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Strategies to harvest peaks and bridge lulls in sector integrated energy systems

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ABSTRACT

Sector integrated renewable-based energy systems require new concepts for optimal operation and supply security assessment. Using an integrated optimization model of the German energy system, we identify two future peak loads: a *harvesting peak load* of ~287 GW, where flexible sector coupling technologies and energy storage maximize renewable electricity use, and a *resilience peak load* of ~139 GW, which occurs during dark lulls and must be met by flexible power plants. Our findings highlight that the flexibility of sector coupling technologies, alongside sufficient energy storage, is essential for balancing supply and demand in volatile renewable-based energy systems. A sensitivity analysis shows that limiting electrolyzer flexibility – by requiring at least 8000 full load hours – doubles renewable electricity curtailment and raises system costs by 10.5% compared to the reference scenario. Therefore, policymakers should incentivize flexible sector coupling and electricity demand while ensuring the expansion of long-term energy storage.

1. Introduction

1.1. Motivation

In ongoing efforts to reduce greenhouse gas emissions, countries around the world are transforming their energy systems from fossil fuel-based systems to renewable energy-based systems [1]. The European Union has set the goal to become greenhouse gas neutral by 2050 [2], while Germany has legally pledged to reach this target already by 2045 [3]. Future energy system designs which achieve ambitious emission targets will likely be based on volatile renewable sources such as wind and solar power and feature electrification of end-use sectors in order to reduce emissions [4]. This electrification is supported by sector coupling technologies such as electrolyzers, heat pumps and battery electric vehicles [5], which also help to integrate high shares of renewable energy into the system [6]. Operational strategies for such sector-integrated energy systems present an ongoing research challenge in energy system modelling [7]. Additionally, as the share of renewables sources in the system increases, concerns about the security of supply [8] and the resilience of the future energy system to disruptions also increase [9].

1.2. Literature review

As different terms in the research area of security of supply and energy resilience overlap [10], an introduction into relevant terms and their application is given. Afterwards, existing studies analyzing energy security are presented.

In the context of energy systems, resilience can be seen as the “ability to anticipate, absorb, recover from, and adapt to disruptions” [11]. Typically these disruptions are unexpected events with low probability, but high impact on the energy system [11] like hurricanes, terrorist attacks or dark lulls [10]. In contrast, energy system reliability analysis focuses on maintaining energy supply during expected conditions [11]. Both energy resilience and energy reliability are important parts of the security of supply in energy systems, which can be defined as “maintaining energy supply at all times” [10]. However, most existing studies neglect the potential impact of the demand side in sector-integrated energy systems and only focus on the supply side for analyzing energy security [9]. Another related aspect is the system adequacy, which is the “ability to meet all demands [..] at every moment in time” [12]. Thus, it is apparent that definitions for the different aspects of energy security overlap, and, as a result, methodologies to evaluate these aspects overlap as well [10]. System adequacy can cover a wide range of time

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scales, from long-term capacity investment, which are typically analyzed with optimization or simulation models [10], to voltage and frequency security analyses on a time scale of seconds, which can be analyzed with mixed-integer linear programming or bi-level planning models [13]. While assessments of security of supply have in the past focused on the analysis of supply chains of primary energy carriers [14], the impact of weather conditions on the supply security of renewable energy systems is now analyzed using simulation and optimization models [10]. To assess the resilience of these renewable-based energy systems, the usage of optimization under uncertainty approaches is a viable option to explicitly capture disruptive events and their impact on short- and long-term energy system design and operation [10]. Furthermore, stochastic modelling approaches like Monte-Carlo simulations are used to model power plant availability and their impact on security of supply from a capacity planning perspective [15]. Another aspect of energy security is the need for flexibility in renewable-based energy systems [16]. This flexibility can be needed for the power system in the form of frequency or voltage stability, for the energy system in the form of matching supply and demand over longer periods and in the form of transfer capacity of electricity grids to prevent local bottlenecks [17]. Flexibility measures that ensure the balance of the energy system include flexible powerplants with fast ramping responses, energy storage, sector coupling technologies, grid infrastructures, but also demand side management [18].

In existing literature, various studies have assessed the security of supply and resilience of energy systems with different methodological approaches. First, studies which focus on the supply side of the energy system are presented: Grave et al. [19] analyze supply adequacy for the German power sector by calculating the secured generation of volatile renewable energy sources. To determine the needed capacity of hydrogen backup power plants in a carbon-neutral German power system, Brunner et al. [20] use an electricity market model and show how additional flexibility of sector coupling options reduces the maximum and minimum residual load. The effects of large shares of volatile renewable energy sources on the residual load in Germany are also analyzed by Schill [21] with a simple linear cost minimization model which optimizes storage investments and operation of power plants. He shows that electricity storage and curtailment are options to deal with renewable surpluses.

Other existing literature analyzes the needed short- and long-term flexibility in renewable energy systems: Suna et al. [22] use a power and district heating optimization model to assess the future flexibility needs of the Austrian electricity system. Using the concept of residual load in this renewable-based energy system in the year 2030, they show that pumped hydro power is important for covering daily to monthly flexibility needs, but cross-border electricity grids are needed for annual balance of supply and demand. The flexibility demand for the German transmission grid is analyzed by Büttner et al. [23] using an optimization model for electricity and natural gas grids. They show that coupling the heating and mobility sectors to the electricity sector is beneficial for integration of renewable energy sources into the electricity grid. Chyong et al. [24] use a European optimization model covering energy supply and the demand sectors industry, mobility, residential and commercial. They show that, in a decarbonized European energy system, energy storage and flexible operation of heat pumps provide temporal flexibility while electricity grid expansion is important for spatial flexibility. A linear optimization model is used by Göke et al. [25] to show that the flexibility of sector coupling technologies helps to integrate volatile renewable energy sources and halves the residual peak load in a fully renewable European energy system. Additionally, Boehnke et al. [26] show in a European case study that decentral flexibility options such as battery storage systems, heat pumps and electric vehicles have a high value for the energy system. They coupled an electricity market model with an optimization model for demand side technologies to analyze the possible revenues of local flexibilities, like heat pumps or smart charging of electric vehicles. The effects of integrating large electrolyzer capacities into the German transmission grid are studied by Lieberwirth and Hobbie [27] with an electricity market model. Their results show that curtailment of renewable energies is reduced, if electrolyzers are sited with respect to grid constraints and can be operated flexibly.

Next, studies that assess the potential contributions of the demand side for resilient energy systems are shown: By analyzing the results of an expert survey, Papaefthymiou and Dragoon [28] promote an active role of the electricity demand in the system management, as well as the need for energy storage and expansion of transmission networks in 100% renewable energy systems. For analyzing the role of demand side management for integration of renewable electricity sources Balasubramanian and Balachandra [29] develop a mixed-integer linear programming model which they apply for a case study of the electricity system in a South Indian state. Karimi et al. [30] develop an integrated multi-energy system model using multi-objective and multi-attribute decision making to show that demand side management of electrical and thermal demands helps to integrate intermittent renewable generation and simultaneously reduces operating costs. By coupling an integrated assessment model with an hourly energy system model, Odenweller et al. [31] introduce a method to model demand side flexibility in long-term scenarios of integrated assessment models. They show that, in a climate-neutral Germany, demand side flexibility can achieve system-wide economic benefits and reduces required expansion of renewable energy sources.

Last, the impact of weather conditions and climate change on security of supply is analyzed by a rising number of studies: Gøtske et al. [32] use a sector-coupled, European energy system model and 60 historical weather years to show the need for robust design of backup capacities and energy storage to bridge challenging weather conditions. Additionally, Kittel and Schill [33] provide methods to analyze energy droughts and expand their methodology to negative residual load events with renewable surplus generation. Furthermore, Liu et al. [34] use global climate models to analyze the impact of climate change on energy systems based on wind and solar energy. They conclude that climate change will impact the supply-demand matching and should be considered in the long-term planning of energy systems. An approach to include climate change uncertainty into a European energy system optimization model is presented by Plaga and Bertsch [35]. They use data from six climate models, a time clustering algorithm and decomposition methods to show that the general design of the European electricity system is independent from climate change uncertainty, but investment in long-term hydrogen storage varies.

1.3. Research gap

As shown, existing literature has assessed security of supply in energy systems from various perspectives. However, a holistic analysis for a renewable-based national energy system, which contains and connects the most relevant aspects for security of supply, is missing. Thus, a systemic assessment of energy resilience should investigate the required expansion and operation of flexible power plants and energy storage, explicitly considering challenging weather conditions, like droughts, dark lulls, or the impact of climate change on the renewable-based energy system. Furthermore, this analysis should also examine the role of sector coupling options for balancing supply and demand, while considering other flexibility measures such as curtailment, demand side management or grid expansion. Such coherent assessments of security of supply in sector-integrated energy systems are currently missing.

Existing research also does not provide operation strategies for resilient, renewable-based energy systems. While several studies show how specific energy system components should be operated, they do not deduce general insights applicable to other sector-integrated energy systems. Additionally, existing studies lack strategies for harvesting generation peaks by renewable energy sources in sector-integrated energy systems. Therefore, such operation strategies, which are transferable to other energy systems with high shares of volatile renewable energies, are needed.

1.4. Contributions

Following this, we assess the resilience of a sector-integrated renewable-based energy system in this work from the perspective of security of supply. We provide a holistic analysis on a future energy system design which ensures security of supply by investment into flexibilities and their optimal operation. Furthermore, we show operational strategies for both bridging challenging situations, like dark lulls, and harvesting renewable energy surpluses during favorable weather conditions.

Key research questions in this work are:

- What criteria are suitable to evaluate the security of supply in sector integrated energy systems?
- What are optimal operational strategies of sector coupling technologies in renewable energy-based systems?
- How does limiting the flexibility of electrolyzers affect a sector integrated energy system?
- How are operational strategies for sector integrated energy systems affected by different weather conditions?

We answer these questions using the future German energy system as a case study. As Germany has pledged to become greenhouse gas neutral already by 2045, answering these research questions and providing policy implications is more urgent for the German energy system than for other cases where the transformation can take place over a longer timeframe. Using the sector integrated optimization model ETHOS.Infrastructure, we contribute novel insights to existing literature. Considering electricity, hydrogen and heat demand of the entire energy system, we can model the operation of sector coupling technologies accurately. Modeled sector coupling technologies include electrolyzers, heat pumps and power-to-heat applications. Additionally, the model can also invest into short-term and long-term energy storage, flexible power plants and renewable energy sources like photovoltaic and wind energy. Furthermore, the hourly resolution in combination with weather data enables identification of critical situations for the security of supply, like dark lulls, and enables curtailment of renewable energy in case of surpluses. We chose this optimization model to evaluate the resilience of the integrated energy system holistically from a systematic view. This energy system model allows us to analyze the expansion of technologies and their operation, and derive conclusions that are not only applicable to the German energy system, but can also be generalized to other sector integrated energy systems that rely on volatile renewable energy sources.

This paper is structured as follows: In Section 2, the German energy system model ETHOS.Infrastructure is introduced and the scenario assumptions are outlined. In Section 3, we introduce new concepts for analyzing the peak load in sector integrated energy systems, which we derived from our optimization results. These results are presented and discussed together with the results of the conducted sensitivity analyses in Section 4. Finally, the paper is concluded, and strategic implications are derived in Section 5.

2. Methodology

To analyze operating strategies for sector coupling technologies and to assess the resilience of energy systems, the model suite ETHOS (Energy Transformation pathway Optimization Suite) is used [36,37]. ETHOS comprises tools and models for energy systems analysis on regional, national and global scale, global trade, renewable potentials, resources, life cycle assessment, network modeling, macroeconomics, socioeconomics and more. The basis of most of the models is the open-source, python-based optimization framework ETHOS.FINE (Framework for Integrated Energy system assessment) [38]. The framework allows the modelling of systems with multiple regions, time steps, commodities, and investment periods. The objective function is the minimization of the system costs. Within this study, the analyzes are conducted with the German energy system model ETHOS.Infrastructure [39,40].

