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Review

The future need for flexibility and the impact of fluctuating renewable power generation

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ABSTRACT

A power system with 80% renewable energy sources (RES) requires significant provision of flexibility to balance the deviations of fluctuating solar and wind power. This paper focuses on how a smart mix of renewable generation technologies can reduce the demand for flexibility and therefore the overall system costs. To measure the demand for flexibility in systems with high RES generation, the term flexibility is defined and described using predictable indicators such as the difference between the highest and the lowest residual demand or the number of hours with negative residual load during a year. This definition is required to determine the optimal mix of RES installations. Optimization is performed for Germany based on the grid development plan of the transmission system operators. In contrast to most studies of the future energy system that foresee a further expansion of onshore wind, this paper shows that higher shares of offshore wind and, to some extent, photovoltaic are better suited to reducing the demand for flexibility and thus the cost of integrating fluctuating RES into the system.

Contents

1. Introduction

The continuous increase of electricity generated by intermittent

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renewable energy sources (RES) is changing the present generation structure considerably. In addition to fluctuations in demand, generation is becoming more and more volatile as well. The remaining residual load to be covered by conventional power plants and dispatchable RES will become dominated by the character of intermittent RES. In particular, the gradients of the residual load increase whenever volatile demand and stochastic RES generation coincide [1]. In order to utilize a high share of weather-dependent RES, the electricity system, which was originally designed to follow fluctuating demand, needs to become more flexible than it is today.

The level of flexibility needed to balance a fluctuating RES-based energy system depends largely on the underlying assumptions about the future energy system [2]; p. 66). When comparing different studies on the development of the energy system, as done by Sterner & Stadler [3]; p. 114), among others, it becomes clear that the need for flexibility ranges widely, even with comparable ratios of RES. There is extensive literature on the influence different assumptions have on the future need for flexibility. These include, for instance, premises regarding the actual share of different RES types [4,5,33], the operation mode of RES generation in terms of feed-in priority, curtailment and export options [6,31], the development of conventional generation [7] as well as interactions between different flexibility measures and other energy sources and sectors [8].

All these factors together lead to high uncertainty concerning the precise share of the different intermittent RES types and the future need for flexibility. Additionally, because there is a political goal of stronger market integration and a more competitive expansion of RES [9]; p. 82), the exact shares of intermittent RES are hard to predict. Due to their individual generation characteristics, various possible combinations of these fluctuating RES also lead to uncertainty regarding the actual flexibility requirements for the future.

Most of the above-mentioned literature analyzes the future need for flexibility by examining characteristics such as the quantity of surplus energy generated by RES [32] and is based on assumptions, for example, about the installed future RES capacities [10,11]. In contrast, the focus of this paper is on analyzing what combinations of fluctuating RES capacities can help to minimize the need for flexibility in a future energy system with 80% variable RES. In addition, since the term flexibility is often not sufficiently defined, it is subdivided into different dimensions. Two main questions arise in this context. First, whether an optimal combination of intermittent RES can minimize the future need for flexibility, and second, whether the dominant role of onshore wind predicted in most scenarios of the future energy system, e.g. in the Grid Development Plan [12] of the German transmission system operators (TSO), is the right strategy. This paper explores whether there are other combinations of fluctuating RES that might have a higher levelized cost of electricity, but require less flexibility and are therefore able to reduce the system integration costs of intermittent RES.

To set the foundation for this analysis, the second part of this paper focuses on the dissimilar nature of photovoltaic (PV) and onshore as well as offshore wind power generation. The third part explains how the time series for intermittent RES is determined. Part four focuses on deriving three parameters that can be used to characterize the future need for flexibility in more detail. Based on this, part five calculates the optimal combinations of intermittent RES with respect to these different dimensions of flexibility. Finally, the last part summarizes the main findings and conclusions.

2. Characteristics of intermittent renewables

Weather-dependent RES, such as PV and wind power, are characterized by strongly intermittent generation. However, the effects of this dependence on meteorological conditions differ considerably between PV, onshore and offshore wind.

PV, for instance, has a day-night rhythm that correlates to some extent with the aggregated daily demand pattern of consumers (see Fig. 1a). Nevertheless, due to changing weather conditions with varying degrees of cloudiness, PV also shows intraday fluctuations [1]. Furthermore, the annual sun path in the northern hemisphere means that PV displays seasonal patterns as well and the average PV generation in Germany varies remarkably between summer and winter (see Fig. 1b).

In general, all time series are based on actual data from 2011, as this year was close to the long-term average in Germany in terms of temperature, solar radiation and wind speed. For the same reason, this year was chosen as the basis for the German Grid Development Plan 2025 [13]; p. 31). In addition, using historical data from this year also has the advantage that the demand load of the entire system is free of extraordinary effects like the financial crisis in 2008–2009.

Although onshore and offshore wind also display seasonal profiles, wind power generation is more stochastic. Depending on the actual weather situation, the available amount of wind energy can fluctuate heavily within hours or remain quite constant over several days. Therefore, the course of the average availability of onshore and offshore wind throughout the day is rather flat as illustrated in Fig. 1a. However, in general, it can be expected that wind generation in Germany is higher in winter than in summer (see Fig. 1b).

Furthermore, in terms of average availability, there is a significant difference between onshore and offshore wind (see Fig. 1a and b). Due to higher average wind speeds and less influence of surface roughness, offshore wind power generation has lower variability and therefore higher full load hours than onshore wind power generation.

Despite differences in their overall availability, Fig. 1b shows that onshore and offshore wind are highly correlated on a monthly basis. That this interdependence also holds true for shorter time resolutions becomes evident in Fig. 2a, which compares the yearly coefficient of determination (R^2) for both wind power types on an hourly basis. High variation of onshore wind availability is noticeable during times with maximum offshore wind availability, i.e. the accumulation of points in Fig. 2a that almost looks like a solid line. This higher availability of offshore wind compared to onshore wind can be attributed to the differing variability between onshore and offshore wind mentioned above.

The complementarity of PV and onshore/offshore wind that is already indicated on a seasonal level in Fig. 1b can also be confirmed on an hourly basis by the annual correlations shown in Fig. 2b and c. Again, the more continuous availability of offshore wind compared to onshore wind is apparent when comparing the accumulation of points for high offshore availabilities on the far right-hand side on Fig. 2b, which is missing for the maximal onshore wind situations in Fig. 2c. However, it should be noted that another main factor for the very low yearly R^2 factor between PV and both types of wind power is the day-night rhythm of PV, which results in operating hours of zero for about half of the year, while wind power can be generated night and day.

