Flexibility options for enhanced use of electricity from renewable energy sources

A qualitative study on two regions in Germany

Submission to the proceedings of the 15th SDEWES Conference Cologne 2020

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Date: 28.08.2020

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ABSTRACT

The expansion of renewables leads to new economic and social challenges, for example grid congestions and land-use conflicts. This study investigates supply-oriented flexibility options for the electricity system (i.e. battery storages, power-to-heat, demand-side management) and their potential to enhance the integration of renewable energy sources into the energy system. Two different approaches to integrate flexibility options are used in individual case studies. In a qualitative manner, we compare these case studies along challenges to decarbonize the energy sector. Both case studies make use of well-researched, region-specific and verified data for model calculations. The techno-economic potential is analyzed by using a dispatch optimization energy system model, applied to different scenarios that cover various combinations of renewable energy penetration, regulatory framework, and flexibility options. The analysis shows that flexibility options have great technical potential to increase effective use of otherwise curtailed electricity produced by wind turbines. However, the current regulations are found to inhibit the economic use of curtailed energy. Furthermore, we find that the land-use regulations need to be adapted in order to increase renewable capacities required for a deep decarbonization of the energy sector. The qualitative comparison of the two case studies shows significant regional differences regarding challenges of the integration of renewables. Likewise, the potential of flexibility options to address these challenges varies. In general, we show that coupling of energy supply sectors has high potential for enabling flexibility in the electricity supply sector.

KEYWORDS
Integration of renewable energy; energy system modeling; flexibility; CO_2 reduction; regional energy supply; energy autarky; land use; open source

1 INTRODUCTION

1.1 Motivation

As the energy transition in Germany progresses, the share of renewable energy sources (RES) in gross energy consumption increases yearly, adding up to 42,1 % in 2019 (AGEE-Stat / Umweltbundesamt, 2020). This is important for achieving the negotiated greenhouse gas emission reduction targets (UNFCCC, 2015). But it also creates new challenges. In particular, the electricity grid is affected by varying locations and patterns of power generation. This leads to

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enormous grid extension needs (Nahmmacher et al., 2020) and curtailment (Joos and Staffell, 2018) to cope with grid congestions. As curtailment cost is part of the grid surcharges, cost of energy supply increase as well (Bundesnetzagentur, 2019). In addition, new RES generation units are being built dispersed across the country, which leads to a change towards more decentralized generation. In order to use this energy locally, close to the generation site, a new balancing demand at regional level arises.

Within the research project *WindNODE*, that aims to find new solutions to cope with imbalances between demand and intermittent supply from RES, we analyze the value of new flexibility options for regional energy supply systems. Therefore, we conduct two energy system modeling studies for two regions in Germany with very different conditions. The one characterized by large-scale wind energy curtailment imposed by increasing grid congestions. The other aiming at local and sustainable energy supply options at competitive cost. In both studies, new flexibility options (battery storages, power-to-heat (PtH), power-to-gas (PtG), demand-side management (DSM)) are studied regarding their potential to support the individual goals of both regions. For evaluating the added value a specific flexibility option might offer on a broader level, a qualitative comparison of both studies is conducted.

1.2 Background and literature review

RES have been evolving over the past decades introducing large amounts of intermittent capacity into the power system. This leads to increased mismatches between supply and demand – in magnitude and in frequency (Cruz et al., 2018) – for several reasons: First, rapid changes of weather conditions can lead to extreme positive or negative feedin-in ramps. As their magnitudes cannot be predicted perfectly, with increasing shares of RES, it becomes more and more challenging to meet the residual load at any time using traditional plants or storages (Huber et al., 2014). Second, energy needs to be shifted due to inherent mismatches between production and demand across various temporal scales (e.g. diurnal, seasonal). In addition, mainly introduced by changed locations of decentralized generation from RES, grid congestions become more frequent, at both, transmission and distribution grid level. By today, and because the re-dispatch market cannot properly respond to the grid congestions, curtailment of RES generated electricity, as the ultimate measure to safeguard the electricity system in a reliable state, has massively scaled up in the past decade (Joos and Staffell, 2018). In 2019 in Germany, 6.5 TWh were curtailed (thereof 78 % from wind energy) resulting in total cost of compensation for the operators of around 710 million EUR (Bundesnetzagentur, 2019). At the same time, due to increasing intermittent generation, the supply-side flexibility which compensates mismatches in demand and supply by dispatching conventional power plants decreases, because of decommissioned capacity (Cruz et al., 2018). In short: more flexibility is needed and new sources of flexibility are required.