2.1. German energy system model: ETHOS.Infrastructure

The model ETHOS.Infrastructure determines the minimum-cost spatial and temporal design of electricity, gas, hydrogen and heating infrastructure in Germany, taking into account the emission reduction targets. The optimization is performed as a linear program for a single year at hourly resolution. To investigate the transformation pathway from today's energy system to future energy systems, the individual optimizations can be connected in series, with the results being transferred to the subsequent optimization. The spatial resolution amounts to 80 regions. Region definitions are derived from the network buses density of the high voltage electricity grid based on an aggregation method developed by Hörsch and Brown [41]. In addition, two offshore regions are introduced to represent offshore wind farms in the North and Baltic Seas and their connections to the mainland. The analysis is performed for the target year 2045. It is assumed that Germany will achieve its goal of becoming greenhouse gas-neutral by 2045 with a complete coal phase-out. An overview of all modeled components, which are considered in this analysis, is shown in Fig. 1.

These components include renewable energy sources, e.g. wind and solar power, conversion processes, e.g. gas-fired power plants and water electrolysis, transmission technologies, e.g. electricity and gas grids, and storage technologies, e.g. batteries and underground storage for hydrogen. In addition, the model can import commodities from outside the model boundaries, e.g. hydrogen and electricity from neighboring countries. Each region in Germany has its own predefined demand profiles for various commodities, including those required for industrial processes, transportation, heating, etc. The model optimizes the sizing and operation of the given options, taking into account technical and environmental constraints, to always meet the demand profiles in all modeled regions.

As greenhouse gas neutrality needs to be achieved in Germany by the year 2045, the share of renewable energy sources will be high. This will likely lead to a highly volatile feed-in from renewable energy sources and will require flexibility in the cost-optimal energy system design to adapt to the prevailing conditions. The energy system can benefit from numerous flexibility options: The modeled options include short- and long-term storage that is charged when renewable energy feed-in is high and discharged when renewable energy feed-in lags demand. The model considers battery storage and hydroelectric pumped-storage power plants as options to store electricity. Instead of storing electricity directly, it can also be converted into other commodities which can be directly used or stored. In combination with storage options, the demand can be met flexibly although the conversion processes are geared to electricity supply. These options include power-to-gas conversions, e.g. hydrogen production via water electrolysis, and power-to-heat conversions, e.g. electric boilers. The options can be combined with hydrogen and heat storage to meet demand at later time steps. Furthermore, the model can decide to curtail the feed-in of renewable energies instead of dimensioning flexibility options to the maximum feed-in. This economic curtailment follows the model logic of minimizing the energy system costs and thus is taken if it is cheaper than installation of additional storage capacities or further expansion of flexible sector-coupling technologies.

2.2. Model inputs and assumptions

The model results are highly dependent on their input data. As the focus of this analysis lies on the target year 2045 and the achievement of greenhouse gas neutrality, renewable energy potentials have a great

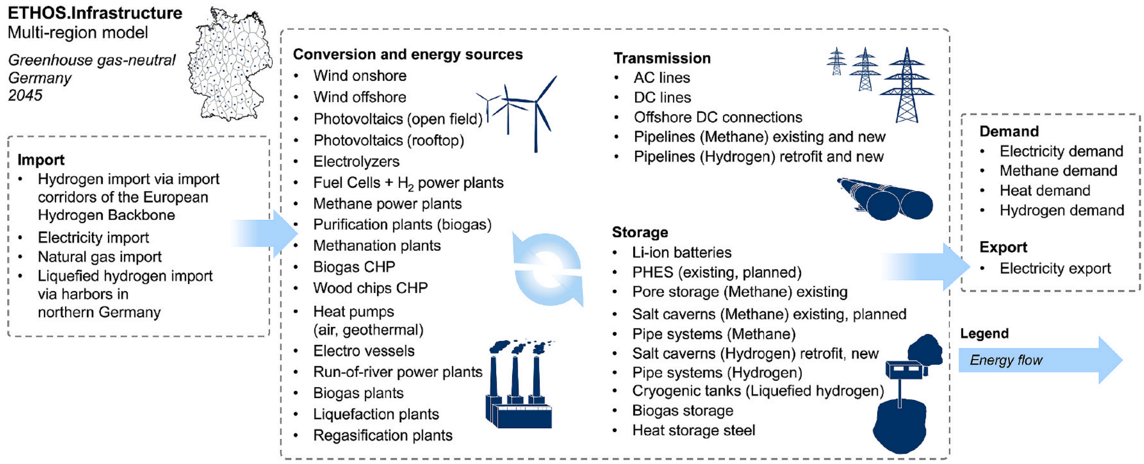


Fig. 1. Components modeled in ETHOS.Infrastructure for this analysis (based on [40]). CHP: Combined Heat and Power, AC: Alternating Current, DC: Direct Current, PHES: Pumped Hydroelectric Energy Storage.

impact on the system design. The underlying renewable potentials for wind onshore and photovoltaics were taken from Risch et al. [42]. The used wind offshore potential was taken from Caglayan et al. [43]. Generation time series are calculated with the open-source python package RESkit (Renewable Energy Simulation toolkit for Python) [44, 45]. The time series calculation for the reference scenario is based on the weather year data for 2013. The electricity grid is based on the network development plan for 2037 with an outlook on 2045 [46]. The potentials for electricity import and export are defined by the positive and negative residual loads of the connected countries. The residual load values are based on the work of Syranidou [47]. The layout of the gas grid was taken from Ref. [48]. It is assumed that all existing natural gas pipelines can be retrofitted to transport hydrogen in the future. Additionally, new hydrogen pipelines can be built along existing pipeline corridors. Cost assumptions are aligned with the assumptions of the European hydrogen backbone [49]. Hydrogen can be produced domestically via water electrolysis, or it can be imported via the import corridors of the European hydrogen backbone [50] or by ship to harbors in northern Germany. As seasonal storage options, existing salt caverns can be retrofitted for storing hydrogen and new salt caverns can be built based on the potential analysis of Caglayan et al. [51]. The assumed techno-economic parameters are based on the study conducted by Maier et al. [52].

Demand projections are taken from scenario calculations with the German energy system model ETHOS.NESTOR [52–54]. The model optimizes the transformation pathway for Germany with high sectoral coverage. The underlying model algorithm allows the selection of the most cost-effective reduction measures across all sectors and their combination into a coherent national greenhouse gas strategy [37]. Due to the lack of spatial resolution in ETHOS.NESTOR, grid restrictions cannot be analyzed. Therefore, the optimized demand projections are given to the spatially resolved ETHOS.Infrastructure model, which is able to model grid restrictions, but with less sectoral coverage.

To be able to use the national demand profiles as input, the profiles are regionalized based on individual proxies, e.g. population, employment, and emissions [40]. In the end, every region has its own combination of different demand profiles depending on their characteristics. This process has been done for the demand of electricity, methane, hydrogen and heat, thereby each end-consumer sector was individually regionalized. Demand projections for the energy sector, such as electricity demand for hydrogen production or hydrogen demand for power plants, are not included as inputs because they are part of the optimization result of ETHOS.Infrastructure.

Background information and techno-economic parameters of the underlying scenario calculations with ETHOS.NESTOR are described in Maier et al. [52]. Fig. 2 shows the national demand profiles for electricity and hydrogen from these calculations, which can be interpreted as inflexible demand that needs to be met. While electricity demand follows a daily pattern, hydrogen demand is almost constant. In the summer, there are peaks in electricity demand for cooling applications. It is assumed that these applications are not flexibly operable. Demand side management, i.e. shifting demand to a time when supply conditions are better, is not considered in the model.

In addition to this inflexible demand, the heating demand allows for several flexibility options, using heat pumps, thermal power plants, or other power-to-heat applications, such as electric boilers combined with heat storage. Their demand for electricity, hydrogen, or other commodities is part of the optimization results of ETHOS.Infrastructure.

To obtain a robust system design, a cold and dark lull was introduced for two consecutive weeks in January. In this period, renewable energy supply was reduced to 10% of the original generation potential. Additionally, the heating demand was increased by 25% for these two weeks.

2.3. *Scenario definition*

To define suitable criteria for assessing the security of supply in future greenhouse-gas neutral energy systems and to analyze operational strategies of sector coupling technologies, the energy systems cost optimization was performed for the target year of 2045 with the described input parameters (see Section 2.2). For each hour of the year, the operation of supply and demand, including the flexibility options described in Section 2.1, is optimized. Based on the annual operation time series, the cost-optimal operation strategies for the different sector coupling technologies can be determined. Furthermore, the results show how the demand is met in times when the feed-in from renewable energy sources are low and which measures need to be taken to ensure security of supply.

A sensitivity analysis with minimum full-load hours of electrolysis operation was performed to analyze how limiting flexibility options affects the design of the energy system and system costs. The variations are carried out for 4000, 5000, 6000, 7000 and 8000 full load hours, reducing the flexibility that can be provided by the electrolyzers, i.e. the higher the full load hours of the electrolyzers, the less flexibility they can provide to the system. To prevent domestic hydrogen production from falling to zero and all hydrogen from being imported, the model is given the constraint that at least the same amount of hydrogen must be produced domestically as in the reference scenario. The resulting model outputs are analyzed regarding their changes in the composition of the design, the total annual costs, and the amount of curtailed renewable energy.

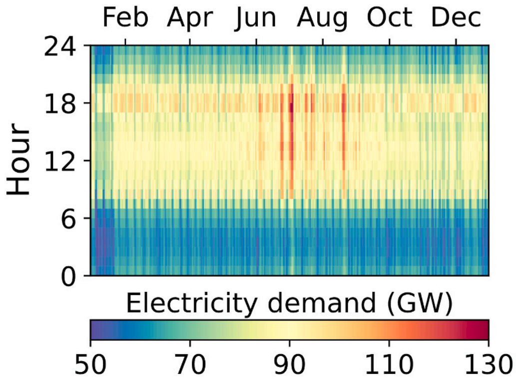


Fig. 2. Inflexible electricity and hydrogen demand profiles in 2045 from ETHOS.NESTOR scenario calculations. Demand for electricity follows a daily pattern, while demand for hydrogen is almost constant.

Another sensitivity analysis investigates the impact of interannual variability of weather conditions on the resilient energy system design and its operation. We use weather data from the historical weather years from 2009 to 2016 and optimize the energy system individually for each weather year. The results are analyzed with focus on peak loads, curtailment and installed capacities in the different weather years.

3. Peak load concepts

Accompanying the transformation of the energy system, the criteria for evaluating security of supply must change. In mostly fossil fuel-based energy systems, an inflexible electricity load was met by flexibly operating powerplants. In contrast, in renewable energy systems a volatile, renewable feed-in by photovoltaic plants and wind turbines dominates the electricity supply. This forces a paradigm shift from a single peak to a double peak energy system: The system must no longer only serve the maximum peak load using flexible electricity supply, it now also needs flexible load to absorb and harvest energy during the peak supply of inflexible and variable renewable energy sources.

Up until recently, the peak load of the electricity system was a deciding factor to analyze security of supply [55]. Due to the rising share of volatile renewable electricity supply in the German electricity system, the residual load is now a more widely used criteria for assessing security of supply. The residual load is defined as that part of the electric load which is not covered by volatile renewable energies and must be covered by flexible power suppliers (see Eq. (1)) [55].

$$\text{Residual Load} = \text{Demand Load} - \text{Variable Renewable Energy Supply} \tag{1}$$

In 2024, the German peak load of 75.5 GW [56] occurred on January 15 between 11 a.m. and 12 p.m., but the residual load during that time was only 41.6 GW and thus significantly lower. In contrast, the highest residual load of 66.3 GW occurred on November 6 between 5 p.m. and 6 p. m. when wind and solar power together only supplied 0.1 GW [56]. Fig. 3 shows the sorted annual load curve and the sorted residual load curve for the year 2024 in the German electricity system. The renewable energy supply could only cover the electrical load for a few hours. In all other hours, additional flexible electricity supply is required to meet the electrical load, represented as blue area in Fig. 3.

The residual load is a good indicator of the flexible generation capacities needed, but neglects flexible loads in sector integrated energy systems. These sector coupling technologies can adjust their electricity consumption according to the available variable renewable energy (VRE) supply by wind turbines or photovoltaic plants, and thus help to balance demand and supply in the electricity system.