3. Determination of hourly time series

The above used time series for the analysis are theoretically possible hourly RES values that are influenced by many factors.

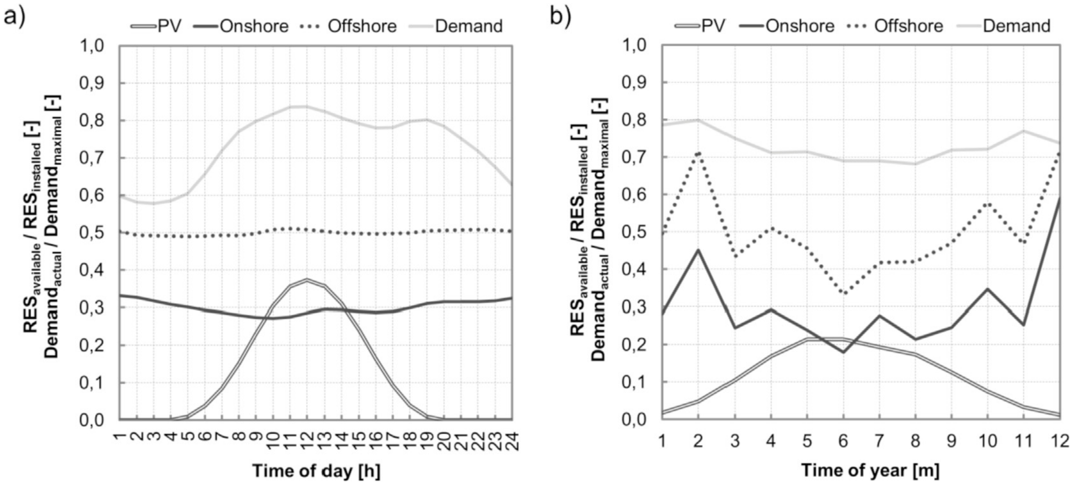


Fig. 1. Yearly average demand and availability for photovoltaic (PV), onshore and offshore wind generation a) per hour of day and b) per month based on the meteorological characteristics in 2011.
Source: Own calculation based on [13–16].

Besides the actual meteorological weather conditions in a particular year, how RES technologies develop is important. Furthermore, the location of the RES units also has an influence because the amplitude of the variations decreases with the aggregation of units due to spatial balancing effects, especially for PV and onshore wind electricity generation [17]; p. 11). The procedures for determining the hourly time series used in the analyses throughout this paper are described in more detail below.

The future development of demand is hard to predict because there are two opposing factors at work. Energy efficiency measures on the consumer side can lower the demand for power, while the electrification of energy demand in other sectors, e.g. mobility, power-to-heat and power-to-gas, can increase it. Therefore, the German Grid Development Plan 2025 assumes that net electricity consumption will remain constant at 543.6 TWh/year over the next decades [13]; p. 31). In order to adjust the future time series of electricity demand to this annual quantity, the 2011 hourly consumption values in Germany, which can be downloaded from the homepage of the European Network of Transmission System Operators for Electricity (entso-e), are linearly scaled [15].

Since the aim is to calculate the optimal combination of the installed capacities of intermittent RES that minimize the future need for flexibility, the hourly time series for all weather-dependent RES have to be normalized. To eliminate sub-annual capacity expansion effects of about 7.5 GW for PV and about 1.7 GW for onshore wind in 2011 [18]; p. 12), the actual generation values for this year are adjusted accordingly (anemos, 2013). The comparison in Table 1 shows that the historical full-load hours for 2011 differ from the future values assumed by the TSO [13]; p. 76). Reasons for these deviations are, among others, the above-mentioned technical development and the changing regional RES distribution. Since the full-load hours for PV are supposed to decrease from 1,009 h/year to 941 h/year in the future, the normalized time series for 2011 is scaled down linearly by that ratio, i.e. a factor of 0.93. In contrast to PV, the annual full-load hours for onshore wind are assumed to increase slightly. The TSO assumptions can be explained by the fact that the predominant expansion of onshore wind at less windy locations in southern Germany is largely compensated by technological developments, such as rising hub heights and increased rotor power. Hence, to derive the hourly values for onshore wind in the future, the 2011 normalized time series are scaled up linearly by a factor of 1.01.

Due to the later deployment of offshore wind compared to PV and onshore wind, the quality of actual generation data for offshore wind in 2011 is not really sufficient for future projections. Both the low absolute number of units in 2011 and the higher proportion of facilities in the Baltic Sea would underestimate the regional distribution effects that is likely to increase with a significant expansion of offshore wind. Therefore, a different process is used to derive the offshore wind time series. Wind speed data from 2011 at 116 m above sea level for 17 locations in the North Sea and Baltic Sea [16] and the power curves of two different wind turbines are used in combination with the assumption that more units will be installed in the North Sea in the future than in the Baltic Sea [19]. To account for planned and unplanned non-availabilities, the maximum normalized German offshore wind potential is set to 95%, deduced from historical wind speed data. This is in line with literature values that range between 90% [20]; p. 9) and 97% [21]; p. 72). Furthermore, as illustrated by the dotted line in Fig. 4, the yearly duration curve of availability for offshore wind is very different to those for PV and onshore wind. While harnessing PV is limited to daylight hours, i.e. about 4,000 h/a, onshore and offshore wind can be utilized all year round, even if only to a very small extent. Another difference is that the annual availability duration curve of offshore wind is quite flat at the top. The assumed maximum availability of 95% is achieved for approximately a few hundred hours per year. Thus, setting a maximum feed-in cap for offshore wind would considerably reduce the cost effectiveness of wind power from the North and Baltic Seas. In addition, since offshore wind is supposed to make a significant contribution to the energy supply from RES, the TSOs have to prepare recurring offshore grid development plans to facilitate an efficient and sustainable expansion of the electricity grid [22]. Therefore, the curtailment assumed for onshore wind and PV is neglected for offshore wind in the future.

