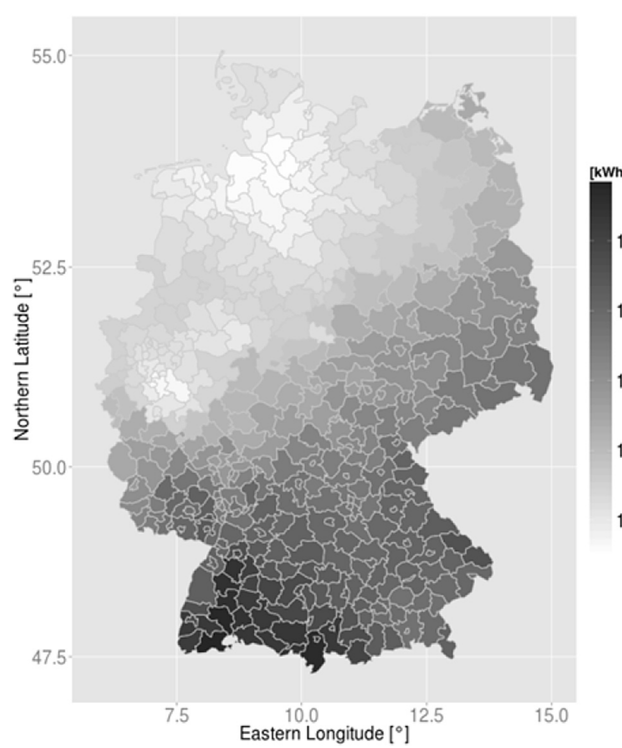

Fig. 1. Global irradiance on a horizontal surface 2012 (author's own illustration).

In this paper, weather data from the year 2012 is used. The sum of DNI (direct normal irradiance) and DHI (diffuse horizontal irradiance), i.e. global irradiation, is displayed in Fig. 1. The roughness length is needed to calculate the wind speed for different hub heights from the wind speed at 10 m with the logarithmic wind profile as demonstrated in Ref. [22]. An overview of the average wind speed at 100 m is given in Fig. 2.

2.1.2. PV and wind model

The basis for the PV- and Wind-Model are hourly time series of the weather data, described in the previous section, and an individual methodology for each technology, as presented in this section.

In order to simulate the generated power for individual PV-systems, the points in Fig. 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.

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

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 Fig. 5 and Fig. 6. A statistical analysis with empirical 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 by Mainzer et al. [27] 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

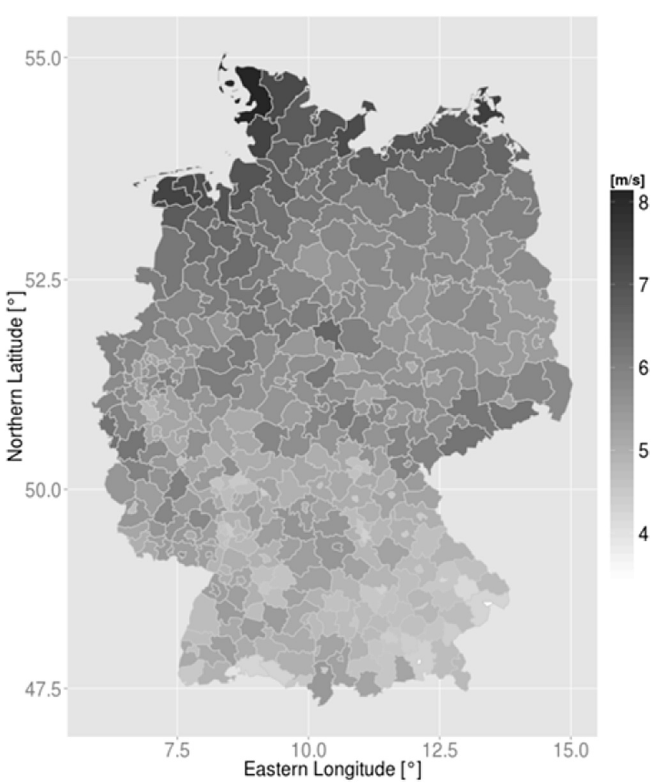

Fig. 2. Wind speed in 100 m height 2012 (author's own illustration).

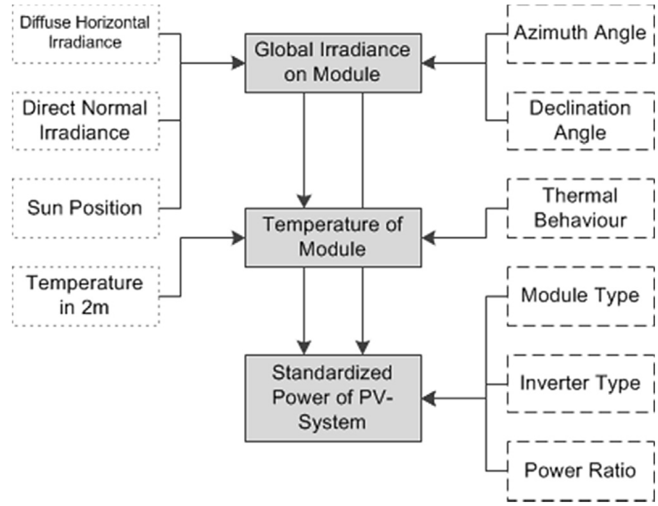

Fig. 3. Methodology to simulate standardized PV power (author's own work, based on related methods described in Refs. [23–26]).

irradiance 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 by assuming an even distribution of module orientations.