To account for the dual peaks in renewable energy systems, we extend the definition of the residual load to the negative range (electricity demand < volatile renewable electricity supply). In addition, we focus on the inflexible part of the hourly electricity demand and exclude flexible loads such as electrolyzers or energy storage from the equation. This brings us to the definition of the ***inflexible residual load*** for every time step (t) in equation (2).

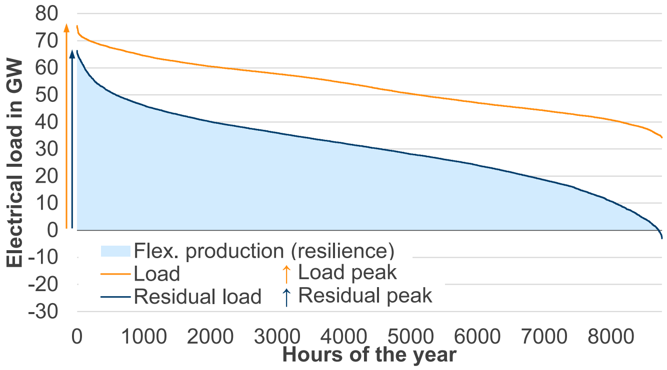


Fig. 3. Sorted annual load curve and sorted residual load curve for the year 2024 (based on data from Ref. [56]). The blue area represents the load that needs to be covered by flexible electricity supply.

$$\text{Inflexible Residual Load}_t = \text{Inflexible Demand}_t - \text{Inflexible Supply}_t \tag{2}$$

With $\text{Inflexible Demand}_t$: Electricity demand in time step t, minus electricity demand from available flexibility options in t and with $\text{Inflexible Supply}_t$: Volatile renewable electricity supply in time step t

The ***inflexible demand*** is not a fixed value, but varies throughout the year depending on demands from industry, buildings and mobility. Furthermore, sector coupling technologies, like heat pumps or power-to-heat applications, could be included in the inflexible demand, if they are forced to operate due to constraints in heating supply and, in turn, are no longer flexible. The ***inflexible supply*** in a 100% renewable-based energy system is the volatile renewable electricity supply e.g. through weather dependent photovoltaics and wind power generation. In energy systems with inflexible power plants such as coal power plants, which, if activated, are constrained by minimum production thresholds, the inflexible supply could also contain these power plants. However, this is not applicable to this work, as no such power plants are in service in a greenhouse gas-neutral Germany in the year 2045.

The extreme points of the *inflexible residual load* during the year form two peaks of renewable energy systems. We propose the terms ***harvesting peak load*** (see Eq. (3)) and ***resilience peak load*** (see Eq. (4)).

$$\text{Harvesting Peak Load} = \left| \min_t (\text{Inflexible Residual Load}_t) \right| \tag{3}$$

$$\text{Resilience Peak Load} = \left|\max_t(\text{Inflexible Residual Load}_t)\right| \tag{4}$$

The ***harvesting peak load*** is defined as the absolute value of the minimum inflexible residual load which must be absorbed by flexible consumers, as shown on the right side of Fig. 4. It describes the maximum renewable production surplus, which is harvested by flexible loads, including electrolyzers, large-scale heat pumps and charging of battery storage. The harvesting peak load is explained in more detail in section 4.2.2.

The ***resilience peak load***, on the other hand, is defined as the maximum inflexible residual load which must be covered by flexible power plants. The inflexible electricity demand exceeds the variable renewable energy supply (see left side of Fig. 4). This situation can occur during dark lulls. The *resilience peak load* determines the required flexible power plant capacity in the renewable energy-based energy system. In the case of a 100% renewable energy system, power plants running on hydrogen and bio-based fuels as well as energy storage discharge could serve as flexible production options. The resilience peak load is explained in more detail in section 4.2.1.

Fig. 4 shows these newly derived definitions for the inflexible residual load as well as the *harvesting* and *resilience peak loads* for a renewable based energy system.

In energy systems with high shares of renewable energy, the inflexible residual load curve moves further into the negative space where the inflexible supply exceeds the inflexible demand. Instead of a single peak load as shown in Fig. 3, there are two peaks on either side of the inflexible residual load curve. The procedure how we derived equations (2)–(4) and the terms *harvesting peak load* and *resilience peak load* from the hourly optimization results is explained in the following section 4.1 with Fig. 6.

4. Results and discussion

The transformation of the German energy system towards greenhouse gas neutrality by 2045 leads to extensive changes in all sectors of the energy system. In particular, the transition of the electricity sector from a fossil fuel-based sector to a renewable energy-based sector is key for the energy system transformation. It enables emission reductions in other sectors of the energy system through sector coupling technologies. Thus, our optimization results show that the electricity demand rises from 464 TWh [56] in the year 2024 to 1330 TWh in the year 2045 (Fig. 5). Major drivers for the increase in electricity consumption are electrolyzers with 311 TWh/a electricity demand, heat pumps with 175 TWh/a and power-to-heat applications in industry with 168 TWh/a. While heat pumps are used to decarbonize the room heating, power-to-heat technologies, such as electric boilers, supply process heat for industrial applications. Hydrogen becomes an important energy carrier, with a demand of 517 TWh/a in 2045, of which 55% is used in industry, primarily as a feedstock in the chemical industry and to produce steel, and 20% is used in the mobility sector, with the largest share consumed by heavy duty trucks. Electrolyzers supply 218 TWh/a of hydrogen domestically, while 300 TWh/a are imported from other European countries or Northern Africa via pipelines.

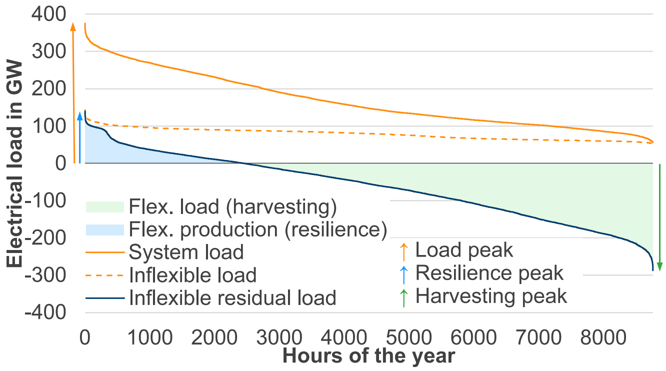


Fig. 4. Sorted annual load, inflexible load and inflexible residual load curve for a renewable based energy system. The blue area represents the load that needs to be covered by flexible electricity supply; the green area represents the excess power that must be absorbed by flexible consumers.

To supply the electricity needed, a significant expansion of electricity generation capacity is necessary. Thus, the installed generation capacity increases from about 264 GW [57] in the year 2024 to 800 GW in 2045. Wind energy and photovoltaics (PV) become the backbone of the German electricity supply with installed capacities of about 257 GW onshore wind energy, 40 GW offshore wind capacity, and 404 GW PV (Fig. 5). In total, wind and solar energy have a total installed capacity of 700 GW and supply 90% of the total electricity in the year 2045. However, flexible power plants with a capacity of 97 GW are installed to supply electricity during times when photovoltaics and wind energy cannot meet the electricity demand on their own. These power plants are hydrogen gas turbines and biomass power plants and only reach about 1175 full load hours in the year 2045. Furthermore, battery storage has a total installed storage capacity of 244 GWh and is mostly charged during the day and discharged during the night.

4.1. Derivation of peak loads

Based on the concepts introduced in Section 3, the two peak loads are derived for the model results of the year 2045. The deduction of the previously introduced inflexible residual load, harvesting peak load and resilience peak load is explained in Fig. 6. By ordering the hourly time series for electricity supply and demand by the volatile renewable electricity generation, we create ordered load curves. To make identifying the patterns easier, we included a stylized version of the ordered load curves.

When ordered by variable renewable energy supply, three regimes become apparent: the harvesting, transition and dark lull period. During the harvesting period, the *inflexible production* is larger than the *inflexible load*. Flexible consumers such as electrolyzers are deployed to harvest excess energy. In the transition period, the *inflexible production* is less than the *inflexible load*. Flexible energy sources such as batteries are used to meet the demand. During the dark lull period, the inflexible demand does not only consist of the final energy demand of the sector in question (here: electricity), but also of loads to supply energy demands in other sectors. Heat pumps act as an additional sector coupling load during the cold dark lull. In order to serve this load, additional flexible producers, such as hydrogen power plants, are used.

The maximum load of the energy system in 2045 is 375 GW. Most of this load consists of flexible consumers who operate during periods of high renewable electricity supply and are therefore not relevant for assessing the resilience of the energy system (see Fig. 6). The critical *resilience peak load* is 139 GW, which is only about a third of the maximum load. This shows that in future energy systems, the peak load and the critical *resilience peak load* are more decoupled from each other. Still, the resilience peak in 2045 is more than twice as large as the residual peak in 2024 (see Fig. 3), which means that a considerable amount of flexible emission-free powerplants have to be installed in order to meet the growing demand for electricity, even in dark lull periods.

Comparing the residual loads for the year 2024 (see Fig. 3) and the results for the year 2045 (see Fig. 6), it is visible that in 2024, the residual load hardly reaches negative values where the renewable supply is higher than the demand. In contrast, the model results for 2045 show that the *inflexible residual load* is negative, i.e. there is a renewable overproduction, for more than 70% of the hours of the year. This overproduction reaches its maximum, the *harvesting peak*, at 287 GW. This means that there is a need for flexible consumers about double the capacity of flexible power plants in 2045 and about three times as high

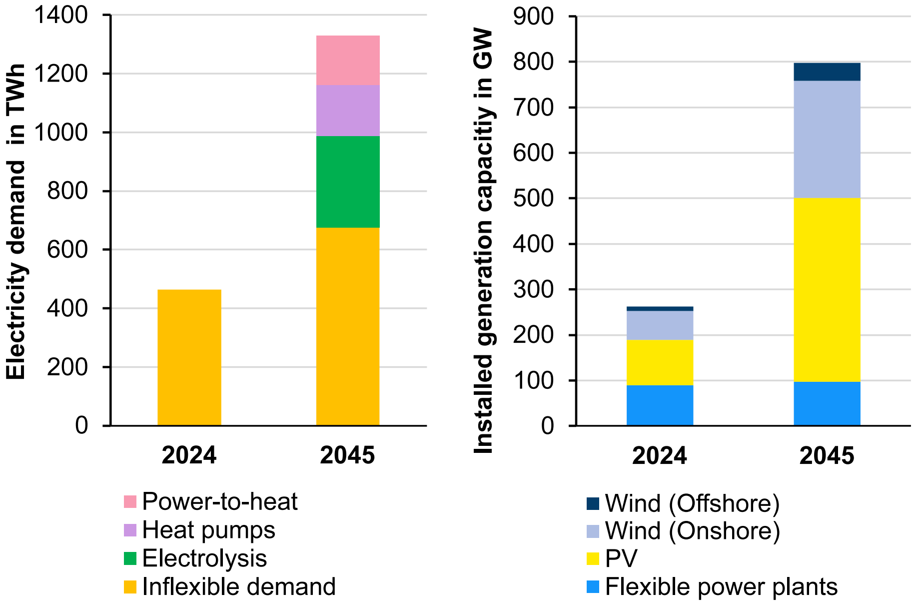


Fig. 5. Electricity demand and installed generation capacities in the year 2024 in Germany [57] and in the model year 2045.

as flexible power plants today.

The implication is that in addition to building capacity for renewable energy supply, we must also focus on managing the two peaks of the future energy system by building flexible capacities: On the one hand, there is the need for flexible generation to serve the *resilience peak* during the lull, and on the other hand, there is the need for flexible consumers to absorb the *harvest peak* during the renewable overproduction. Note that overproduction refers to temporary overproduction; over the entire year, this energy is not excess, but harvest.

4.2. *Flexibility as key for electricity supply and demand*

Sector-integrated renewable energy systems require both supply and demand flexibility. To analyze how flexible generation helps to bridge lulls, how flexible demand technologies help to harvest energy and what role curtailment can play, we look at these exemplary situations in the following paragraphs.