With respect to the different availability profiles, adapting the full load hours for the offshore time series to a specific weather year by simple linear scaling would lead to unrealistic results. For example, in the case of an upscale, the availability would always be above the defined maximum limit of 95% for several hundred hours per year. Hence the following scaling algorithm is used to retain the temporal characteristics of the 2011 normalized time series, but to

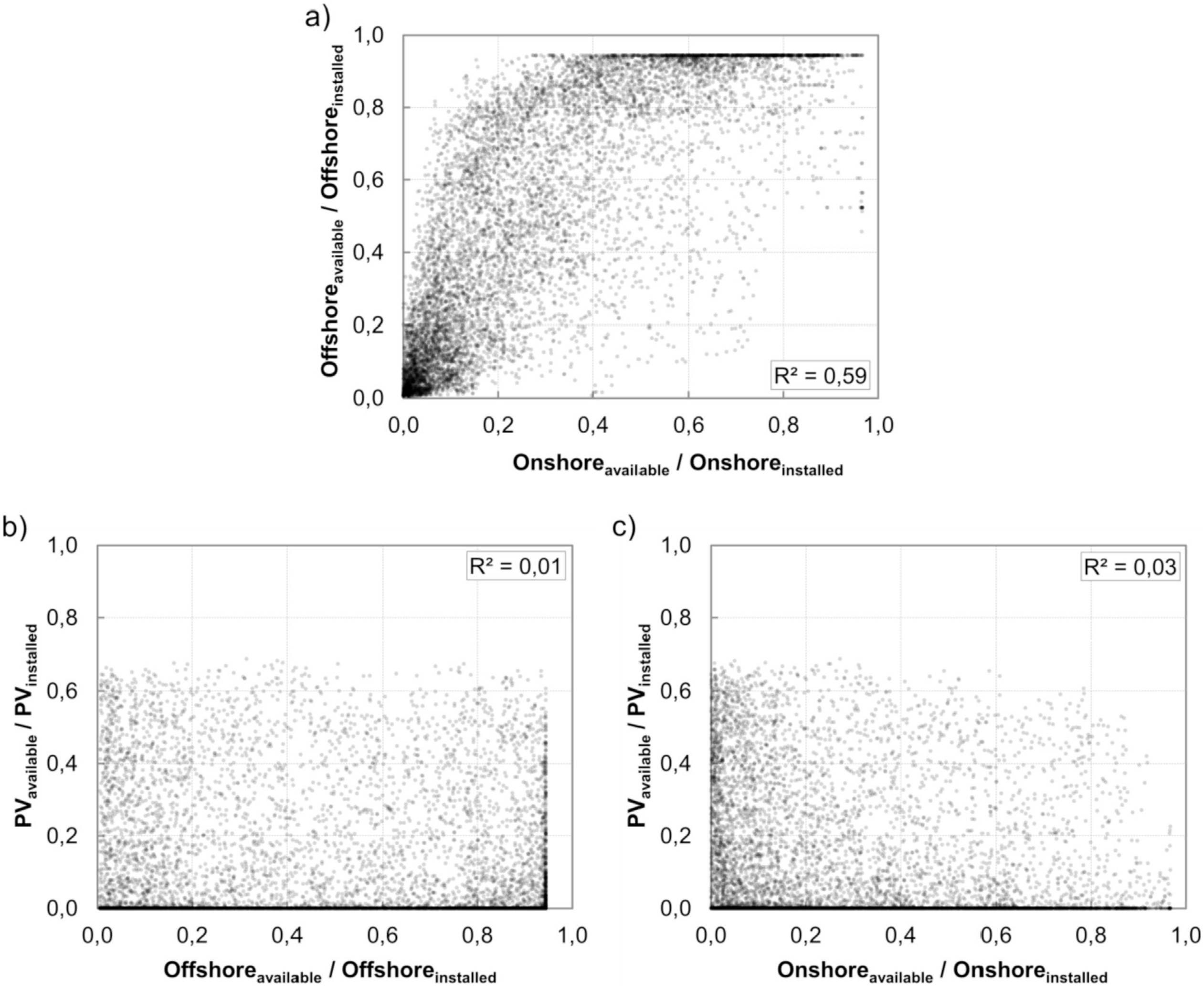


Fig. 2. Yearly coincidence and coefficient of determination (R^2) of a) offshore and onshore wind supply b) photovoltaic (PV) and offshore wind supply c) photovoltaic (PV) and onshore wind supply each in an hourly time resolution based on the meteorological characteristics in 2011.
Source: Own calculation based on [13,14,16].

Table 1
Actual full load hours per year for different fluctuating renewable energy sources in 2011 and assumptions for 2025 and beyond.

Technology	Actual data in 2011 [h/a]	Assumption for 2025 and beyond [h/a]
Photovoltaic	1,009	941
Onshore wind	1,946	1,973
Offshore wind	4,379	4,402

Source [13]: and own calculation based on (anemos, 2013) [16].

ensure realistic minimum and maximum values that are visible in the s-shaped availability duration curve of offshore wind.

$$p_{NEP}(t) = (1-(max(p_{2011}(t))-p_{2011}(t))\cdot s)\cdot p_{2011}(t), \quad \forall\ t = \{1,\ \ldots,\ 8760\} \tag{1}$$

$p_{2011}(t)$: Normalized value of time series derived from the meteorological data of 2011 in hourly time resolution $[-]$

$p_{NEP}(t)$: Adjusted value of the normalized time series $p_{2011}(t)$ with yearly full load hours according the German Grid Development Plan 2025 (NEP) in hourly time resolution $[-]$
s: Scaling factor $[-]$

As indicated in Fig. 3, this formula includes an additive and a multiplicative part. The additive part describes increased generation due to higher hub heights. These effects are considered in a simplified way as a shift of the turbine power curve to the left compared to today's power curve at lower hub heights (dotted line). The multiplicative part takes higher part load efficiency into account, mainly achieved by better rotor-to-generator ratios (dashed line).

In order to avoid grid expansion for using the last kWh of power from RES, it is already usual and socially accepted today to limit the generation of wind and PV units during supply peaks. Since the TSOs also assume a certain limitation of onshore wind and PV generation due to grid issues in the future, the peak values for the standardized time series are capped according to the figures given in the German Grid Development Plan, i.e. 1.2% of the annual energy supply from PV, and 1.7% for onshore wind [13]; p. 40). Fig. 4 depicts the difference between the theoretically possible and the limited maximum actual RES generation in the future. The solid, framed and dotted lines show the normalized yearly duration curves in hourly time resolution for PV, onshore and offshore wind, respectively.

4. Definition of future flexibility needs

According to the definition of the International Energy Agency (IEA), flexibility in an energy context is the general ability of an energy system to react to changes in generation and demand over time [23]; p. 35). The ongoing increase of electricity generation from fluctuating RES is expected to raise the system's need for flexibility even further. A suitable measure to describe the future need for flexibility is the development of the residual load. According to Fig. 5 and equation (2), the residual load curve can be derived from the difference between the hourly demand load of the entire system and non-dispatchable RES, i.e. run-of-river, PV, onshore and offshore wind.