For wind, the cost-potential results from McKenna et al. [28] 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 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

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. [27], an exemplary result is given in Fig. 7.

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

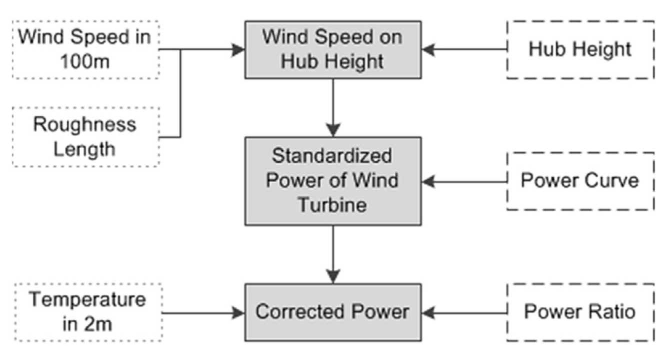

Fig. 4. Methodology to simulate standardized wind power (author's own work, based on related methods described in Refs. [22,26]).

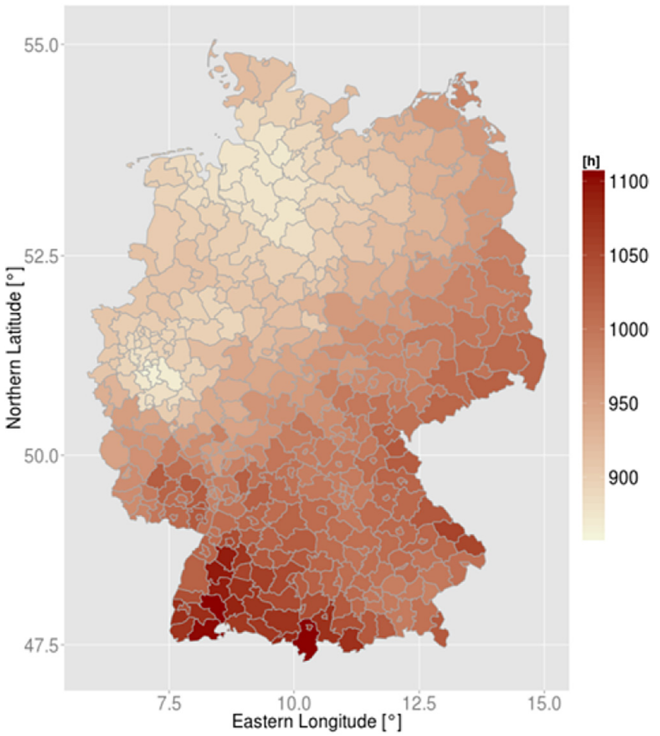

Fig. 5. Full load hours for a representative mixture of PV power plants in 2012 (author's own illustration).

on available irradiance 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. Fig. 8 gives an overview of the regions. FLH (Full load hours) were simulated according to the methodology presented in chapter 2.1 for a mixture of different PV-system and wind turbines.

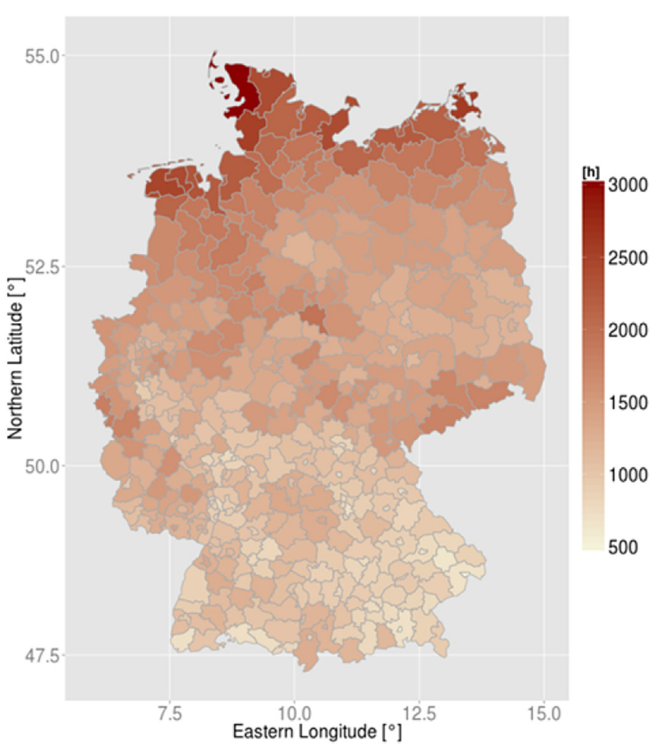

Fig. 6. Full load hours for a representative mixture of wind turbines in 2012 (author's own illustration).

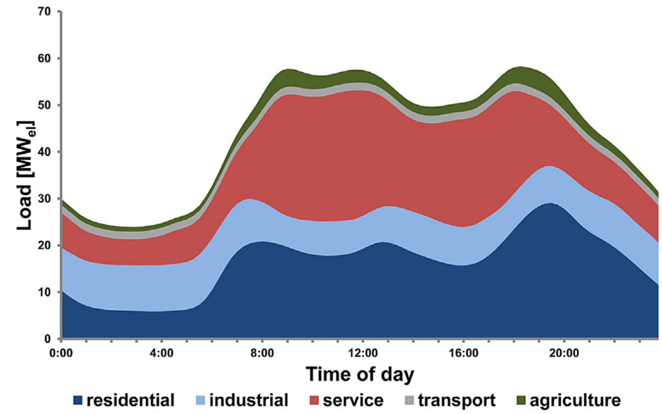

Fig. 7. Electricity demand profile for a winter workday in Garmisch-Partenkirchen (own illustration).