But what exactly is flexibility? Various definitions, different in detail, for the flexibility of a power/energy system exist (Lund et al., 2015; Alizadeh et al., 2016; Cruz et al., 2018). Although the definitions are different, they have in common that they define flexibility as the ability of the system to react to unforeseen changes of supply or demand and eliminate the resulting mismatches. Huber et al. (2014) characterize the flexibility requirements by ramp magnitude, ramp frequency and response time.

Traditionally, flexibility in the power system is provided on a short-term by dispatching conventional power plants and on a long-term by extending grid capacity. Since conventional generation capacity is diminishing and although traditional grid expansion can relieve the need and decrease the costs for balancing power and curtailment of RES (Joos and Staffell, 2018), further approaches exist to address this issue and increase the system's flexibility (Taibi et al., 2018).

Looking at future flexibility requirements from a systems planning and modeling point of view, Alizadeh et al. (2016) categorize the provision of flexibility options along their response time. Four categories are found: long-term (i.e. regulatory changes, transmission capacity upgrades), mid-term (i.e. dispatchable generation, energy storage systems, DSM), short-term (i.e. spatial smoothing, large rotating masses) and very-short-term (i.e. low voltage ride-through, reactive power control). Cruz et al. (2018) propose to categorize flexibility options into sources of origin: power generation, demand side, network side and energy storage facilities. Whereas in a broad review on available flexibility options for future energy supply, Lund et al. (2015) state that typically a classification is used that fits the specific context and honestly say that searching for the ultimate classification that covers all contexts is not worth the effort. We agree on that and must admit it would go beyond the scope of this paper. However, Lund et al. (2015) make an important point for all technological options: the potential of a certain flexibility option is highly dependent on the electricity market regime. The market must create signals to incentivize investments into flexibility options and offer products for cost-effective allocation of flexibility in operation. A good example for this are large-scale battery storages. At the moment, the only profitable market for large-scale battery storages is the primary control reserve market in which a saturation can already be observed (Figgener et al., 2020).

For the assessment of the value of flexibility, it can be divided into technical, economic and market potential, which are each assessed differently (Kondziella and Bruckner, 2016). The technical potential can be described by a residual load curve outlining the maximum positive and negative balancing capacity required to match demand and supply.

The economic potential (or value) incorporates cost and is assessed using a dispatch or a combined dispatch and investment model to compare different flexibility options based on their cost. Typically, the competitive capacity of flexibility options is determined by minimizing total system cost. The resulting capacity of each technology considered is understood as the economic potential. In addition to cost, the economic potential of flexibility options can also be assessed based on avoided curtailment (Kulms et al., 2018) or based on resulting CO_2 emissions (Comaty, 2013).

The market potential of flexibility incorporates specific electricity market schemes representing the current situation in energy trade. Thus, in addition to the economic potential, bidding schemes and market constraints are considered here. Goutte and Vassilopoulos (2019) assess the value of flexibility provided by a combined-cycle gas turbine (CCGT) for bids in day-ahead and intra-day market. Both case studies that are compared in this article focus on the assessment of the economic potential by using avoided cost and CO_2 emissions as key parameters. Details for each study are described in section 2.1.

In line with the case studies presented here, we focus on residential DSM (or demand response), battery storages, and PtH with thermal storages.

DSM can be described as the modification of electrical demand patterns. Lund et al. (2015) describe three categories DSM can be divided into with regard to the load: increase, decrease and rescheduling. Rescheduling the load means to shift power on a temporal scale which can be broken down to an increase and decrease of load at different times within a certain time slot. For the potential of DSM, different categories are proposed by Dranka and Ferreira (2019) which complement the concepts of potential Kondziella and Bruckner (2016) – the behavior and decision making of consumers must be incorporated for accessing DSM which results in achievable potential as an additional category (Lund et al., 2015; Dranka and Ferreira, 2019). Brouwer et al. (2016) assess various flexibility options in scenarios with RES penetration levels up to 80 % in Western Europe, employing an energy-only investment and dispatch model based on the flexibilities' net present value. In that study, DSM is found to be able to lower the total system cost effectively, but do not provide sufficient shifting capacities for highly renewable settings.