From an economic point of view, it is always sensible to use these RES if available because of their low variable costs compared to other fuel-based power plants. It is assumed that these low variable costs of RES can also be neglected in the dispatch decision for the future. This assumption is based on the expectation that rational consumers will adapt their behavior in the long run, e.g. via power-to-heat or power-to-gas, if significant quantities of RES electricity with negligible marginal generation costs become available more often [24]; p. 57). While the non-dispatchable RES generation from run-of-river, PV, onshore and offshore wind is considered explicitly when calculating the residual load, other factors are disregarded. As can be seen in Fig. 5, this means that fuel-based generation from other RES or conventional power plants as well as so-called must-run generation to fulfil obligations for providing combined heat and power or ancillary services are neglected as are imports/exports from/to neighboring countries.

In the past, the residual load was always positive without exceptions. However, in some local regions in Germany, surpluses of RES generation are already occurring during very sunny and windy hours that coincide with low electricity demand [25]. Given the growing share of intermittent RES, it is expected that situations with negative residual load will occur for the aggregated German residual load as well.

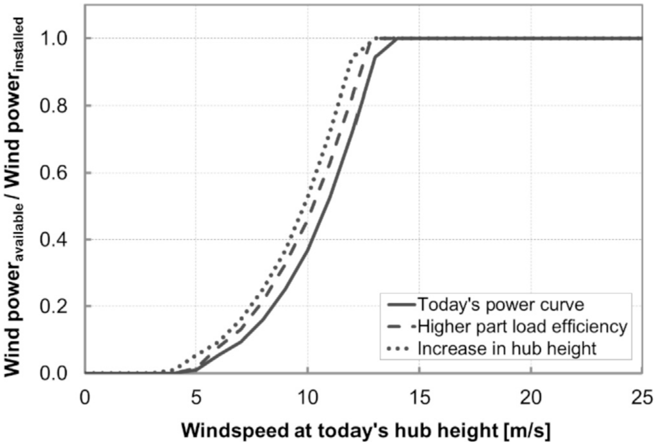


Fig. 3. Illustration of additive and multiplicative effects addressed in time series scaling procedure for offshore wind.

The interaction of fluctuating load demand and weather-dependent electricity generation leads to different residual load patterns and different flexibility needs. In general, four residual load curve sections can be distinguished in terms of the need for flexibility as displayed in Fig. 6. On the one hand, the curve can be split into positive and negative residual load depending on the surplus or lack of RES electricity. On the other hand, there are phases with increasing or decreasing gradients of the residual load.

Besides the change of the residual load over time, there are further parameters that can be used to characterize the system's need for flexibility. These attributes can be derived with the help of the residual load duration curve as displayed in Fig. 7 and are described below:

- A) Residual load range: Difference between highest and lowest residual demand of the year.
- B) Surplus energy: Cumulated negative residual load over the year.
- C) Surplus time: Number of hours with negative residual load.

The following analysis focuses on the divergence of these three flexibility characteristics. Different optimization problems are executed to derive the optimal combination of fluctuating RES for a future energy system with 80% RES that minimizes the flexibility needs with respect to these characteristics.

5. Optimal combination of intermittent renewables

5.1. Assumptions and constraints

The reference scenario is based on the assumptions in the first draft of the German Grid Development Plan 2025 (A 2025 scenario). This scenario describes the lower bound of the RES growth expected by the German TSO and the responsible regulatory authority. The key figures of this scenario are summarized in Table 2. The share of intermittent RES accounts for 36% while the total share of RES is 46%. However, the total installed capacity of RES is assumed to comply with the long-term renewable target of [9]; which aims at a total RES share of 80%. The difference between 46% and 80%, which amounts to 186.7 TWh/year, is supposed to be covered by PV, onshore and offshore wind. This paper uses a scenario analysis to derive the optimal combination of these three RES in terms of demand for flexibility. An additional aim is to analyze the impact of the outlined variations in availability and contemporaneity of wind and solar power (see section 2) on the three different flexibility characteristics (see section 4) under otherwise equal conditions.

As the gap to the RES target of 80% is closed solely by additional fluctuating wind and solar power, the first constraint for all three optimizations is (3).

$$RES_{TAR} = RES_{REF} + \mathrm{RES}_{\mathrm{PV}+} + \mathrm{RES}_{\mathrm{ON}+} + \mathrm{RES}_{\mathrm{OF}+} \tag{3}$$

RES_{TAR}: Required electricity from renewable energy sources (RES) in the target scenario [TWh/a]
RES_{REF}: Available electricity from renewable energy sources (RES) in the reference scenario [TWh/a]
RES_{PV+}: Additional electricity from photovoltaic [TWh/a]

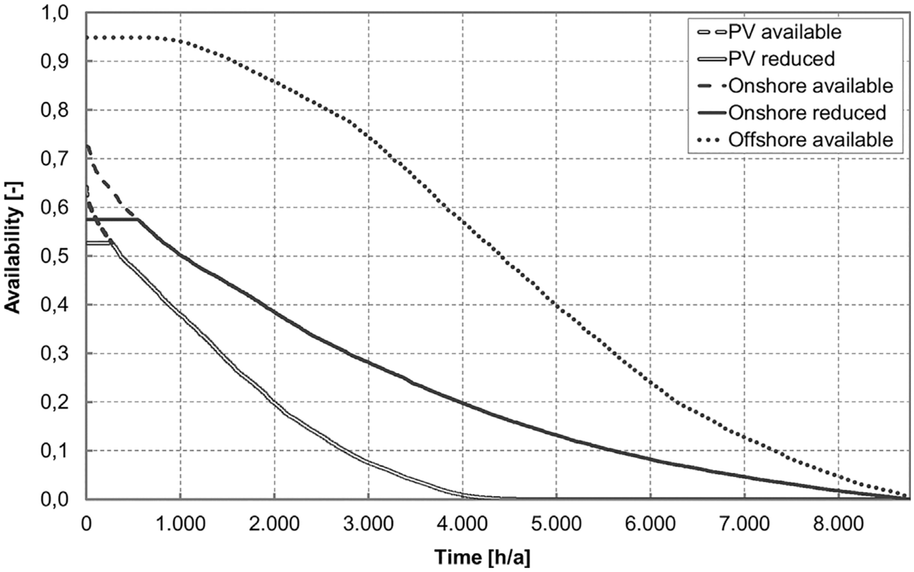


Fig. 4. Yearly duration curve of availability for photovoltaic (PV), onshore and offshore wind generation based on the meteorological characteristics in 2011. Source: Own calculation based on [13,14,16].