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 unit of electricity is rated by calculating the avoided emissions that the conventional power plant fleet would have produced, depending on fuel types and efficiencies. 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. Fig. 9).

Using technology-specific CO_2-equivalent emissions retrieved from Refs. [29–31] combined with the information about which power plants were in use during each hour (power plant dispatching data was retrieved from Ref. [32]), an hourly CO_2-equivalent emission curve of the German power plant mix has been constructed for the year 2012, as shown in Fig. 9.

It is clear from Fig. 9 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 maintenance) and differ up to 20% between 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 optimisation approach, are presented and listed in the Appendix.

2.4.1. Decision variables and indices

The decision variables for each region r are the installed capacity IC for each combination of azimuth A and inclination angles I for PV and the installed wind capacity.

$$IC^{PV}_{A,I,r} \quad \forall A, I, r \tag{1}$$

$$IC^{Wi}_{r} \quad \forall r \tag{2}$$

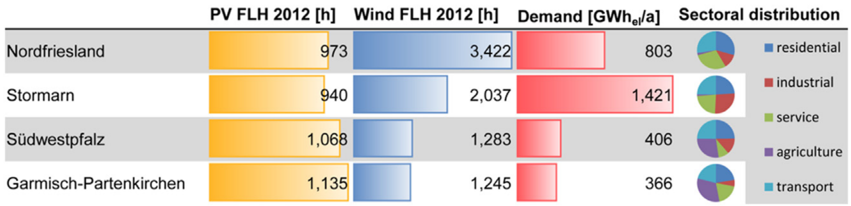

Fig. 8. Characterization of the four study regions.

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 indices A and I.

$$A = \{East; South; West\} \tag{3}$$

$$I = \{20°; 35°; 50°\} \tag{4}$$

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

2.4.2.1. Economic efficiency. The criterion *economic efficiency* involves taking a macro-economic perspective to determine the most economically efficient allocation of resources. In this case the criterion consists of three parts, which combined form the annual costs AC_r of a given solution from a macro-economic point of view: annual investment IV_r (assuming a straight-line-depreciation), power consumption costs $PC_{t,r}$ and the economic value of feed-in $FI_{t,r}$. The criterion as defined here does not consider specific subsidisation schemes, which compensate each generated kWh of electricity with a fixed tariff, as these merely represent a reallocation of resources within the economy and are therefore only relevant from an investor's perspective.

$$\min AC_r := \frac{IV_r}{DP} + \sum_t PC_{t,r} - \sum_t FI_{t,r} \quad \forall r \tag{5}$$

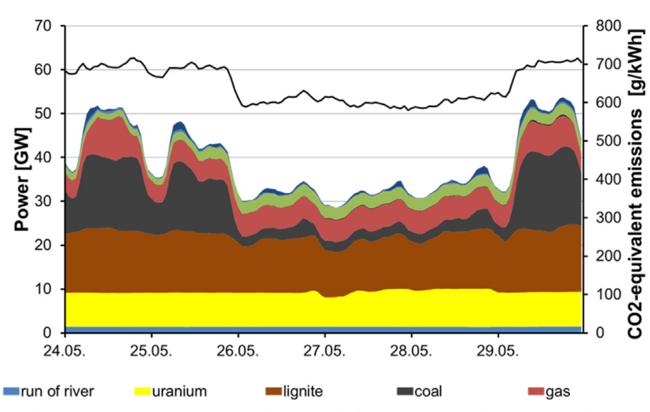

Fig. 9. Excerpt from conventional power plant production schedule and hourly CO_2-equivalent emissions curve for 2012 (own illustration).

The investment IV_r depends on specific investments SI [€/kW$_p$] and the installed capacity IC [kW$_p$] of each technology.

$$IV_r := SI^{PV} * \sum_{A,I}\left(IC^{PV}_{A,I,r}\right) + SI^{Wi} * IC^{Wi}_r \quad \forall r \tag{6}$$

An important time series for all optimisation criteria is the residual load $RL_{t,r}$, which is the difference between the regional electricity demand profile $D_{t,r}$, simulated by the methodology described in chapter 2.2, and the total renewable electricity supply profile $S_{t,r}$ generated by all PV-systems and wind turbines with an installed capacity IC_r and normalized generation $G_{t,r}$.

$$RL_{t,r} := D_{t,r} - S_{t,r} \quad \forall t, r \tag{7}$$

$$S_{t,r} := \sum_{A,I}\left(IC^{PV}_{A,I,r} * G^{PV}_{A,I,t,r}\right) + IC^{Wi}_r * G^{Wi}_{t,r} \quad \forall t, r \tag{8}$$

The power consumption costs $PC_{t,r}$ depend on the residual load $RL_{t,r}$, the German power price GPP_t, given for each time step by the EEX-Transparency platform [31] and the network charge NC which is parameterized with 5.94 €cent/kW [33]. They are only positive when the residual load is positive, otherwise they are zero.

$$PC_{t,r} := \begin{cases} RL_{t,r} * (GPP_t + NC), & RL_{t,r} \geq 0 \\ 0, & RL_{t,r} < 0 \end{cases} \quad \forall t, r \tag{9}$$