4.2.1. *Resilience peak load*

As shown in Fig. 6, the *resilience peak* load occurs during periods with low renewable electricity generation. These periods occur during dark lulls, when weather conditions limit the electricity generation of photovoltaics and wind turbines to a small share of their installed capacity. These situations are critical for a sector integrated energy system. Using just one weather year as input data for future resilient energy system designs can underestimate the critical impact of dark lulls on the entire energy system [32]. Therefore, we conducted an additional sensitivity analysis (see section 4.4), in which we optimized the energy system for each of eight historical weather years individually. However, this approach could still underestimate the impact of dark lulls or climate change uncertainty on a renewable-based energy system. Thus, as explained in section 2.2, we use a different approach for designing a resilient energy system and include a synthetic two-week cold dark lull in January. Comparing our added synthetic dark lull with analysis of historical dark lulls, Ryberg [58] shows that a two week dark lull with this extent is highly unlikely in Germany. Ryberg [58] shows that between the years 1980 and 2016 the longest period in which PV and wind energy delivered less than 25% of their average generation in Germany was about seven days. Thus, the inclusion of the two-week cold dark lull is a pessimistic assumption to ensure a resilient energy system design even under extreme future scenarios.

The *resilience peak load* for the year 2045 occurs during the cold dark lull as shown in Fig. 7. During the dark lull, wind energy and PV contribute very little to the electricity generation during these two weeks. Instead, flexible power plants must supply most of the electricity during this period. At the *resilience peak load* of 139 GW at 5 p.m. on January 14th, hydrogen gas turbines provide 64 GW of electricity, biomass combined heat and powerplants 32 GW, and energy storage 48 GW of electricity. It is worth noting that the contribution of battery storage during an extended lull is often small, because they cannot be completely recharged when renewable electricity generation is low for multiple days. During the resilience peak only about a fifth of the electricity storage capacity is used.

On the other side of the energy balance, the load is reduced as much as possible during the cold dark lull by shutting down electrolyzers and power-to-heat applications as well as reducing the load of heat pumps. Thus, the required flexible power plant capacity of 97 GW in the year 2045 is determined by this inflexible electricity demand during the dark cold lull.

The reduction in electricity consumption of flexible sector coupling technologies is only possible in 2045 because long-term storage capacities for hydrogen and heat are installed. For hydrogen storage, existing salt caverns are repurposed and new salt caverns are built, resulting in a hydrogen storage capacity of 73 TWh in 2045. These hydrogen storages are used during the dark lull to supply the hydrogen demands in the sectors industry and mobility, while also providing hydrogen for the hydrogen gas turbines to cover the electric load. Furthermore, heat storage in district heating networks and combined heat and power plants enable the reduction of electricity demand of power-to-heat applications and heat pumps. However, for certain heat demands in decentral room heating and process heating in industry, no sufficient heat storage capacities are available. This leads to the need to operate heat pumps and power-to-heat applications during the cold dark lull (see Fig. 7). Battery storage plays a minor role in bridging dark lulls as it is cost-optimally designed to balance supply and load during a day or between two days with 314 storage cycles in 2045. Therefore, the interplay between flexible power plants and flexible sector coupling technologies allows bridging the cold dark lull as a critical situation for the security of supply.

4.2.2. *Harvesting peak load*

While bridging lulls requires flexibility to reduce the electricity

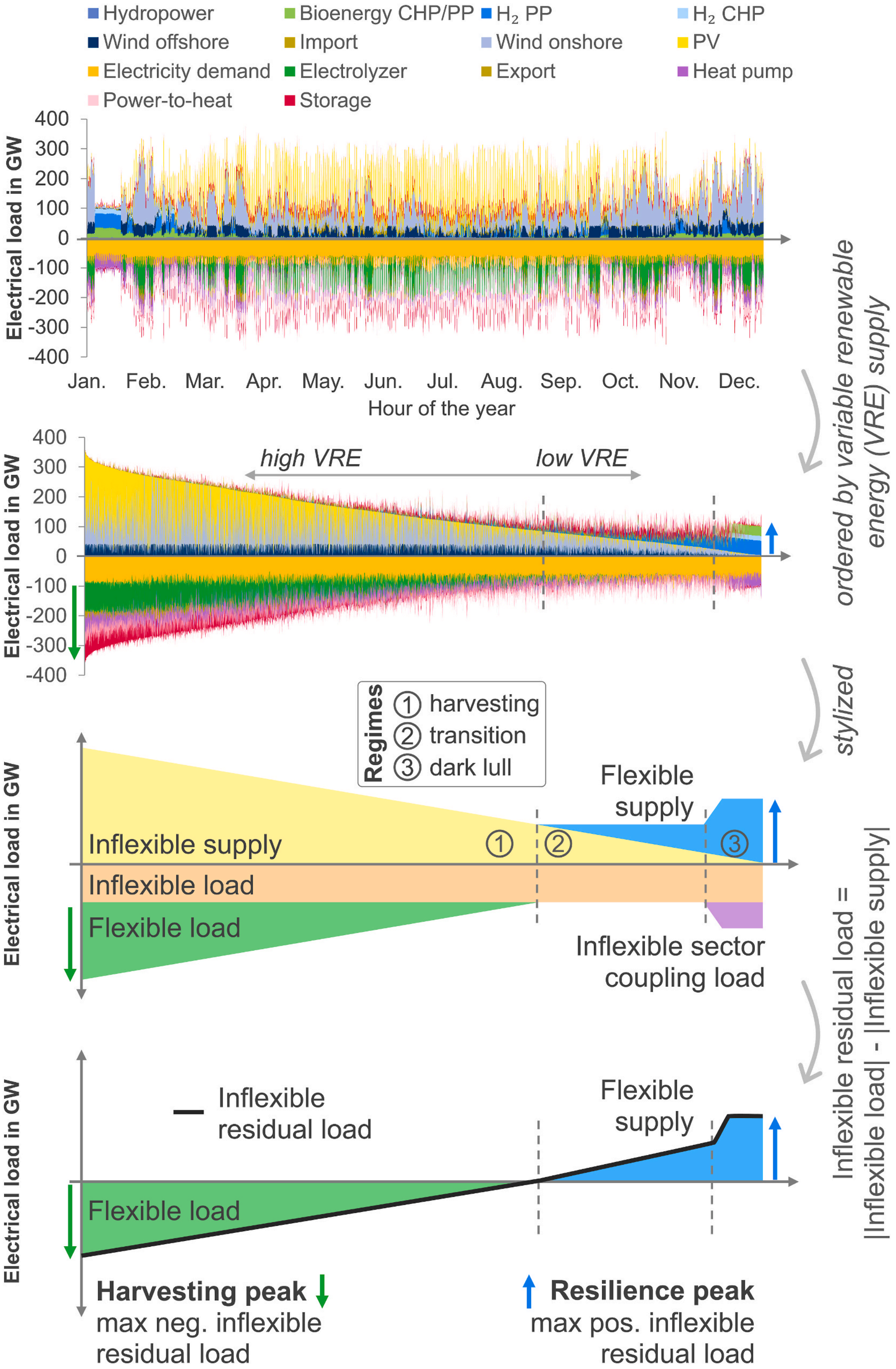


Fig. 6. Deduction of the harvesting and resilience peak load for the year 2045. CHP: combined heat and power plant, PP: power plant.

demand, harvesting renewable peaks in energy supply requires flexibility of sector coupling technologies to increase their electricity demand. As Fig. 8 shows, the harvesting peak load of 287 GW occurs at 11 a.m. on March 27th, 2045.

In this situation, the renewable energy sources supply 374 GW of electricity, while the inflexible electricity demand is at 87 GW, leaving a remaining harvesting peak load of 287 GW. To absorb this load, electrolyzers increase their electricity consumption to 97 GW, heat pumps to

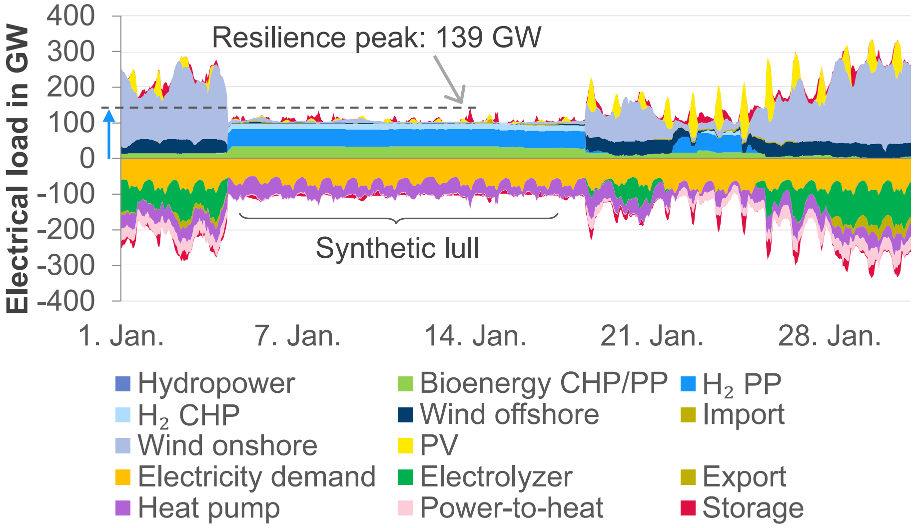


Fig. 7. Resilience peak: minimum inflexible production at maximum inflexible demand in 2045. CHP: combined heat and power plant, PP: power plant.

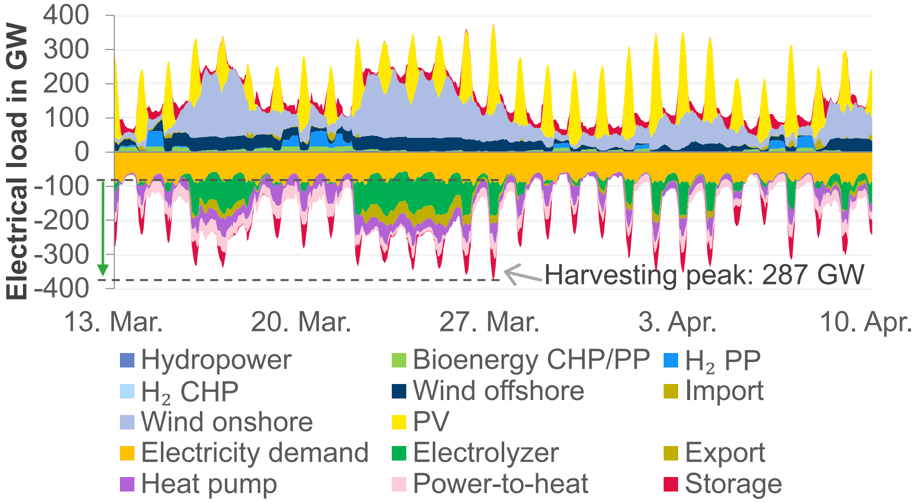


Fig. 8. Harvesting peak: maximum inflexible production at minimum inflexible demand in 2045. CHP: combined heat and power plant, PP: power plant.

41 GW and other power-to-heat technologies to 46 GW. Furthermore, battery storage is charged with 80 GW and electricity exports reach 23 GW. Thus, the flexible sector coupling technologies and storage are used to harvest as much renewable electricity as possible. The harvested electricity can be converted into hydrogen or heat in order to decarbonize other sectors of the energy system. In the case of hydrogen, the harvested energy can be stored over longer periods and later be used in hydrogen gas turbines to produce electricity again and bridge lulls. Therefore, the harvesting peak load is not a critical situation for security of supply, but instead beneficial for the resilience of the energy system.

4.2.3. *Curtailment in sector integrated energy systems*

Harvesting all renewable energy supply is not always economically feasible. Instead, curtailment of PV and wind energy is necessary in highly sector-integrated energy systems. Fig. 9 shows two weeks with the maximum curtailment of variable renewable electricity production. The maximum curtailment of 152 GW occurs on June 2nd at 9 a.m. As the highest solar production is in summer and the highest wind production in winter, the combined maximum production – and also curtailment - occurs in the transitional seasons of fall and spring.