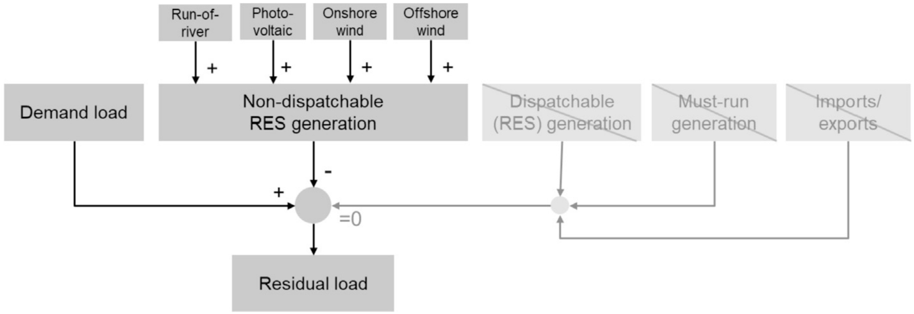
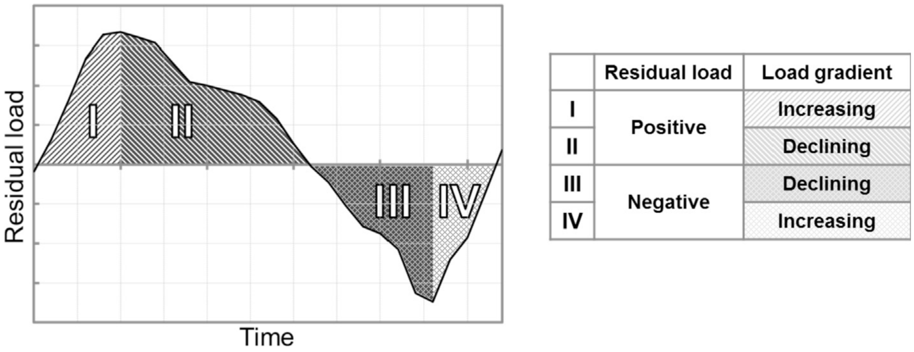


Fig. 5. Determining the residual load.

$$RL(t) = DL(t) - RR(t) - PV(t) - ON(t) - OF(t) \tag{2}$$

RL(t): Residual load of the entire system in time period t [GW]
DL(t): Demand load of the entire system at time t [GW]
RR(t): Available electricity from run-of-river at time t [GW]
PV(t): Available electricity from photovoltaic at time t [GW]
ON(t): Available electricity from onshore wind at time t [GW]
OF(t): Available electricity from offshore wind at time t [GW]



	Residual load	Load gradient
I	Positive	Increasing
II		Declining
III	Negative	Declining
IV		Increasing

Fig. 6. Typical sections of the residual load and the associated flexibility need [26]; p. 7).

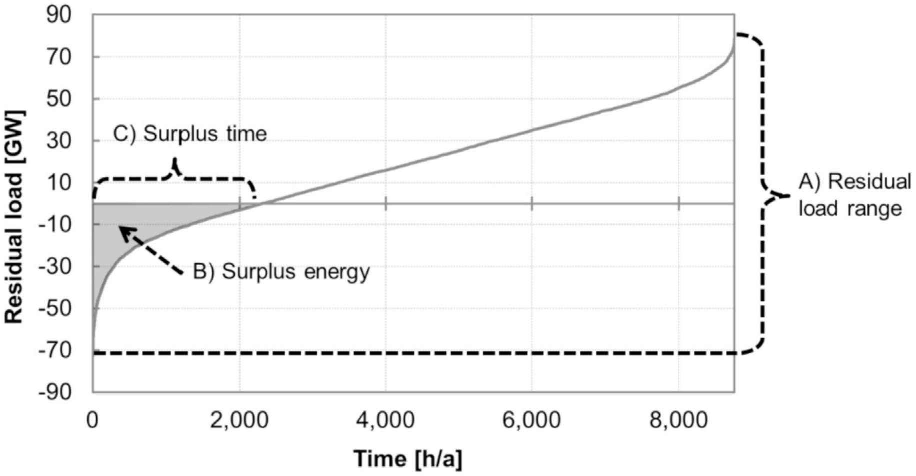


Fig. 7. Flexibility characteristics derived from the yearly residual load duration curve for an energy system with a high share of fluctuating renewable energy sources.

RES_{ON+}: Additional electricity from onshore wind [TWh/a]
RES_{OF+}: Additional electricity from offshore wind [TWh/a]

The decision variables for each optimization are therefore the installed capacities of onshore wind, offshore wind and PV. The lower bounds for these RES capacities are the reference system values (scenario A 2025 of the German Grid Development Plan) given in Table 2. These limitations ensure that the political RES targets for 2025 are achieved and prevent any uneconomic decommissioning of these units shortly after.

The upper limits are derived by assuming that the RES gap between the targeted energy system with a total renewable share of 80% and the reference system with 46% RES is only closed with one of the three available fluctuating RES types. These maximal capacities are derived using the assumed annual full-load hours in the German Grid Development Plan (A 2025 scenario) that are also implicitly given in the data in Table 2. Thus, further constraints for the three optimization problems are (4) to (6) with the corresponding minimal and maximal capacities listed in Table 3.

$$PV_{MIN} \leq PV_{OP} \leq PV_{MAX} \tag{4}$$

$$ON_{MIN} \leq ON_{OP} \leq ON_{MAX} \tag{5}$$

$$OF_{MIN} \leq OF_{OP} \leq OF_{MAX} \tag{6}$$

$PV_{min}/ON_{min}/OF_{min}$: Minimal capacity for photovoltaic/onshore wind/offshore wind [GW]
$PV_{op}/ON_{op}/OF_{op}$: Optimal capacity for photovoltaic/onshore wind/offshore wind [GW]
$PV_{max}/ON_{max}/OF_{max}$: Maximal capacity for photovoltaic/onshore wind/offshore wind [GW]

Table 2
Assumptions for renewable energy sources (RES) in the reference system with 46% RES based on scenario A 2025 of the German Grid Development Plan.