The macro-economic value of feed-in $FI_{t,r}$ on the other hand, as opposed to the value $PC_{t,r}$, depends on the residual load $RL_{t,r}$, the German power price GPP_t and the network charge NC. It should be noted that a negative value for $GPP_t - NC$ could occur in cases when market prices are lower than the costs of electricity transportation.

$$FI_{t,r} := \begin{cases} 0, & RL_{t,r} \geq 0 \\ -RL_{t,r} * (GPP_t - NC), & RL_{t,r} < 0 \end{cases} \quad \forall t, r \tag{10}$$

2.4.2.2. Sustainability. The second objective of the energy policy triangle, *environmental sustainability*, is interpreted in a way to avoid greenhouse gas emissions GHG_r and hinder the environmental impact. In contrary to other sustainability indicators, greenhouse gas emissions are easily quantifiable and have been proven by climate researchers to be the driving factor of anthropogenic climate change. Using the hourly CO_2-equivalents E_t 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 $RL_{t,r}$) in times of high CO_2-equivalents of conventional power generation. There is no distinction between positive and negative residual load, which expresses the assumption that feeding (renewable) electricity to the grid is equivalent to replacing grid electricity.

$$\min GHG_r := \sum_t (RL_{t,r} * E_t) \quad \forall r \tag{11}$$

2.4.2.3. 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 and thus to reduce the regional stress on the distribution grid, this objective function minimizes the standard deviation of the residual load SD_r, which is a measure of its variation from the average value. This minimization thus yields a more constant residual load with lower peaks.

$$\min SD_r := \sqrt{\frac{1}{t-1}\sum_t \left(RL_{t,r} - \overline{RL_r}\right)^2} \quad \forall r \tag{12}$$

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 $S_{t,r}$ and demand $D_{t,r}$ with the option to import/export electricity is pursued.

$$\sum_t S_{t,r} = \sum_t D_{t,r} \quad \forall t, r \tag{13}$$

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

$$\sum_{A,I} \left(IC^{PV}_{A,I,r}\right) \le P^{PV}_r \quad \forall r \tag{14}$$

$$IC^{Wi}_r \le P^{Wi}_r \quad \forall r \tag{15}$$

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

Table 1 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.

2.5. Model size and implementation

The previously described optimisation model consists of ten continuous decision variables. The objective function of *environmental sustainability* is linear; the model has been solved with Microsoft Excel's Simplex LP solver in this case. In the cases of *economic efficiency* and *security of supply*, the objective functions are nonlinear, which is why Microsoft Excel's GRG Nonlinear solver was used for the model. The computing time ranges from 2 s (linear model) to 30 s (nonlinear model) on a machine with a 2.5 GHz Quad-Core processor and 4 GB RAM.

Table 1
Overview of exogenous data used with respective sources.

Exogenous data	Value	Unit	Source
$D_{t,r}$ $\forall\, t, r$	Time series for 2012	kW	Chapter 2.2
$G^{PV}_{A,I,t,r}$ $\forall\, A, I, t, r$	Time series for 2012	kW	Chapter 2.1
$G^{Wi}_{t,r}$ $\forall t, r$	Time series for 2012	kW	Chapter 2.1
E_t $\forall t$	Time series for 2012	g CO_2e/kWh	Chapter 2.3
GPP_t $\forall t$	Time series for 2012	€/kWh	[34]
NC	5.94	€ cent/kWh	[33]
SI^{PV}	1400	€/kWp	[3]
SI^{Wi}	1400	€/kWp	[3]
P^{PV}	Variable	kWp	[27]
P^{Wi}	Variable	kWp	[28]
DP	20	a	Assumption

3. Results

3.1. Economic efficiency

Fig. 10 shows the optimal regional allocation of different PV-systems and wind turbines in percentage of the overall installed capacity when optimising for *economic efficiency*. Three aspects become apparent.

- The incoming global irradiance and the average wind speed in a region have strong influence as the ratio of investment and power generation improves with increasing values.
- Wind turbines and PV systems are needed together in regions with similar full load hours of both technologies over the year.
- PV systems facing south are obviously preferred when the *economic efficiency* is to be maximized.

It should be noted that PV systems are needed in Stormarn as the potential of wind turbines was reached.

3.2. Environmental sustainability

When optimising for *environmental 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.

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 Fig. 12 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 though with a share below 50%.

3.4. Comparison of three objectives

In Table 2, different parameters of two criteria and their relative change compared to *economic efficiency* are displayed. These values

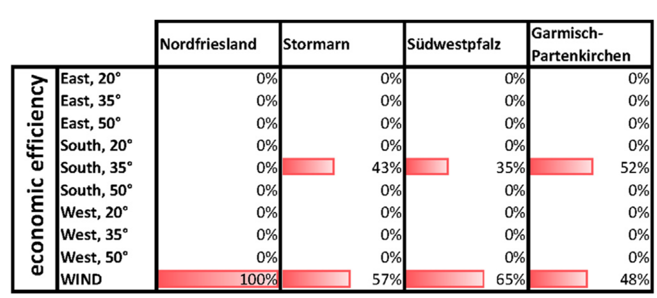

Fig. 10. Composition [% of total capacity] for different PV-systems and wind turbines for the criterion economic efficiency.

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 as having the same influence. In the second step the average of all standardized, regional parameters was built and compared to the criterion *economic efficiency*.