Multiple conditions must be met for curtailment to take place. First, high wind energy supply during the night allows the operation of all sector-coupling flexibility options. Second, there is no need for discharging battery storage during the night. Finally, high solar and wind energy supply during the day allows the operation of all sector-coupling flexibility options. In this case, the battery storage is not discharged at night, thus there is no need to charge the battery during the prior day. By not charging the battery during peak renewable energy supply, the system loses flexible load and relies on curtailment as a last resort. This means that curtailment is an additional flexibility option that is used as a substitute when other options are not available, such as when Li-Ion batteries reach their maximum state of charge. When it comes into effect, it is the most economical option for dealing with inflexible production, as curtailment itself does not cost anything. During the year 2045, a total of 28 TWh of electricity is curtailed, representing only about 2.1% of the total electricity generation.

4.3. *Sensitivity of inflexible demand: minimum full load hours of electrolysis*

The previous results indicate that flexible loads play an important role in balancing out energy systems with high shares of variable renewable energy sources. To test this, a sensitivity analysis is performed, depriving the system of some of its flexibility. In this sensitivity

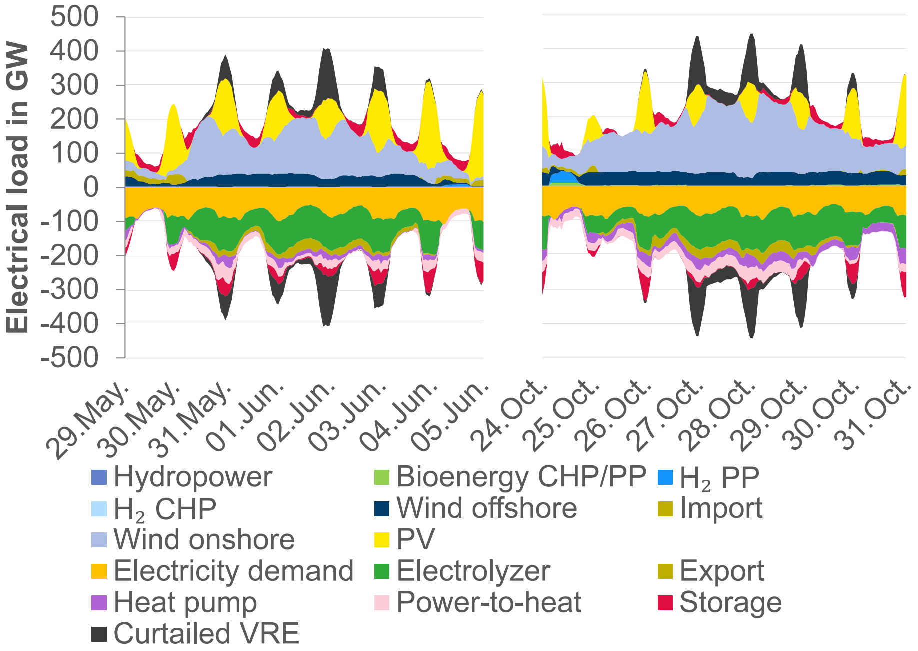


Fig. 9. Two weeks in 2045 with the highest curtailment of variable renewable energy. CHP: combined heat and power plant, PP: power plant, VRE: variable renewable energy.

analysis electrolyzers are required to operate at a specific minimum number of annual full load hours (FLH). In the reference scenario, the optimum FLH of electrolyzers are 3200 with an installed capacity of 98 GW_{el} related to electricity input, resulting in an electricity demand of 311 TWh/a and a hydrogen output of 218 TWh/a. Thus, electrolyzers show the largest flexible electricity demand in the energy system, and in turn, influence the energy system design and operation more than heat pumps or power-to-heat applications. Additionally, delivery contracts with hydrogen consumers could enforce operators of electrolyzers to deliver a constant hydrogen supply, which would prevent a fully flexible operation, as it was shown in the reference scenario. In this sensitivity analysis, the minimum FLH of electrolyzers are set to 4000, 5000, 6000, 7000, and 8000 (see Fig. 10). Electrolyzers are chosen because of their large flexible capacity and thus their impact on the energy system. Additionally, sector coupling technologies which supply heat are sometimes constrained in their flexibility by limited options to store heat or inflexible heat demands (see Fig. 6). Due to the hydrogen storage capacity of 73 TWh, electrolyzers can be operated much more flexible and thus are more suited for this sensitivity analysis.

A further reason for carrying out this sensitivity analysis comes from a policy standpoint: In the current German energy system, large-scale energy consumers are incentivized to operate in a constant manner throughout the year at 7000 to 8000 FLH in order to pay reduced grid fees [59]. This sensitivity analysis shows the effect of applying these base-load-orientated incentives to a future sector integrated energy system. The produced hydrogen is set at a fixed value of 218 TWh/a. This value is derived from the reference scenario and ensures comparability of the scenarios.

With higher minimum FLH, the electrolyzer capacity is reduced by up to 60% while still producing the same annual amount of hydrogen (Fig. 10). On the other hand, there is an increased capacity expansion of battery storage from 244 GWh in the reference scenario to 699 GWh in the scenario with 8000 FLH. Furthermore, the installed capacities of offshore wind energy and solar energy increase by up to 25%. The total annual system costs already increase by 4% in the scenario with 6000 FLH compared to the reference scenario, and by 10.5% in the scenario with 8000 FLH (Fig. 11).

In the latter scenario, the decreased size of the electrolyzer capacity leads to cost reductions of 2.9%. But, to account for the true cost of the continuous operation, the other system costs must also be considered. It becomes clear that the reduced electrolyzer costs are offset by higher costs for additional Li-Ion battery-, PV- and offshore wind-capacities as

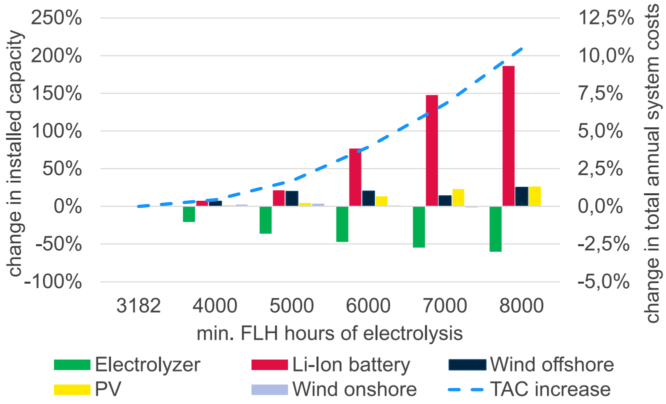
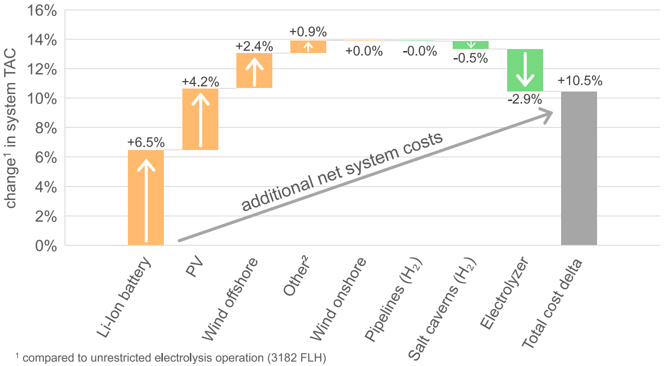


Fig. 10. Change in installed capacities (left axis) and total annual system costs (TAC, right axis) based on the minimum must-run hours of electrolysis.



[1] compared to unrestricted electrolysis operation (3182 FLH)

[2] other net costs are composed of:
increasing: wood chip CHP, electro vessel , … decreasing: heat pump, CCPP (NG), H_2 GT, compressor stations, …

Fig. 11. Change in total annual system costs (TAC) between the reference and the 8000 h must-run electrolysis scenario.

shown in Fig. 11. In total, this results in an increase of 10.5% of the total annual system costs. Fig. 12 shows the ordered load curve for the 8000 FLH scenario.

Compared to the reference scenario shown in Fig. 6, these are the key differences that can be identified: In the optimal case, electrolysis is operated at times of favorable variable renewable energy (VRE) production. For continuous operation at 8000 FLH, the electrolysis must also be operated during times of unfavorable VRE production, especially at night, as shown in Fig. 13. Electrolyzer operation during unfavorable VRE periods must be provided by battery storage. The *resilience peak load* of the system does not change significantly as the electrolyzers do not operate during the dark lull. However, the proportion of the year when flexible production and storage discharge is required increases from 28% in the reference scenario to 39%. Therefore, the system becomes more dependent on flexible energy suppliers as the *harvesting regime* shortens and the *transition regime* lengthens (cp. Fig. 6).

To charge the batteries, additional renewable energy supply capacities are added to the system, which increases the volatile production peaks. The peak electricity supply rises from 375 GW in the reference scenario to 443 GW in the 8000 FLH scenario, resulting in an increase in *harvesting peak load* from 287 GW to 317 GW. This means that the more continuous operation of electrolysis, with a lower nominal power requirement of 39 GW, leads to an increase in the overall peak load in the energy system.

As a result of the increase in renewable electricity supply, while final energy demand remains the same, curtailment and the use of inefficient technologies increase: Curtailment increases from 28 TWh/a to 45 TWh/a. At the same time, the use of power-to-heat applications is increased from 168 TWh/a to 316 TWh/a, whereas the operation of more efficient heat pump systems is reduced from 176 TWh/a to 146 TWh/a. The reason for these measures is to eliminate excess energy and to compensate for the loss of flexibility, as electrolyzers with a minimum of 8000 FLH provide an inflexible, rather than a flexible, load to the energy system.

To conclude, electrolysis operation with a high number of full load hours leads to a double burden on the system: (1) During unfavorable, volatile renewable energy supply, more inflexible base load must be supplied. (2) During favorable volatile renewable energy supply, higher volatile production peaks must be absorbed by the system. Overall, the system with higher must-run electrolysis becomes more expensive, more inefficient, and has higher peak loads.

4.4. *Sensitivity of inflexible generation: weather year dependency*

The previous results highlight the dependency of sector-integrated energy systems on weather-dependent renewable energy generation. As future energy systems should not be designed for a single year, but for long-term secure supply of energy, a resilient energy system design needs to take varying weather conditions into account. Therefore, this sensitivity analysis addresses the impact of interannual variability of weather conditions on the energy system design and operation. The following optimizations are done with renewable generation time series calculated with an updated and improved workflow introduced by Dunkel et al. [44] for historical weather years from 2009 to 2016. In contrast to the weather data used in the reference scenario, a synthetic dark lull has not been included in these weather years to avoid overlapping effects. All other scenario assumptions and model input data remain the same.

Table 1 summarizes the modelling results for the selected weather years. In general, all energy system designs rely on a combination of PV and wind energy, backed up with flexible power plants and energy storage. The ratio of installed capacities for PV and wind technologies varies from 1.35 (2009) to 1.65 (2015), showing the effect of varying solar irradiance and wind conditions on a cost-effective energy system. Compared to the results of the reference scenario, with 40 GW of offshore wind energy installed, significantly less offshore wind energy is installed. This is only partly due to the impact of the dark lull, but also stems from the updated workflow for time series generation, as the used workflow now includes an additional validation step, which leads to more realistic, but lower capacity factors of offshore wind in the German North Sea.

Comparing the results for the weather year 2014 with the other years, we can see that higher wind offshore capacities reduce the required expansion of flexible power plants. Furthermore, fewer electrolyzers and less hydrogen storage are built in the year 2014, which results in a lower hydrogen demand for electricity generation. We can also see that energy systems with a high PV/Wind ratio need more battery storage capacities for daily balancing of electricity supply and demand. Additionally, the results show that even without a synthetic dark lull, a significant investment into flexible powerplants and long-term hydrogen storage is needed. Compared to the installed 97 GW of flexible power plants in the reference scenario, most weather years install slightly less flexible power plants (74 – 90 GW if the year 2014 is excluded), and the resulting hydrogen storage capacity with a maximum of 57 TWh (2009) is also lower than the 73 TWh in the reference scenario. This shows that the inclusion of a synthetic dark lull in a single weather year ensures enough flexible power plant expansion and long-term storage capacity for a resilient energy system design in multiple historical weather years.