	Installed capacity [GW]	Annual generation [TWh/a]
Photovoltaic	54.1	50.9
Onshore wind	53.0	104.6
Offshore wind	8.9	39.2
Biomass	6.4	35.9
Run off river	3.9	14.8
Other RES	0.5	2.8

The weather-dependent nature of solar, onshore and offshore wind power generation represents an additional constraint for the optimization problems. As indicated in (7) to (9), a normalized structure with hourly time intervals is used to represent the fluctuating availability of these RES types over time (see section 3 and Fig. 4).

$$f_{PV}(t),\ t = \{1,\ \ldots,\ 8760\} \tag{7}$$

$$f_{ON}(t),\ t = \{1,\ \ldots,\ 8760\} \tag{8}$$

$$f_{OF}(t),\ t = \{1,\ \ldots,\ 8760\} \tag{9}$$

$f_{PV}(t)$: Normalized availability of photovoltaic in hourly time resolution [−]
$f_{ON}(t)$: Normalized availability of onshore wind in hourly time resolution [−]
$f_{OF}(t)$: Normalized availability of offshore wind in hourly time resolution [−]

The overall electricity demand and the availability of wind and solar power are both functions over time, so the residual load in the target scenario is highly time-dependent as well. The detailed calculation of the residual load in the target scenarios is shown in (10). The residual load calculations are based on hourly time series from 2011 for the overall system demand (entso-e, 2014) and meteorological data (anemos, 2013) for wind onshore, wind offshore and PV in Germany.

$$RL_{TAR}(t) = DL_{REF}(t) - RR_{REF}(t) - (PV_{OP} \cdot f_{PV}(t)) - (ON_{OP} \cdot f_{ON}(t)) - (OF_{OP} \cdot f_{OF}(t)),\ \forall\ t = \{1,\ \ldots,\ 8760\}, \text{s.t. } (4) - (9) \tag{10}$$

Table 3
Minimal and maximal installed capacities as upper and lower bounds for the decision variables.

	Minimal capacity [GW]	Maximal capacity [GW]
Photovoltaic	54.1	253.1
Onshore wind	53.0	148.2
Offshore wind	8.9	51.4

$RL_{TAR}(t)$: Residual load of the entire system for the target scenarios in time period t [GW]
$DL_{REF}(t)$: Demand load of the entire system for the reference scenario at time t [GW]
$RR_{REF}(\mathrm{t})$: Available electricity from run-of-river for the reference scenario at time t [GW]

The framework conditions described above form the basis for minimizing the flexibility need of the future energy system. In the following, the three optimization approaches are described in detail. As indicated by the time component *t* in constraints (7) to (9) and in constraint (10) in particular, the optimization results are strongly determined by the time-dependent availability of RES and the fluctuation of the overall system demand. For consistency, all the calculations are based on the weather conditions in 2011 and the results represent this specific meteorological year.

5.2. Objectives

5.2.1. Minimal range of residual load

The aim of this optimization problem is to minimize the need for flexibility in terms of the total capacity required in the system to balance all the residual load situations. Figuratively speaking, this can be described as the difference between the maximal and minimal residual load that occurs within a given time period. In Fig. 7, this difference is indicated by the span between the upper and lower end of the annual residual load duration curve. The mathematical formulation of this optimization problem is given in (11). The decision variables are the installed capacities of photovoltaic, onshore and offshore wind with the respective individual constraints defined in (4) to (9). The most important constraint with regard to this optimization problem is constraint (10), which describes the residual load calculation.

$$\begin{aligned}\Delta RL(PV_{OP},\ ON_{OP},\ OF_{OP}) \ &= \ max(RL_{TAR}(PV_{OP},\ ON_{OP},\ OF_{OP},\ t)) \\ &\quad - min(RL_{TAR}(PV_{OP},\ ON_{OP},\ OF_{OP},\ t)), \\ &\forall\ t \ = \ \{1,\ \dots,\ 8760\}, \\ &\rightarrow minimize, \\ &\text{s.t. } (4) \ - \ (10)\end{aligned} \tag{11}$$

$\Delta RL\ (PV_{OP},\ ON_{OP},\ OF_{OP})$: Range of residual load of the entire system for a particular weather year with the capacities of photovoltaic, onshore and offshore wind as decision variables [GW].

5.2.2. Minimal surplus energy

The motivation behind this optimization is to identify the combination of photovoltaic, onshore and offshore wind that minimizes the surplus energy in the system. In Fig. 7, this case is illustrated by the sum of electricity during RES surplus periods within one year that can be described as the integral of the negative residual load (grey-shaded area B). This approach follows the argumentation that lower RES surpluses lead to less curtailment and therefore higher RES utilization. This might not be the macroeconomic optimum, but is nevertheless a reasonable aspiration for the future energy system. The underlying objective function for this optimization is described by (12), and the limiting constraints are the same as for the one above that minimizes the total range of the residual load.

$$\begin{aligned}W_{RL-}(PV_{OP},\ ON_{OP},\ OF_{OP}) \ &= \ \sum_t RL_{TAR}(PV_{OP},\ ON_{OP},\ OF_{OP},\ t), \\ &\forall\ RL_{TAR}(PV_{OP},\ ON_{OP},\ OF_{OP},\ t) \ < \ 0, \\ &t \ = \ \{1,\ \dots,\ 8760\} \\ &\rightarrow minimize, \\ &\text{s.t. } (4) \ - \ (10)\end{aligned} \tag{12}$$

$W_{RL-}(PV_{OP},\ ON_{OP},\ OF_{OP})$: Sum of surplus electricity of the entire system from non-dispatchable renewable energy sources for a particular weather year with the capacities of photovoltaic, onshore and offshore wind as decision variables [GWh].

5.2.3. Minimal surplus time

The final approach to minimize the future need for flexibility in the target scenario addresses the surplus time. This is defined as the number of hours in one year with surplus electricity from non-dispatchable RES. As depicted in Fig. 7, it can be illustrated as the intersection of the residual load duration curve and the abscissae. Equation (13) describes the corresponding optimization problem using the signum function. Again, the constraints for this optimization are the upper and lower bounds for the installed capacities of photovoltaic, onshore and offshore wind as well as the time-dependent residual load calculation defined by (4) to (10). In contrast to the two other flexibility properties, this is of particular importance for those wanting to invest in the future energy system. For instance, it helps both investors in additional RES units and financiers of flexibility options to estimate their future operating hours, which are essential when calculating profitability.

$$\begin{aligned}T_{RL-}\left(PV_{OP}, ON_{OP}, OF_{OP}\right) &= \sum_t sgn\left(RL_{TAR}\left(PV_{OP}, ON_{OP}, OF_{OP}, t\right)\right), \\ &\forall\ sgn(RL_{TAR}(PV_{OP}, ON_{OP}, OF_{OP}, t)) = -1 \\ &t = \{1, \dots, 8760\} \\ &\rightarrow minimize, \\ &\text{s.t. } (4) - (10)\end{aligned} \tag{13}$$

$T_{RL-}\ (PV_{OP},\ ON_{OP},\ OF_{OP})$: Number of hours with an aggregated surplus from non-dispatchable renewable energy sources of the entire system for a particular weather year with the capacities of photovoltaic, onshore and offshore wind as decision variables [−]

All three optimizations were carried out in Microsoft Excel. The chosen solver was executed with the generalized reduced gradient (GRG) algorithm ignoring integer constraints and using a multistart option.