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 large 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 the shift to western oriented plants, as shown in Fig. 11.

Taking a closer look at the criterion *security of supply* reveals smaller positive and negative load change gradients and a higher minimum residual load, which was the aim of the objective function itself. Investments are 29% 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 as has been shown by Kreifels et al. [35]. The smaller gradients and a more constant residual load are a consequence of PV-systems facing east and west (Fig. 12), 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 the energy grid needs alternative generation or storage systems to cover the load.

4. Discussion

In order to investigate the transferability of the results to other regions in Germany, the three optimisation criteria are analysed in the following sections including the results of Figs. 10–12. 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 Fig. 8 lead to regional differences in the generated energy, which are high especially in the case of wind turbines.

4.1. Economic efficiency

The optimisation criterion consists of two main parts: the (avoided) energy costs (when regional demand exceeds generation) and, respectively, the economic value of the electricity fed back to the net (when generation exceeds demand). The investment is the other factor and accounts for one third up to more than half of the target value.

On average, it is more lucrative to use electricity for self-consumption rather than to feed it into the local grid due to network charges. Increasing self-consumption and matching load in peak times has therefore a strong influence on this optimisation criterion. This has to be realized with an efficient portfolio of renewables with high full load hours and therefore low electricity productions costs. Therefore there is a strong tendency towards wind turbines, especially in the northern regions Stormarn and Nordfriesland. The full load hours of renewables are more equal in Garmisch-Partenkirchen and Südwestpfalz, enabling the installation of south oriented PV-systems with an inclination of 35°, which generate the highest amount of energy in Germany compared to other PV-systems [24]. Although on average the highest German power prices are reached in the morning and late afternoon, east- and western oriented PV systems cannot yet compensate their higher specific investments. This might change in the future.

In result, an energy system with high *economic efficiency* has to consist of a well-balanced mixture of PV-systems and wind turbines. The exact regional ratio depends mostly on the temporal distribution and the overall yearly production of the individual generation profiles.

sustainability	Nordfriesland	Stormarn	Südwestpfalz	Garmisch-Partenkirchen
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%

Fig. 11. Composition [% of total capacity] for different PV-systems and wind turbines for the criterion environmental sustainability.

security of supply	Nordfriesland	Stormarn	Südwestpfalz	Garmisch-Partenkirchen
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%

Fig. 12. Composition [% of total capacity] for different PV-systems and wind turbines for the criterion security of supply.

4.2. 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 Fig. 13. The diurnal average of CO_2-equivalent emissions is displayed for a representative month in winter and summer. The figure shows clearly that daily differences are small with a peak in the early evening, but seasonal differences are more significant. In summer, emissions are larger due to a high percentage of coal powered plants in the energy system.

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 optimisation, 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

Table 2
Selected parameters and their relative change compared to criteria economic efficiency.

	Environmental sustainability	Security of supply
Min residual load change gradient	42%	−8%
Max residual load change gradient	50%	−10%
Min residual load	35%	−4%
Max residual load	0%	0%
Investment	50%	29%
Installed PV-systems	254%	103%
Installed wind turbines	−78%	−18%
FLH for PV plant mix	−15%	−25%

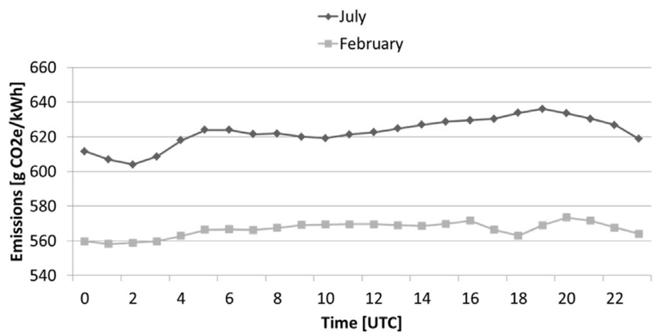

Fig. 13. Diurnal average of CO_2-equivalent emissions for February and July 2012 (own illustration).

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.

4.3. Security of supply

The results in Fig. 12 exhibit a very similar composition for all regions. The regional load has a daily variation between 60 and 120 MW in Nordfriesland, visualized in Fig. 14. 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.

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 Fig. 14: 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. 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,

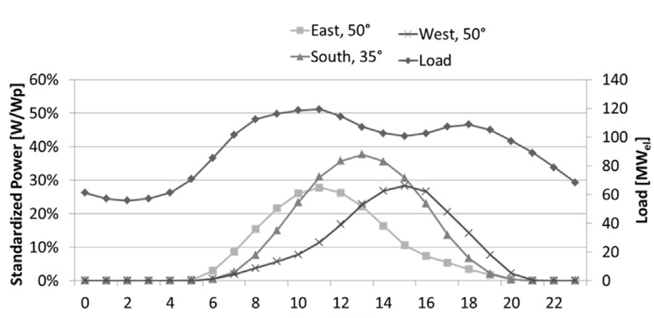

Fig. 14. Diurnal average load and PV generation profiles for Nordfriesland (own illustration).

which allow drawing a general trend for each criterion, as it has been done in this section.

4.4. 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 (section 4.4.1). Finally, the sensitivities of the results to the input data are analysed (section 4.4.2).

4.4.1. The objective functions, input data and model regions

First, the goals of the policy triangle have to be addressed in the right way. To limit complexity, simplifications had to be made by choosing one objective criterion for each policy goal. Hence, the entire policy framework cannot be completely represented.