Table 2 shows the harvesting and resilience peak loads for the

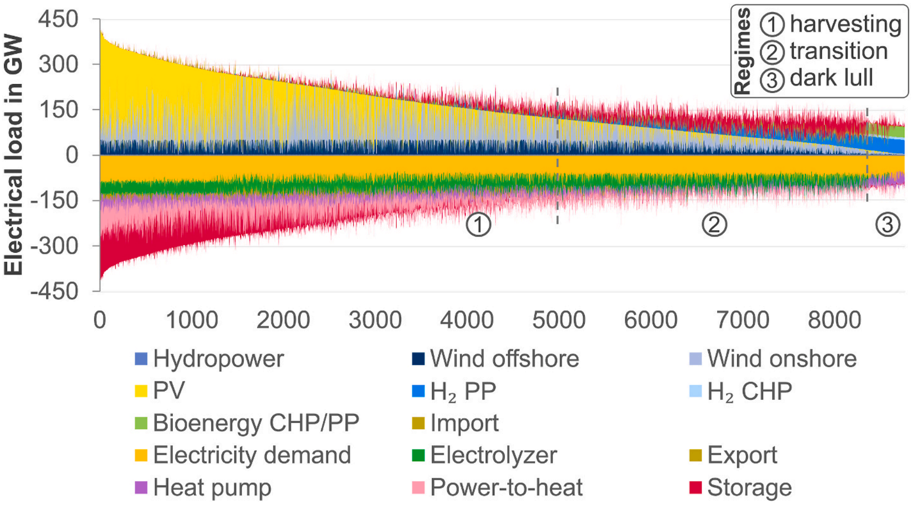


Fig. 12. Ordered annual load curve of the scenario with 8000 FLH of electrolysis. CHP: combined heat and power plant, PP: power plant.

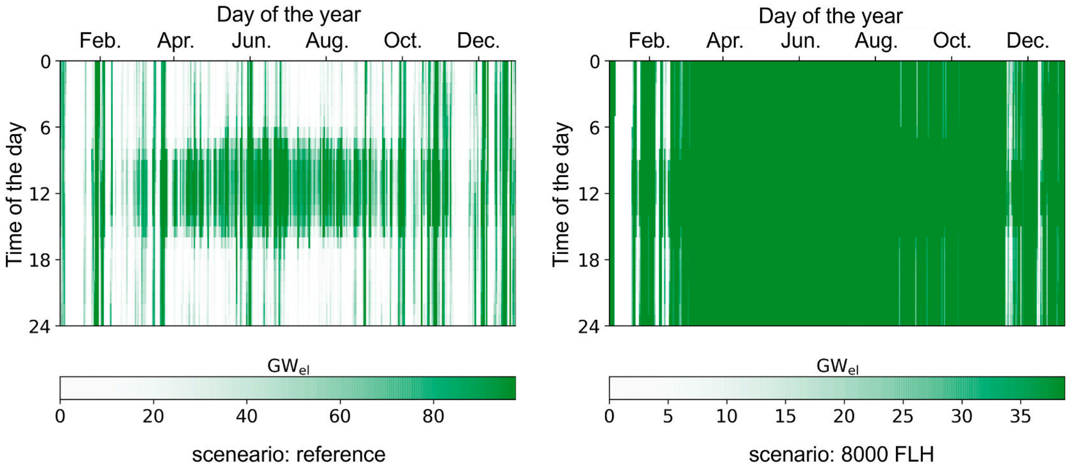


Fig. 13. Electrolyzer operation in the reference scenario (left) and the 8000 FLH scenario (right).

Table 1
Installed capacities for the selected weather years. PHES = pumped hydro energy storage, H2 UGS = underground gas storage for hydrogen.

	2009	2010	2011	2012	2013	2014	2015	2016
Wind onshore (GW)	288	278	252	253	272	224	236	261
Wind offshore (GW)	8	8	12	11	9	25	11	9
PV (GW)	401	437	384	398	438	399	408	441
Electrolyzer (GW$_{el}$)	96	96	85	84	95	66	82	82
H2 Gas Turbines (GW)	54	47	55	61	57	33	55	54
Biogas PP/CHP (GW)	27	34	19	29	31	19	20	25
Batteries (GWh)	403	473	376	415	403	426	488	537
PHES (GWh)	49	49	49	49	49	49	49	49
H2 UGS (GWh)	57,274	50,840	51,116	52,348	53,558	44,840	50,664	52,012

Table 2
Harvesting and resilience peak loads as well as occurring curtailment for the different weather years. Calculations without integrated synthetic dark lull.

	Harvesting Peak Load (GW)	Resilience Peak Load (GW)	Curtailment (TWh)
2009	286	112	46
2010	273	116	38
2011	270	160	45
2012	258	132	31
2013	258	134	42
2014	249	98	32
2015	276	131	46
2016	278	126	41

different weather years. Results for the weather year 2014 show that the resilience peak load is lower than for other weather years, which explains why less flexible power plant capacity is needed. The highest resilience peak load occurs for the weather year 2011. To cover this peak load, the maximum of flexible power production is required. Nevertheless, this does not mean that there is no electricity generation by renewable energy sources for this time. As shown in Table 1, the amount of installed flexible powerplants is with 70 GW lower than the resilience peak load of 160 GW. Additionally, Table 2 summarizes the curtailment of PV and wind power. For all weather years, curtailment varies from 30 to 46 TWh. This is higher than in the reference scenario (28 TWh), showing that there is a higher need to curtail PV and wind onshore electricity generation than wind offshore electricity generation in renewable-based energy system configurations.

Fig. 14 shows the ordered summed electrical load for the optimization results with the selected weather years. The depicted pattern is very similar for all weather years, and only the weather year 2014 can be clearly distinguished due to its lower electrical load for roughly 50% of the year. The weather year 2010 shows the highest electrical load over the year, and consequently, it is further analyzed together with the year 2014.

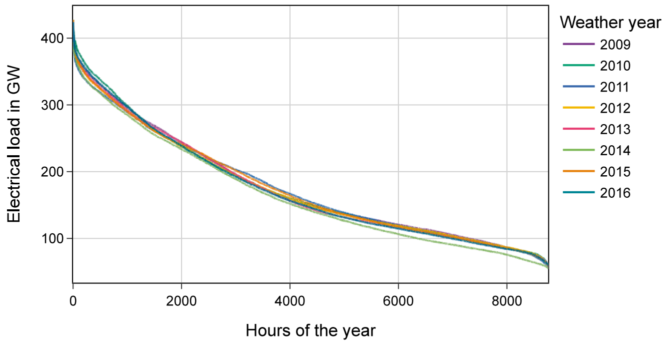


Fig. 14. Ordered electrical load for the scenario calculations with different weather years (rolling median trendline).

Fig. 15 shows the electricity mix for these two weather years. The electricity mix is similar, with the largest share produced by wind onshore and PV. Differences can be seen for the higher share of 8% electricity produced by offshore wind energy in the year 2014 compared to 2010. In turn, hydrogen and biomass power plants only supply 5.6% of electricity compared, to 7.9% in the year 2010.

Fig. 16 depicts the ordered annual electricity load curves for the two weather years. The three operational regimes of harvesting, transition and dark lull are still visible, but the dark lull regime is significantly shorter without explicit addition of a synthetic dark lull. In comparison, the dark lull regime is shorter in the year 2014 compared with 2010, due to less weather patterns during which renewable energies have no significant generation, and the installation of offshore wind energy which provides a more stable electricity generation. Comparing the length of

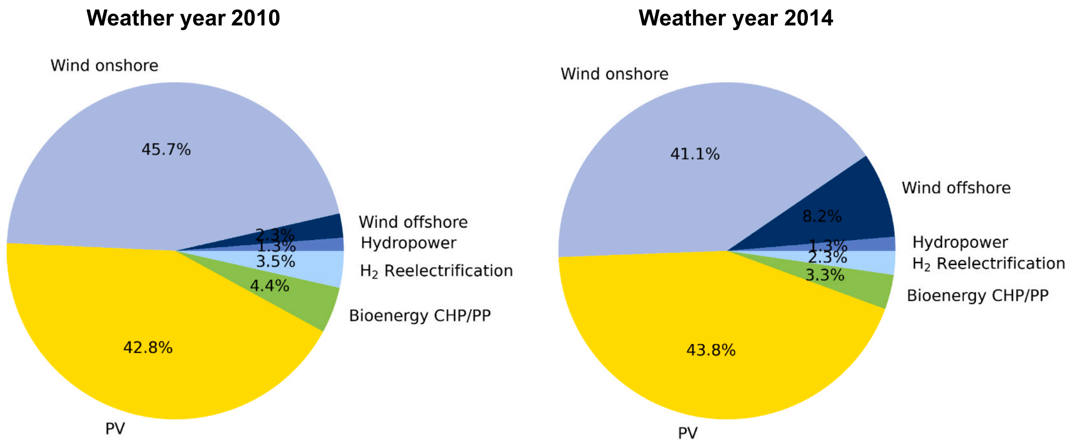


Fig. 15. Electricity mix of the scenario with weather year 2010 (left) and weather year 2014 (right). Calculations without integrated synthetic dark lull.

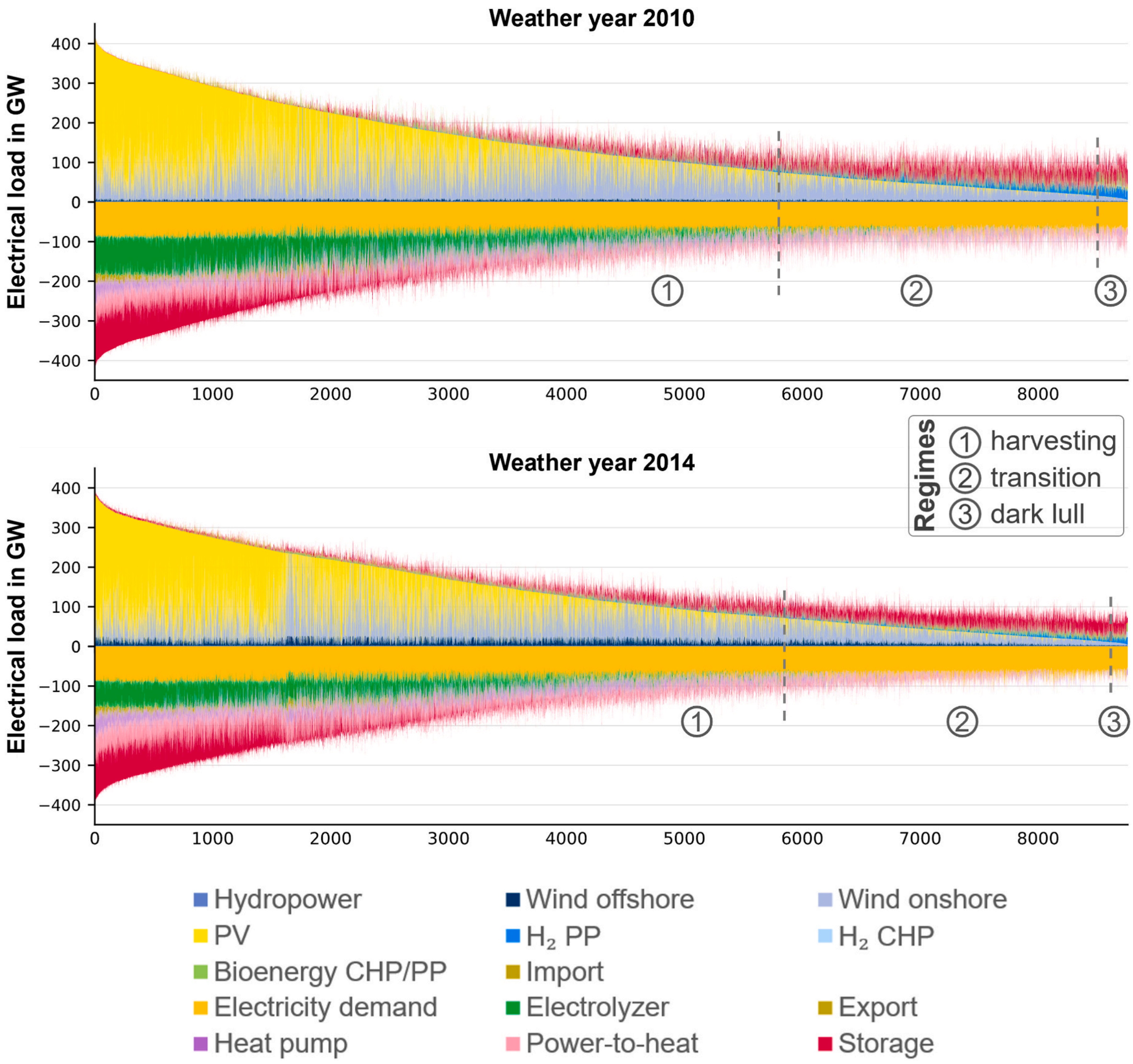


Fig. 16. Ordered annual load curve of the scenario with weather year 2010 (top) and weather year 2014 (bottom). Calculations without integrated synthetic dark lull.

harvesting regimes, no difference can be observed between the reference scenario and the years 2010 and 2014. Thus, the derived operating regimes are valid for the depicted weather years.