5.3. Results

Table 4 shows the outcomes of the three different approaches to deriving the optimal combination of fluctuating RES for a future energy system with 80% RES. It must be pointed out here that these results would be different for different meteorological years.

When minimizing the overall range of the residual load, the results suggest that only offshore wind should be expanded further (+42.4 GW or +186.7 TWh/year) compared to the reference scenario. That PV and onshore wind should remain at their reference levels can be explained by their higher supply variability and lower operating hours compared to offshore wind (see Figs. 1 and 4).

When minimizing surplus energy, the optimization results indicate that a combination of additional PV (+42.9 GW or +40.4 TWh/year) and offshore wind (+33.2 GW or +146.4 TWh/year) should be favored. The basic argument for this RES mix is the highly uncorrelated availability of PV and offshore wind (see Fig. 2b). This means that expanding both these RES types makes it possible to exploit the less volatile offshore wind generation with higher full-load hours per year as well as the day-night rhythm of PV that partly correlates with the daily demand load pattern (see Fig. 1b). Onshore wind, which currently has the lowest generating cost of all three fluctuating RES types, should remain at reference level in this scenario as well.

This is not the case when minimizing the surplus time. Here, the optimization results in various possible combinations of additional RES. However, the figures vary only slightly within in a range of 6–20 GW per RES as displayed in Table 4. It is noticeable that, with about 85%, increased PV is supposed to cover the major share of the additional RES needed to meet the overall future target in this scenario (between +215.5 GW and 236.2 GW).

Fig. 8 illustrates the optimization results as hourly duration curves of the residual loads. Although the RES shares vary quite considerably between the scenario with the minimal range of residual load and the scenario with the minimal surplus energy, it becomes clear from the figure that the differences in the course of the residual load are less distinct. Hence, the results suggest that only increasing offshore wind is likely to cause a similar need for flexibility as a combination of additional PV and offshore wind.

However, if the major share of the RES expansion is achieved by PV, as is the case in the third scenario, the course of the residual load duration curve differs quite considerably. Of all three target scenarios, this one shows the biggest integrals of the residual load, above as well as below the abscissae in Fig. 8. Hence, the minimization of surplus time is apparently associated with a doubling of surplus energy (see Table 4).

The significant variation between the high PV scenario and the other two scenarios can also be seen when comparing the frequency distribution of the hourly load gradients of all three scenarios in Fig. 9a. The fat tails of the minimal surplus time scenario indicate that this not only has the biggest absolute annual range of residual load (see Table 4 and Fig. 8), but also the highest hourly gradients, i.e. the change in residual load from 1 h to another.

The dissimilar temporal change of the need for flexibility is especially evident when looking at the course of the load gradients over several hours. Due to the strong and comparatively regular intraday fluctuations in demand and PV production [1,27], the greatest difference in the residual load gradient usually occurs within a day. To show the most extreme deviations, Fig. 9b and c compare the days with the maximum and minimum gradients of the residual load for the meteorological year 2011, which was used in all the scenarios. While there are hardly any significant differences between the three scenarios for days with minimum deviations of the residual load, the minimal surplus time scenario with the biggest share of PV shows the highest maximal variations. For this scenario, in particular, the coincidence of weather-dependent RES generation and fluctuating demand is likely to cause more extreme residual load gradients in the morning and evening hours.

6. Conclusions

In light of the increasing shares of RES, the future need for flexibility is broadly discussed in the scientific literature with the aim of evaluating the influence of different factors. This paper uses a new approach to shed light on the uncertainty about the flexibility needs of the future energy system. By defining three different flexibility dimensions: range of residual load, surplus energy and surplus time, and then minimizing them in optimizations, this paper shows the impact on the residual load of the different characteristics of weather-dependent PV, onshore and offshore wind, as well as their actual installed capacities. For an exemplary German energy system with 80% RES, it is shown that a scenario with increased offshore wind has a similar effect on the residual load as a combination of increased PV and offshore wind. The scenario with increased offshore wind minimizes the range of the residual load, while the scenario with increased PV plus offshore minimizes the surplus energy. With very high PV shares, the daily pattern of electricity generation minimizes the surplus time but strongly increases the hourly gradients as well as the quantity of surplus energy. This further hampers the utilization of the surplus energy in other sectors, e.g. via power-to-heat or power-to-gas, mainly due to the reduced full-load hours for such technologies.

The constraints (7) to (10) for all three optimization problems are based on the weather conditions in 2011. This year is considered a normal year with average feed-in of wind and solar. Although the optimal combination of fluctuating RES is likely to vary for different meteorological years, the general conclusions of this exemplary analysis of the German energy system remain valid. Without specifying the term flexibility in more detail than the cited definition by IEA, it is not possible to determine the optimal combination of intermittent RES that will minimize the future energy system's need for flexibility. The scenario results for the three different flexibility attributes derived in this analysis may serve to open a discussion about a more precise definition and understanding of the term flexibility and the future need for it. This may lead to a prioritization and maybe to a weighting of the three flexibility attributes presented here: a) minimal range of residual load, b) minimal surplus energy and c) minimal surplus time, or help to identify other aspects that should be considered. It does not seem realistic that a sole focus on these attributes will guide future RES expansion. Nevertheless, this paper fosters an understanding of how the generation characteristics of PV, onshore and offshore wind influence the need for flexibility. Onshore wind is a

Table 4

Optimal combination of fluctuating renewable energy sources (RES) and key figures for the residual load in three future scenarios with 80% RES compared to a reference system in 2025.