A critical aspect during optimisation is in the *economic efficiency* scenario, where the day-ahead spot market price, taken to be representative for all traded electricity, is combined with a fixed network charge. Although a fixed network charge is also used for consumer power prices, not every kWh of energy will cause the same transmission costs. Especially the maximum generation of renewables and peak load will determine the overall network design and be responsible for a high share of the total network charge. However this topic exceeds the scope of the paper and was not regarded in detail.

In the *environmental sustainability* scenario, repercussions on the energy system have not been considered. These would occur though if every region changed their generation patterns. Hence, CO_2-factors, being the objective function's base, would change in that case. The carbon footprint of PV and wind power is considered small enough to be neglected in the calculations.

In terms of *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 on average, the criterion could not avoid rare high peaks. Energy storage such as batteries could deal with this.

Exogenous data is another critical aspect as it only can reflect a simplified reality. In Table 3 some relevant limitations caused by the data which was used are presented.

A last aspect deals with the results' representativeness. The geographical distributions of renewable electricity generation within the studied regions as well as the topology of the distribution grid have not been explicitly considered. It should also be noted that only a part of the energy system is regarded in this paper: the heat and mobility sectors as well as other generation and storage technologies have been excluded from the analysis. Considering these would permit the analysis of interactions between sectors and technologies which could enhance the method, as shown by Lund, Andersen et al. [36].

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

4.4.2. Sensitivity analysis

Due to the multi-dimensional nature of the results as well as the input time series, a complete sensitivity analysis, where each

Table 3
Critical assessment of exogenous data.

Exogenous data	Critique
$D_{t,r} \quad \forall t,r$	• Synthetic → more variation and higher peaks are possible in reality
$G^{PV}_{A,I,t,r} \quad \forall A,I,t,r$	• One year of hourly weather data from numeric weather model → due to averaging over 1 h, more variation and higher peaks expected in reality
$G^{Wi}_{t,r} \quad \forall t,r$	• One year of hourly weather data from numeric weather model → due to averaging over 1 h, more variation and higher peaks expected in reality
$E_t \quad \forall t$	• Power mix will change when generation portfolio changes on a large scale in Germany
$GPP_t \quad \forall t$	• Time-series of only one year → possible future changes due to market design, structure of the generation as well as demand side are not considered
NC	• Future changes are very likely but not considered here
SI^{PV}	• Different for individual PV-systems and year of construction
SI^{Wi}	• Different for individual PV-systems and year of construction
P^{PV}	• Only residential buildings considered → true potential might be larger • Directional distribution of potential is unknown → exploitation of singular directions might be unrealistic
P^{Wi}	• Determined with different wind turbines, but generation simulated only for the most suitable Vestas V90 turbine → Different technical potential for V90

parameter is varied and the relative change of the target value is measured, does not seem appropriate for the model presented in this paper. However, a sensitivity analysis has been conducted by varying some of the most critical parameters and describing the change of the results in a more qualitative way. This is summarized in this section.

In terms of *economic efficiency* the specific investments of each technology and the network charge are the most relevant parameters and have thus been varied:

- The ratio between the specific investments for PV-systems and wind turbines obviously impacts the resulting share of installed PV-systems and wind turbines. High specific investments of one technology lead to a substitution by the other technology.
- If the specific investments of PV are low, efficiency becomes less important and can be sacrificed in favour of a better balancing of supply and demand and better matching with the German power price, leading to an increasing share of east- and west oriented systems with an inclination of 50°.
- If the network charge is low, the German power price and the investments are the dominant influences. When the charge increases, self-consumption becomes more attractive while minimizing import and export. This leads to a broad generation portfolio (similar to scenario *security of supply*) with east- and west-oriented PV-systems and wind turbines.

In section 3.2, the results of *environmental sustainability* were presented, exhibiting regional differences caused by the limiting potential of PV. For this reason only the potential for PV was varied:

- Increasing the potential of PV systems in Nordfriesland and Stormarn leads to a higher share of PV systems and fewer wind turbines.
- If the PV potential is increased, wind turbines are increasingly substituted by southern oriented PV systems. If the PV potential further increases, western oriented PV systems are favoured, matching the temporal variable incentives by the optimisation criterion in the best way.

For the criterion *security of supply*, only the residual load is relevant, but the time series of generation and demand are difficult to vary without losing their representation of reality. Seasonal time changes or changes in the behaviour on the other hand can lead to a temporal shift. Furthermore, a certain robustness in the results is guaranteed through the selection of four structurally different regions. Therefore, the time series of demand were shifted for one to 2 h in both directions: this leads only to minor changes in the composition of east- and western oriented PV-systems, exhibiting a high robustness of the results presented in Fig. 12.

It can be concluded 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 optimisation tool, building on simulated time series for supply and demand, as the absolute height is difficult to simulate but the temporal characteristics for a large region with aggregation effects are more easily resolved.