Differences between the weather years 2010 and 2014 are also visible in the operation of electrical storage, which are significantly more operated in the year 2010 and thus provide more balance between supply and demand. Furthermore, the higher electrical load of electrolyzers in the year 2010 is shown. However, the operation strategy for electrolyzers is consistent between the two historical weather years and the reference scenario.

The conducted sensitivity analysis shows that, in all investigated historical weather years, flexibility provided by power plants, energy storage technologies and flexible operation of sector-coupling options are key for security of supply. Furthermore, the optimization results show that energy systems with higher shares of PV typically need more short-term energy storage capacity. Additionally, we show that significant investment into flexible power plant capacity and long-term hydrogen storage is needed in all investigated weather years, but is always lower compared to the reference scenario with included synthetic dark lull.

5. Conclusions

This study introduces two new concepts for characterizing the peak load in sector-integrated energy systems with high shares of volatile renewable energy sources. One of these concepts is the harvesting peak load, which occurs when maximum volatile renewable electricity generation is met by maximum electricity demand by flexible sector coupling technologies, like electrolyzers, heat pumps and power-to-heat applications. Energy storage and sector coupling options harvest as much renewable energy as possible to feed it back to the electricity system at a later point in time or decarbonize the other sectors of the energy system. Thus, the harvesting peak load is beneficial for the energy system and not a critical situation for supply security. In contrast, the concept of resilience peak load characterizes a critical situation for the security of supply. In this situation a maximum inflexible electricity load must be met by flexible generation options, such as hydrogen or biomass power plants. Typically, the resilience peak load occurs during dark lulls, which characterize periods with minimum electricity supply by volatile renewable sources. To bridge these dark lulls, the flexibility to reduce the electricity demand by sector coupling options and long-term storage capacities are crucial for a resilient energy system. However, limitations regarding the final energy demands for heat and hydrogen have to be considered. Such limitations could be operational constraints, like ramp-up times or minimum output thresholds, or contractual constraints, which enforce a steady supply of heat or hydrogen. These constraints limit the flexibility of sector coupling technologies, but installation of heat or hydrogen storage can relieve these constraints through decoupling of supply and demand for heat or hydrogen. Thus, installation of short- and long-term energy storage in sector-integrated energy systems increases the security of supply.

Furthermore, our optimization results for the future German energy system show that a paradigm shift from fossil fuel-based energy systems to renewable-based systems takes place. In sector integrated, renewable energy systems, the electricity load must adjust to the volatile renewable electricity supply. Thus, the flexibility of sector coupling technologies to adjust their demand is a key aspect of optimal operation strategies of such energy systems. However, it is not economically feasible to use the entire renewable energy supply. Thus, economic curtailment of renewable energy sources is necessary if the maximum flexibility of sector coupling technologies is already used.

Additionally, we show that limiting the flexibility of electrolyzers leads to a significant increase in the total system costs by up to 10.5%. To replace the lack of flexibility, significantly more storage capacities have to be built, and curtailment of renewables increases.

Finally, we show that our operation strategies for sector-integrated energy systems are also valid for other historical weather years. An inclusion of a two-week synthetic dark lull leads to higher needed flexible power plant and long-term storage capacities compared to all eight investigated weather years. Thus, the energy system design is potentially more secure and resilient than it would need to be from a cost-optimal point of view.

We deduce four main strategic implications from the results, which are relevant for decision-makers and policymakers involved in national energy system planning:

Incentivize flexibility of electricity demand: To ensure a resilient energy system design, policymakers should support the flexible operation of sector coupling technologies, such as electrolyzers or heat pumps, depending on volatile renewable energy supply. This would reduce national energy system costs and the need for additional storage capacities. Thus, incentives for a continuous operation of sector coupling technologies should be removed and no additional burdens should be introduced which could negatively affect the flexibility of the electricity demand. Similarly, existing grid fee reductions for large-scale energy consumers to operate in a constant manner throughout the year should be removed or converted into financial incentives, which support more flexibility of the electricity demand.

Ensure sufficient expansion of storage capacity: Bridging dark lulls and ensuring the flexible operation of electrolyzers is only possible with sufficient hydrogen storage capacity. However, given past and future implementation gaps, decision-makers must prepare for prolonged green hydrogen scarcity [60]. As business models for hydrogen storage operators are currently unclear, policy support should secure hydrogen investments while prioritizing applications where hydrogen is indispensable. Furthermore, expansion of electricity and heat storage is also crucial for sector integrated energy systems. Policymakers should make sure that taxes and fees do not hinder the usage of these storage options and instead incentivize additional investments in storage capacities.

Consider dark lulls in energy system planning: As emphasized in this study, dark lulls are critical for the security of supply in renewable energy systems. The development of resilient energy system designs should ensure that dimensioning of flexible power plant capacities and planning of long-term energy storage take dark lulls into account during the planning phase. This approach can make sure that even under extreme conditions, the security of supply is guaranteed, and sufficient flexible power plant capacities and storage capacities are built. Possible options for taking dark lulls into account are calculations of needed power plant and storage capacities with a multitude of different historical weather years or introducing new sets of weather patterns to define energy system stress. Relying on a single historical weather year in energy system modelling can potentially lead to energy system designs which can't ensure security of supply under different weather conditions. However, for determination of needed flexible power plant capacities and long-term energy storage, model runs with a single weather year, which includes a synthetic dark lull, can lead to robust results.

Curtailment of renewable energy should be accepted to a certain extent: Efforts to use the entire energy supply from renewable sources are not economically feasible, even with highly flexible sector coupling technologies. Instead, decision-makers should accept that a share of renewable energy will be curtailed throughout the year. This should only occur when other flexibility options are not available or already entirely used. While curtailment should not be incentivized, likewise, it should not be prohibited by additional fees.

While this work provides valuable insights, it is limited in some respects. We only address the security of supply in sector integrated renewable-based national energy systems from the perspective of a social planner. Thus, using a national energy system model, business cases for operators of electrolyzers or other sector coupling technologies cannot be analyzed. Additionally, market power, taxes, business risks, and subsidies are not part of the macroeconomic perspective of the applied optimization model. Consequently, the derived policy recommendations are directed at decision-makers in the field of national energy system design. Against this background, electricity market models should be applied to identify quantitative recommendations for subsidies or analyze the effects of the proposed policy implications on electricity prices.

Regarding the modeled flexibility options, demand side management and bi-directional charging of battery electric vehicles were not yet included in the used version of the optimization model. This could lead to an overestimation of needed expansion of electricity storage and flexible power plant capacity. Therefore, additional analyses are needed to quantify the contribution of these technologies to the flexibility in a resilient energy system. Model coupling approaches such as presented by Odenweller et al. [31] could be used to investigate the contribution of demand side management to a resilient energy system design.

Furthermore, an expansion of the European electricity transmission grid could reduce the need for national power plant capacity to bridge dark lulls. As the length and depth of dark lulls decrease if the size of the investigated region is increased [58], it is possible that increased electricity imports from neighboring countries could assist in bridging a dark lull in Germany. This contribution of enhanced European interconnection could be analyzed with European energy system models such as the one used by Chyong et al. [24].

While we considered several historical weather years and a synthetic dark lull and their impact on a resilient energy system design, the uncertainty induced through climate change is not addressed. A possible approach to investigate this influence could be the usage of future weather data from climate models as input for the energy system model. However, first results by Plaga and Bertsch [35] show a limited impact of climate change on a European electricity system design.

The findings of this work show that operation and design strategies for future resilient sector integrated energy systems are, in part, significantly different from past strategies. This is also reflected in the policy implications, which show the need to adapt regulations and incentives valid for fossil fuel-based energy systems for renewable energy-based systems. In particular, the paradigm shift from continuous demand to flexible demand is a key aspect. As this work takes the perspective of an energy system planner, the effect of the policy implications on operators of sector coupling technologies or on large industry consumers was not part of the analysis. Thus, all policy implications stem from the perspective of the energy system. Although consideration of dark lulls and expansion of hydrogen storage are not yet relevant for today's energy system, policymakers should include these aspects in planning processes for future national energy systems. Our newly defined concepts, which go beyond previous concepts for measuring security of supply, such as peak load and residual load, provide decision-makers with further means of assessing the optimal design of energy systems.

CRediT authorship contribution statement

Thomas Schöb: Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Investigation. **Theresa Klütz:** Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Visualization, Investigation. **Toni Busch:** Writing – original draft, Writing – review & editing, Methodology, Visualization, Investigation. **Jochen Linssen:** Writing – review & editing, Supervision. **Jann Michael Weinand:** Writing – review & editing, Supervision.

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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Data availability

Data will be made available on request.

References

[1] D. Gielen, F. Boshell, D. Saygin, M.D. Bazilian, N. Wagner, R. Gorini, The role of renewable energy in the global energy transformation, Energy Strategy Rev. 24 (2019) 38–50, https://doi.org/10.1016/j.esr.2019.01.006.

[2] European Commission, Decarbonising Our Energy System to Meet Our Climate Goals, Publications Office of the European Union, 2021 [Online], https://data.europa.eu/doi/10.2775/582723. (Accessed 24 March 2025).

[3] Federal Law Gazette, Federal Climate Change Act of 12 December 2019 (Federal Law Gazette I, p. 2513), as Last Amended by Article 1 of the Act of 18 August 2021 (Federal Law Gazette I, p. 3905), 2021 [Online], http://www.gesetze-im-internet.de/ksg/index.html.

[4] G. Luderer, et al., Impact of declining renewable energy costs on electrification in low-emission scenarios, Nat. Energy 7 (1) (2022) 32–42, https://doi.org/10.1038/s41560-021-00937-z.

[5] B. van der Zwaan, et al., Electricity- and hydrogen-driven energy system sector-coupling in net-zero CO2 emission pathways, Nat. Commun. 16 (1) (2025) 1368, https://doi.org/10.1038/s41467-025-56365-0.

[6] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, Energy 160 (2018) 720–739, https://doi.org/10.1016/j.energy.2018.06.222.

[7] M. Fodstad, et al., Next frontiers in energy system modelling: a review on challenges and the state of the art, Renewable Sustainable Energy Rev. 160 (2022) 112246, https://doi.org/10.1016/j.rser.2022.112246.

[8] B. Johansson, Security aspects of future renewable energy systems–a short overview, Energy 61 (2013) 598–605, https://doi.org/10.1016/j.energy.2013.09.023.

[9] J. Jasiūnas, P.D. Lund, J. Mikkola, Energy system resilience – a review, Renewable Sustainable Energy Rev. 150 (Oct. 2021) 111476, https://doi.org/10.1016/j.rser.2021.111476.

[10] R. Schmitz, F. Flachsbarth, L.S. Plaga, M. Braun, P. Härtel, Energy security and resilience: revisiting concepts and advancing planning perspectives for transforming integrated energy systems, Energy Policy 207 (2025) 114796, https://doi.org/10.1016/j.enpol.2025.114796.