		Reference (A 2025)	Minimal range of residual load	Minimal surplus energy	Minimal surplus time	
					low	high
RES capacity	Photovoltaic [GW]	54	54	97	216	236
	Onshore wind [GW]	53	53	53	**53**	**64**
	Offshore wind [GW]	9	**51**	**42**	**9**	**15**
Residual load	Annual maximum [GW]	80	77	78	79	79
	Annual minimum [GW]	−11	−51	−64	−110	−103
	Annual range [GW]	91	**129**	142	182	189
	Surplus energy [TWh/a]	0	−34	**−30**	−76	−66
	Surplus time [h/a]	39	2.483	2.238	**1.947**	**1958**

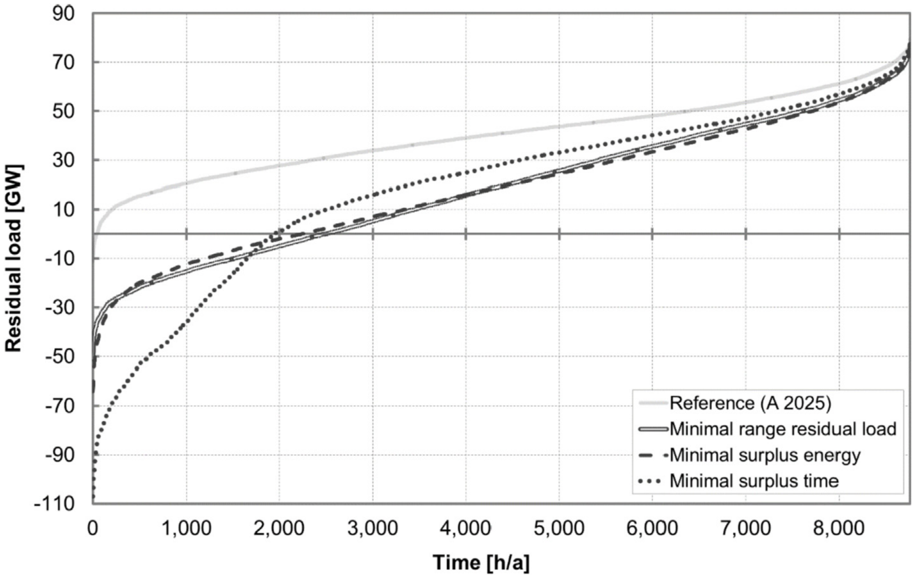


Fig. 8. Residual load duration curves of three future scenarios with 80% renewable energy sources that meet different flexibility criteria compared to a reference system in 2025.

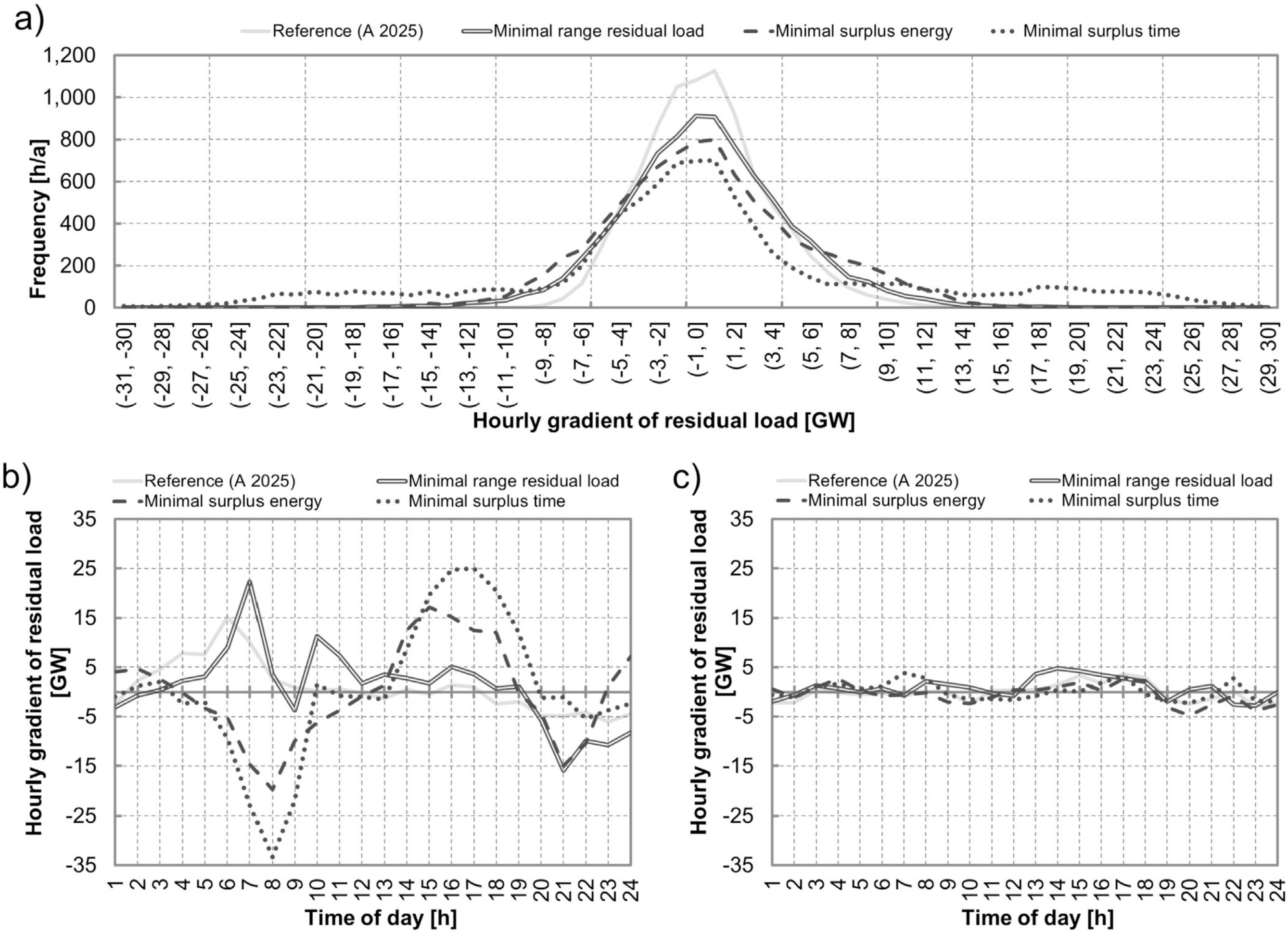


Fig. 9. Hourly gradients of residual load for three future scenarios with 80% renewable energy sources that meet different flexibility criteria compared to a reference system in 2025 a) as yearly frequency distribution in modal classes of 2 GW as well as for the day of the year with b) the maximum and c) the minimum course of the residual load gradients.

fundamental element in most scenarios concerning the development of the energy system due to its relatively low levelized cost of electricity and its market maturity, see, for example, [28]. However, the results presented here indicate there is a cost trade-off between the scenario with the lowest RES generation costs and the one with the lowest need for flexibility. This should be kept in mind when planning any increase in installed RES capacities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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