5. Conclusions

Motivated by attempts to consider *economic efficiency* as well as *environmental sustainability* and *security of supply* aspects, this paper has investigated the extent to which different PV and wind system setups are able to contribute towards the three objectives of the German energy policy triangle from a macro-economic point of view without causing additional investment in local networks and storage. In particular this means the following research questions have been addressed:

- How can optimisation 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 derived 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 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 produce 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 optimisation 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 mainly on the regional load as well as the potential and the fluctuating production by PV and wind turbines, showing local differences but overall similarities, which allow drawing a general trend for each of the different criteria (given as ratio PV:wind):

- *Economic efficiency*: South-oriented PV-systems and a high share of wind turbines are favoured: 0:1 in regions with high wind yields, 1:1 in regions with high solar yields.
- *Environmental sustainability*: A high share of PV-systems (nearly 1:0 if the potential is sufficient) facing west is needed. 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 and an optimal average ratio of 3:2.

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.

Until now, the economics from an investor's point of view have determined RE investments, meaning that the support policies for PV are purely oriented towards the LCOEs and therefore aiming at maximizing output for a given location. Given the objectives defined above, the economic support should be reconsidered towards the three distinctive energy policy goals, which might lead to incentives fostering PV plants and wind turbines to be located and operated in a way that optimises the energy system as a whole.

The quality of results could be enhanced by including measured data of weather stations and satellite based irradiance. Further improvements could also be achieved by correctly assessing the capacity and orientation of existing PV modules and wind turbines, e.g. based on the distribution of building orientations in the area.

Acknowledgements

The authors would like to acknowledge the support of the Nagelschneider Foundation in this work. The authors also gratefully acknowledge the financial support of INTERREG for the project PLAN-EE (Interreg C 31) and BMBF for the project “Wettbewerb Energieeffiziente Stadt” (03SF0415B).

Appendix.

Variables	
$IC^{PV}_{A,I,r}$	Installed capacity of PV with inclination angle *I*, azimuth angle *A* in region *r*
IC^{Wi}_{r}	Installed capacity of wind in region *r*
IV_r	Investment in region *r*
$PC_{t,r}$	Avoided power consumption costs in hour *t* and region *r*
$FI_{t,r}$	Economic value of feed-in in hour *t* and region *r*
$RL_{t,r}$	Residual load in hour *t* and region *r*
$D_{t,r}$	Demand in hour *t* and region *r*
$S_{t,r}$	Supply in hour *t* and region *r*
$G^{PV}_{A,I,t,r}$	Generation of PV system with inclination angle *I*, azimuth angle *A*, in hour *t* and region *r*
$G^{Wi}_{t,r}$	Generation of wind turbine in hour *t* and region *r*
GPP_t	German power price in hour *t*
E_t	CO_2-equivalents emissions in Germany in hour *t*
AC_r	Annual costs – objective function of *economic efficiency*
GHG_r	Greenhouse gas emissions – objective function of *environmental sustainability*
$SD_r(RL_r)$	Standard deviation of residual load in region *r* – objective function of *security of supply*
Parameters	
A	Azimuth angle
I	Inclination angle
R	Region
T	Hour of year 2012
DP	Depreciation period
SI^{PV}	Specific investments of PV
SI^{Wi}	Specific investments of wind
NC	Network charge
P^{PV}_r	Potential of PV in region *r*
P^{Wi}_r	Potential of wind in region *r*

References

[1] Federal Ministry for Economic Affairs and Energy (BMWi). Development of renewable energy sources in Germany 2013. 21.07.2014. Available from: www.bmwi.de.

[2] Federal Ministry for Economic Affairs and Energy (BMWi). Energiedaten Gesamtausgabe: Elektrizität für Haushalte 2013. 2014 [English title: Energy data complete issue: electricity for households 2013].

[3] Kost C, Mayer J, Thomsen J, Hartmann N, Senkpiel C, Philipps S, et al. Stromgestehungskosten Erneuerbare Energien. 28.05.2014. Available from: www.ise.fraunhofer.de/de [English title: Electricity production costs of renewable energies].

[4] Larsson S, Fantazzini D, Davidsson S, Kullander S, Höök M. Reviewing electricity production cost assessments. Renew Sustain Energy Rev 2014;30: 170–83.

[5] Ueckerdt F, Hirth L, Luderer G, Edenhofer O, System LCOE. What are the costs of variable renewables? Energy 2013;63:61–75.

[6] Østergaard PA. Reviewing optimisation criteria for energy systems analyses of renewable energy integration. Energy 2009;34(9):1236–45.

[7] Budischak C, Sewell D, Thomson H, Mach L, Veron DE, Kempton W. Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. J Power Sources 2013;225: 60–74.

[8] Hoicka CE, Rowlands IH. Solar and wind resource complementarity: advancing options for renewable electricity integration in Ontario, Canada. Renew Energy 2011;36:97–107.

[9] Lund H. Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renew Energy 2006;31:503–15.

[10] Weniger J, Tjden T, Quaschning V. Sizing of residential PV battery systems. Energy Procedia 2013;46:78–87.

[11] Widén J, Wäckelgård E, Lund PD. Options for improving the load matching capability of distributed photovoltaics: methodology and application to high-latitude data. Sol Energy 2009;83(11):1953–66.

[12] Mondol JD, Yohanis YG, Norton B. The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system. Renew Energy 2007;32(1):118–40.

[13] Lund H, Marszal A, Heiselberg P. Zero energy buildings and mismatch compensation factors. Energy Build 2011;43:1646–54.

[14] Tröster E, Schmidt J. Evaluating the impact of PV module orientation on grid operation. Darmstadt: Energynautics GmbH; 2012. p. 1–6.

[15] Mondol JD, Yohanis YG, Norton B. Optimising the economic viability of grid-connected photovoltaic systems. Appl Energy 2009;86(7–8):985–99.