In contrast to DSM, battery storages are already being used to provide system flexibility (Taibi et al., 2018). In Germany, a capacity of 930 MWh in small-scale and 550 MWh in large-scale systems was installed in 2018 (Figgener et al., 2020). Due to their nearly instantaneous response time, batteries are suitable for ancillary grid services to improve grid stability. Today, they are almost exclusively operated to serve the primary control reserve market in Germany as only business case viable in the regulatory framework. Decreasing cost and the combination of multiple applications, such as today's frequency containment reserve and other applications e.g. peak shaving, may lead to a higher market penetration of large-scale battery storages in the future according to Figgener et al. (2020).

In Germany, an increase in heat pump installations can be observed adding additional electrical loads to the power system (BWP e.V., 2019). Heat pumps are decentralized PtH systems often combined with heat storages which offer a great flexibility potential. Hilpert (2020) quantifies this potential in an energy system modeling study and in particular investigates to what extent the need for battery storages can be reduced by introducing PtH. He finds that the demand for battery storage capacity for balancing can be reduced by 42 % to 62 %.

In district heating networks, PtH systems such as heat pumps or heating rods in combination with large-scale heat storages could technically replace existing heat generation plants to provide additional load shifting capabilities. Bernath et al. (2019) assessed how heat pumps in district heating grids may contribute to renewable energy integration in Germany using an integrated model for cost-optimization of investment and dispatch. Assuming an increase in natural gas and CO_2 emission allowances prices, their results show that centralized PtH can be competetive and gradually replace heat generation based on natural gas. However, the model used by Bernath et al. (2019) assumes a level playing field setting where grid surcharges and levies according to the German Renewable Energies Act are not considered.

Surcharges that need to be paid when otherwise curtailed electricity from wind energy is used for PtH applications is the main barrier for using such electricity (Gerhardt et al., 2014). This was already found in 2014 and the picture did not change much until now.

Today, an energy supply without importing substantial amounts of energy – often referred to as energy autarky – is a strong vision for many communities (Schmidt et al., 2012). Müller et al. (2011) introduce (regional) energy autarky as a conceptual framework for sustainable regional development. It is build upon three basic principles: the use of endogenous renewable potentials, energy decentralization and an increase in energy efficiency. Possible benefits of autarky include, amongst others, the enhancement of local economic value, the decarbonization of the local energy system by avoiding imports originating from fossil sources and the increase of acceptance and support by residents. Tröndle et al. (2019) assessed to which extend electricity autarky is feasible for different spatial levels in Europe finding that on subnational levels, energy autarky can be achieved primarily in regions with low population density. In one of the two case studies' regions, we conducted workshops with local stakeholders which underlined the importance of energy autarky. Möller (2020) investigated autarky in so-called energy regions in Germany. She found that autarky levels up to 80 % (in some cases up to 90 %) are economically attractive.

1.3 Structure of the article

This article is structured as follows. In section 2, we describe the methods for assessing the value of flexibility in the underlying studies. In the second part, we explain how the qualitative comparison is made. Original results of the two case studies are presented in section 3 in a condensed way. Section 4 presents the actual comparison of the findings from the case studies. First, the features of each study are presented. In the second part, findings are compared along challenges for decarbonizing energy supply. This is followed by a discussion of main findings with results from other research projects and the key limitations of the underlying studies which affect the findings of this paper. The article finishes with conclusions on the integration of RES and the value of certain flexibility options to support this.

2 METHODS

2.1 Assessing the value of flexibility using energy system models (ESMs)

2.1.1 Case study 1: Curtailed wind energy in the Uckermark

The Uckermark, located in the north-east corner of the federal state Brandenburg, is a region with high RES generation and relatively low electricity demand. Since the electricity grid cannot cope with increased reverse power flows from large-scale wind energy production due to delayed grid expansion (Bauknecht et al., 2016), wind turbines get curtailed (190 GWh in 2016) by the so-called feed-in management measures, for which the operators receive compensation (Fattler et al., 2017). This also results in higher grid usage fees for end-users.