[11] Y. Parag, M. Ainspan, S. Zemah Shamir, Why current resilience metrics fall short in the energy transition: a system-level review of gaps and needs, Energy Strategy Rev. 63 (2026) 102023, https://doi.org/10.1016/j.esr.2025.102023.

[12] M. Sulzer, G. Mavromatidis, A. Nuñez-Jimenez, M. Wetter, The energy supply security pyramid: a quantitative framework for planning and policy making, iScience 28 (5) (2025) 112407, https://doi.org/10.1016/j.isci.2025.112407.

[13] Z. Zhang, et al., Multi-type energy storage expansion planning: a review for high-penetration renewable energy integration, Renew. Sustain. Energy Rev. 219 (2025) 115853, https://doi.org/10.1016/j.rser.2025.115853.

[14] B.-J. Jesse, H.U. Heinrichs, W. Kuckshinrichs, Adapting the theory of resilience to energy systems: a review and outlook, Energy Sustainable Soc. 9 (1) (2019) 27, https://doi.org/10.1186/s13705-019-0210-7.

[15] H.C. Gils, S. Bothor, M. Genoese, K.-K. Cao, Future security of power supply in Germany—The role of stochastic power plant outages and intermittent generation, Int. J. Energy Res. 42 (5) (2018) 1894–1913, https://doi.org/10.1002/er.3957.

[16] C. Brunner, G. Deac, S. Braun, C. Zöphel, The future need for flexibility and the impact of fluctuating renewable power generation, Renewable Energy 149 (2020) 1314–1324, https://doi.org/10.1016/j.renene.2019.10.128.

[17] S. Impram, S. Varbak Nese, B. Oral, Challenges of renewable energy penetration on power system flexibility: a survey, Energy Strategy Rev. 31 (2020) 100539, https://doi.org/10.1016/j.esr.2020.100539.

[18] P.D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renewable Sustainable Energy Rev. 45 (2015) 785–807, https://doi.org/10.1016/j.rser.2015.01.057.

[19] K. Grave, M. Paulus, D. Lindenberger, A method for estimating security of electricity supply from intermittent sources: scenarios for Germany until 20301, Energy Policy 46 (2012) 193–202, https://doi.org/10.1016/j.enpol.2012.03.050.

[20] C. Brunner, S. Misconel, P. Hauser, D. Möst, To what extent can flexibility options reduce the need for hydrogen backup power plants? Energy Policy 201 (2025) 114551 https://doi.org/10.1016/j.enpol.2025.114551.

[21] W.-P. Schill, Residual load, renewable surplus generation and storage requirements in Germany, Energy Policy 73 (2014) 65–79, https://doi.org/10.1016/j.enpol.2014.05.032.

[22] D. Suna, G. Totschnig, F. Schöniger, G. Resch, J. Spreitzhofer, T. Esterl, Assessment of flexibility needs and options for a 100% renewable electricity system by 2030 in Austria, Smart Energy 6 (2022) 100077, https://doi.org/10.1016/j.segy.2022.100077.

[23] C. Büttner, K. Esterl, I. Cußmann, C.A. Epia Realpe, J. Amme, A. Nadal, Influence of flexibility options on the German transmission grid — a sector-coupled mid-term scenario, Renewable Sustainable Energy Transit. 5 (Aug. 2024) 100082, https://doi.org/10.1016/j.rset.2024.100082.

[24] C.K. Chyong, M. Pollitt, D. Reiner, C. Li, Modelling flexibility requirements in deep decarbonisation scenarios: the role of conventional flexibility and sector coupling options in the European 2050 energy system, Energy Strategy Rev. 52 (Mar. 2024) 101322, https://doi.org/10.1016/j.esr.2024.101322.

[25] L. Göke, J. Weibezahn, M. Kendziorski, How flexible electrification can integrate fluctuating renewables, Energy 278 (2023) 127832, https://doi.org/10.1016/j.energy.2023.127832.

[26] F. Boehnke, H. Kramer, C. Weber, The value of decentral flexibility in nodal market design – a case study for Europe 2030, Energy Policy 196 (2025) 114396, https://doi.org/10.1016/j.enpol.2024.114396.

[27] M. Lieberwirth, H. Hobbie, Decarbonizing the industry sector and its effect on electricity transmission grid operation—Implications from a model based analysis for Germany, J. Clean. Prod. 402 (2023) 136757, https://doi.org/10.1016/j.jclepro.2023.136757.

[28] G. Papaefthymiou, K. Dragoon, Towards 100% renewable energy systems: uncapping power system flexibility, Energy Policy 92 (2016) 69–82, https://doi.org/10.1016/j.enpol.2016.01.025.

[29] S. Balasubramanian, P. Balachandra, Effectiveness of demand response in achieving supply-demand matching in a renewables dominated electricity system: a modelling approach, Renewable Sustainable Energy Rev. 147 (2021) 111245, https://doi.org/10.1016/j.rser.2021.111245.

[30] H. Karimi, M. Monemi Bidgoli, S. Jadid, Optimal electrical, heating, cooling, and water management of integrated multi-energy systems considering demand-side management, Elec. Power Syst. Res. 220 (2023) 109353, https://doi.org/10.1016/j.epsr.2023.109353.

[31] A. Odenweller, et al., REMIND-PyPSA-Eur: integrating power system flexibility into sector-coupled energy transition pathways, Prog. Energy 8 (2) (2026) 025001, https://doi.org/10.1088/2516-1083/ae3ffe.

[32] E.K. Gøtske, G.B. Andresen, F. Neumann, M. Victoria, Designing a sector-coupled European energy system robust to 60 years of historical weather data, Nat. Commun. 15 (1) (2024) 10680, https://doi.org/10.1038/s41467-024-54853-3.

[33] M. Kittel, W.-P. Schill, Measuring the Dunkelflaute: how (not) to analyze variable renewable energy shortage, Environ. Res.: Energy 1 (3) (2024) 035007, https://doi.org/10.1088/2753-3751/ad6dfc.

[34] L. Liu, et al., Climate change impacts on planned supply–demand match in global wind and solar energy systems, Nat. Energy 8 (8) (2023) 870–880, https://doi.org/10.1038/s41560-023-01304-w.

[35] L.S. Plaga, V. Bertsch, Comparing different methods which improve security of supply in a decarbonized European electricity system under climate uncertainty, Energy 340 (2025) 139125, https://doi.org/10.1016/j.energy.2025.139125.

[36] Jülicher Systemanalyse, ETHOS Model Suite, 2025 [Online], https://www.fz-juelich.de/de/ice/ice-2/leistungen/model-services.

[37] D. Stolten, et al., Neue Ziele auf alten Wegen? Strategien für eine treibhausgasneutrale Energieversorgung bis zum Jahr 2045, in: Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt/Energy & Environment, vol 577, Forschungszentrum Jülich GmbH Zentralbibliothek, Verlag, Jülich, 2022. VI, 81. [Online], https://juser.fz-juelich.de/record/908382.

[38] T. Klütz, et al., ETHOS.FINE: a framework for integrated energy system assessment, JOSS 10 (105) (2025) 6274, https://doi.org/10.21105/joss.06274.

[39] T.M. Groß, Multiregionales Energiesystemmodell mit Fokus auf Infrastrukturen, RWTH Aachen University, 2022, https://doi.org/10.18154/RWTH-2023-01485.

[40] T. Busch, T. Groß, J. Linßen, D. Stolten, The role of liquid hydrogen in integrated energy systems–A case study for Germany, Int. J. Hydrogen Energy (2023), https://doi.org/10.1016/j.ijhydene.2023.05.308. S0360319923027222.

[41] J. Hörsch, T. Brown, The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios, in: 14th International Conference on the European Energy Market (EEM), 2017, pp. 1–7, https://doi.org/10.1109/eem.2017.7982024.

[42] S. Risch, et al., Potentials of renewable energy sources in Germany and the influence of land use datasets, Energies 15 (15) (2022), https://doi.org/10.3390/en15155536. Art. no. 15.

[43] D.G. Caglayan, D.S. Ryberg, H. Heinrichs, J. Linßen, D. Stolten, M. Robinius, The techno-economic potential of offshore wind energy with optimized future turbine designs in Europe, Appl. Energy 255 (2019) 113794, https://doi.org/10.1016/j.apenergy.2019.113794.

[44] E.U. Peña-Sánchez, et al., Towards high resolution, validated and open global wind power assessments, Nat. Commun. 17 (1) (2026) 539, https://doi.org/10.1038/s41467-026-68337-z.

[45] D.S. Ryberg, D.G. Caglayan, S. Schmitt, J. Linßen, D. Stolten, M. Robinius, The future of European onshore wind energy potential: detailed distribution and simulation of advanced turbine designs, Energy 182 (2019) 1222–1238, https://doi.org/10.1016/j.energy.2019.06.052.

[46] Übertragungsnetzbetreiber, Netzentwicklungsplan Strom 2037 mit Ausblick auf 2045, Version 2023 - Zweiter Entwurf der Übertragungsnetzbetreiber, 2023.

[47] C. Syranidou, Integration of Renewable Energy Sources into the Future European Power System Using a Verified Dispatch Model with High Spatiotemporal Resolution, 2019. Thesis.

[48] VGE, Gasversorgungsnetze in Deutschland, WGI und Glückauf Verlag (2010).

[49] J. Jens, A. Wang, K. van der Leun, D. Peters, M. Buseman, Extending the European Hydrogen Backbone - a European Hydrogen Infrastructure Vision Covering 21 Countries, 2021. Report.

[50] EHB, Five Hydrogen Supply Corridors for Europe in 2030, 2022.

[51] D.G. Caglayan, et al., Technical potential of salt caverns for hydrogen storage in Europe, Int. J. Hydrogen Energy 45 (11) (2020) 6793–6805, https://doi.org/10.1016/j.ijhydene.2019.12.161.

[52] R. Maier, J. Behrens, M. Hoffmann, F. Kullmann, J.M. Weinand, D. Stolten, Impact of foresight horizons on energy system decarbonization pathways, Adv. Appl. Energy 18 (2025) 100217, https://doi.org/10.1016/j.adapen.2025.100217.

[53] F. Kullmann, P. Markewitz, L. Kotzur, D. Stolten, The value of recycling for low-carbon energy systems - a case study of Germany's energy transition, Energy 256 (2022) 124660, https://doi.org/10.1016/j.energy.2022.124660.

[54] T. Schöb, F. Kullmann, J. Linßen, D. Stolten, The role of hydrogen for a greenhouse gas-neutral Germany by 2045, Int. J. Hydrogen Energy (2023), https://doi.org/10.1016/j.ijhydene.2023.05.007. S0360319923022358.

[55] Bundesverband der Energie- und Wasserwirtschaft (BDEW), Versorgungssicherheit Strom: Grundlagen und Methodik zur Bewertung der Versorgungssicherheit Strom und politische Handlungsempfehlungen, Berlin, 2021 [Online], https://www.bdew.de/media/documents/20210930_Awh_BDEW-Fakten-und-Argumente_Versorgungssicherheit-Strom.pdf. (Accessed 26 July 2022).

[56] Bundesnetzagentur, SMARD | Marktdaten, 2025 [Online], https://www.smard.de/home/downloadcenter/download-marktdaten/. (Accessed 22 March 2025).

[57] Fraunhofer Institute for Solar Energy Systems ISE, Installierte Leistung | Energy-Charts, 2025 [Online], https://www.energy-charts.info/charts/installed_power/chart.htm?l=de&c=DE&year=2024&stacking=stacked_absolute. (Accessed 22 March 2025).

[58] S.D. Ryberg, "Generation Lulls from the Future Potential of Wind and Solar Energy in Europe," Dissertation, Fakultät für Maschinenwesen, RWTH Aachen, Jülich, 2020.

[59] Federal Law Gazette, § 19 Stromnetzentgeltverordnung. 2005. Accessed: Mar. 24, 2025. [Online]. Available: https://www.gesetze-im-internet.de/stromnev/_19.html.

[60] A. Odenweller, F. Ueckerdt, The green hydrogen ambition and implementation gap, Nat. Energy 10 (1) (2025) 110–123, https://doi.org/10.1038/s41560-024-01684-7.