[16] Hartner M, Ortner A, Hiesl A, Nicoara S. Maximaler Ertrag vs. Kostenminimum: Der Einfluss der Ausrichtung von PV-Modulen auf den Marktwert und die Systemkosten. In: Konferenz Energieinnovation/29. Symposium Photovoltaische Solarenergie Bad Staffelstein; 2014 [English title: Maximum yield vs. minimum costs: the influence of the orientation of PV modules on the market value and the system cost].

[17] Waldmann P, Bhandari R. Vergleichende Analyse der technisch-wirtschaftlichen Bedingungen von PV-Anlagen Mit Süd- und Ost-West-Ausrichtung. Z Energiewirtschaft 2014;38:27–36 [English title: Comparative analysis of the technical and economic conditions of PV systems with south and east-west orientation].

[18] Federal Ministry of Justice and Consumer Protection (BmJV). Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - EnWG). 2005 [English title: Law on electricity and gas supply].

[19] Lund H. Excess electricity diagrams and the integration of renewable energy. Int J Sustain Energy 2003;23(4):149–56.

[20] McKenna R, Heffels T, Merkel E, Fehrenbach D, Killinger S, Fichtner W. Selected approaches to integration management for renewable energies. UmweltWirtschaftsForum 2013;21(3–4):199–207.

[21] Baldauf M, Klink S, Reinhardt T, Schraff CK, editors. Kurze Beschreibung des Lokal-Modells Kürzestfrist COSMO-DE (LMK) und seiner Datenbanken auf dem Datenserver des DWD. Offenbach: German Weather Service (DWD); 2011 [English title: Short description of the local model shortest term COSMO-DE (LMK) and its databases on the server of the DWD].

[22] Quaschning V. Regenerative Energiesysteme: Technologie - Berechnung - Simulation. 8th ed. München: Carl Hanser Verlag; 2013 [English title: Renewable energy systems: technology – calculation – simulation].

[23] Huld T, Gottschalg R, Beyer HG, Topic M. Mapping the performance of PV modules, effects of module type and data averaging. Sol Energy 2010;84(2): 324–38.

[24] Suri M, Huld TA, Dunlop ED, Ossenbrink Heinz A. Potential of solar electricity generation in the European Union member states and candidate countries. Sol Energy 2007;81:1295–305.

[25] Macêdo WN, Zilles R. Operational results of grid-connected photovoltaic system with different inverter's sizing factors (ISF). Prog Photovolt Res Appl 2007;15:337–52.

[26] Schubert G. Modellierung der stündlichen Photovoltaik- und Windstromeinspeisung in Europa. In: 12. Symposium Energieinnovation, 15.-17.2.2012, Graz/Austria; 2012 [English title: Modeling of hourly photovoltaic and wind power generation in Europe].

[27] Mainzer K, Fath K, McKenna R, Stengel J, Fichtner W, Schultmann F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. Sol Energy 2014;105:715–31.
[28] McKenna R, Hollnaicher S, Fichtner W. Cost-potential curves for onshore wind energy: a high-resolution analysis for Germany. Appl Energy 2014;115:103–15.
[29] Wagner H, Koch M, Burkhardt J, Große Böckmann T, Feck N, Kurse P. CO_2-Emissionen der Stromerzeugung: Ein ganzheitlicher Vergleich verschiedener Techniken. BWK 59 2007. 2007. p. 44–52 [English title: CO_2 emissions from power generation: a holistic comparison of different techniques].
[30] Fritsche UR, Schmidt K. Endenergiebezogene Gesamtemissionen für Treibhausgase aus fossilen Energieträgern unter Einbeziehung der Bereitstellungsvorketten: Kurzbericht im Auftrag des Bundesverbands der deutschen Gas- und Wasserwirtschaft e.V. Darmstadt: BGW; 2007 [English title: Total final energy emissions of greenhouse gases from fossil fuels, including the supply chains: summary report on behalf of the federation of German gas and water industries (BGW)].
[31] Heuck K. Elektrische Energieversorgung: Erzeugung Übertragung und Verteilung elektrischer Energie für Studium und Praxis. 8th ed. Wiesbaden: Vieweg + Teubner; 2010 [English title: Electrical power supply: generation, transmission and distribution of electrical energy for study and practice].
[32] EEX Transparency Platform. Transparency in energy markets. 01.01.2013. Available from: www.transparency.eex.com.
[33] German Association of Energy and Water Industries (BDEW). BDEW-Strompreisanalyse Juni 2014. Berlin: Haushalte und Industrie; 2014 (English title: Electricity price analysis June 2014: households and industry).
[34] EPEX Spot. Spotmarket: day-ahead-trading. 28.05.2014. Available from: www.epexspot.com.
[35] Kreifels N, Killinger S, Mayer J, Hollinger R, Wittwer C. Effekte regional verteilter sowie Ost-/Westausgerichteter Solarstromanlagen: Eine Abschätzung systemischer und ökonomischer Effekte verschiedener Zubauszenarien der Photovoltaik. 06.06.2014. Available from: www.agora-energiewende.de [English title: Effects of regionally distributed and east/west-aligned solar power systems: an assessment of systemic and economic effects of different scenarios regarding additional construction of photovoltaics].
[36] Lund H, Andersen AN, Østergaard PA, Vad Mathiesen B, Connolly D. From electricity smart grids to smart energy systems - a market operation based approach and understanding. Energy 2012;42:96–102.