Two cities in the study region – Prenzlau and Schwedt – have district heating grids which serve in total 190 GWh (2016) of thermal demand, mostly generated by natural gas. This offers great potential for the absorption of otherwise curtailed electricity (Jülch et al., 2017). This study (*WindNODE_KWUM*) investigates options for the cost-effective use of otherwise curtailed electricity at low CO_2 emissions. In particular, it is studied how the regulatory framework affects the use of otherwise curtailed electricity by introducing new flexibility options.

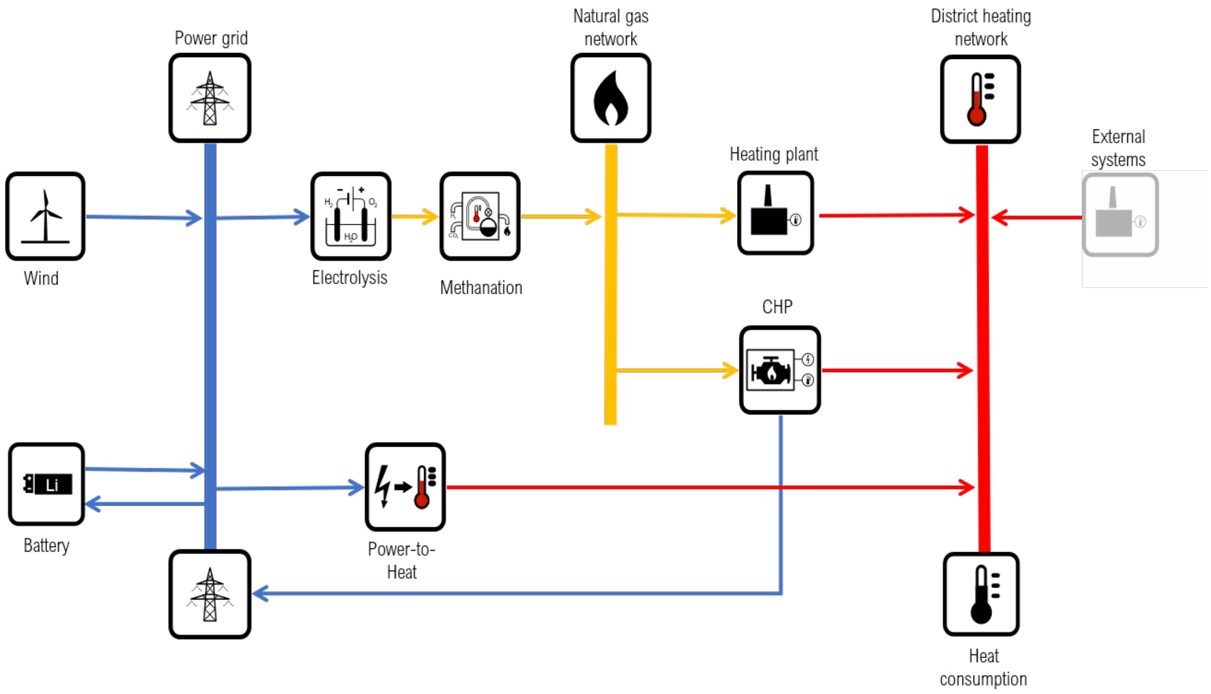


Figure 1: Core elements of the regional energy system model *WindNODE_KWUM* for the region Uckermark.

For the analysis, the regional energy system model *WindNODE_KWUM* was built to represent electricity and heat supply in the north-eastern part of the Uckermark (Reiner Lemoine Institut, 2020d,c). It founds on the work of Romero García (2018) and uses the the energy system modeling framework *oemof-solph* (Hilpert et al., 2018; Oemof Developer Group, 2019). As depicted in Fig. 1, the model incorporates all important heat supply options in this region, while on the electricity side, the focus lies on representing wind energy production and energy trade at the day-ahead market via the national power grid. In addition to the existing energy supply infrastructure, the model considers three flexibility options: battery storages, electrolysis with subsequent methanation, and PtH.

Based on measurement data of wind curtailments in 2016 (provided by the wind turbine operator ENERTRAG (2018)), the techno-economic potential for making use of the excess wind energy by these flexibility options is assessed. The model is formulated as a mixed-integer linear programming (MILP) optimization problem taking operational cost and potential cost for CO_2 emission allowances into account. In short, the goal is to minimize annual operational costs. More details to be found in the original study by Schluzy (2019).

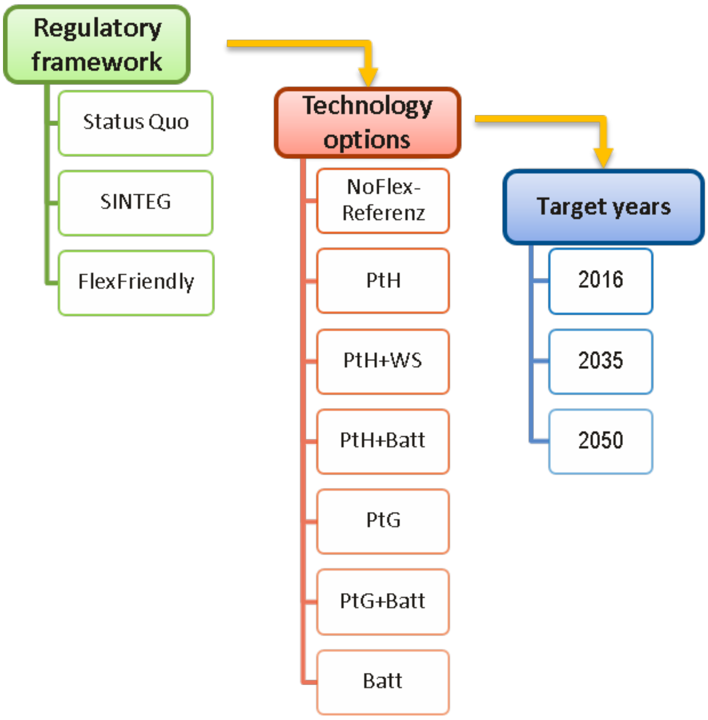


Figure 2: *WindNODE_KWUM* scenario dimensions.

Three dimensions are used to construct scenarios that are analyzed with *WindNODE_KWUM*: regulatory framework that defines regulatory circumstances affecting economic and technical aspects, scenario variations that describe which of the flexibility options is considered, and years that characterize other aspects such as energy demand. Three different regulatory frameworks are considered: *Status quo* reflects the current legal status quo where, for example, flexibility options often carry the burden of high grid surcharges. The temporary juristical act *SINTEG VO* tries to eliminate economic barriers for flexibility options by reduced grid surcharges. *FlexFriendly* describes a totally restructured tax regime aiming for a level playing field across energy sectors.

Out of these dimensions, 63 computable scenarios are constructed. We focus on evaluating the economic performance and impact on climate change mitigation of considered flexibility options under different regulations. Therefore, scenarios are ranked according to resulting supply cost under consideration of total CO_2 emissions.

2.1.2 Case study 2: Regional energy supply in Anhalt-Bitterfeld-Wittenberg

The second case study is located in the east of Saxony-Anhalt comprising the 3 districts Anhalt-Bitterfeld, Wittenberg, and the city of Dessau-Roßlau. Similar to the first case study, substantial amounts of RES are installed in the region. In 2017, 717 MW of wind power and 445 MW of ground-mounted photovoltaic (PV) covered 63 % of the comparatively low regional electricty demand of 20 municipalities.

We identified several issues in workshops with local stakeholders, which we will address in this case study. First, the land use – especially for wind energy – became a key matter of debate in Germany and, to the same extend, in the *Anhalt-Bitterfeld-Wittenberg* (ABW) region as the number of wind turbines have been growing dramatically during the last decades. On the one hand, renewables are perceived as a key element of the energy transition. Superordinate targets set by the federal government have to be implemented on a local level. On the other hand, regional concerns should be considered as the designation of wind turbine sites by regional planning authorities and their realization crucially depend on the acceptance of the people living in the surroundings of those sites (Langer et al., 2018). This matter of conflict motivates our first research question: "To what extent can the region be supplied by renewables considering the available area?" Second, the aim to increase RES is further driven by regional ambitions of energy autarky in the sense that nearly all of the region's demand should be met by renewable generation. As mentioned above, RES already account for the highest share in electricity supply in ABW in terms of the annual balance. However, on a temporal scale, a significantly lower degree of autarky can be expected. Therefore, the second subject of research focuses on the realizable level of autarkic supply in the region. Third, we analyze how new flexibility options can support the integration of RES and enhance energy autarky.

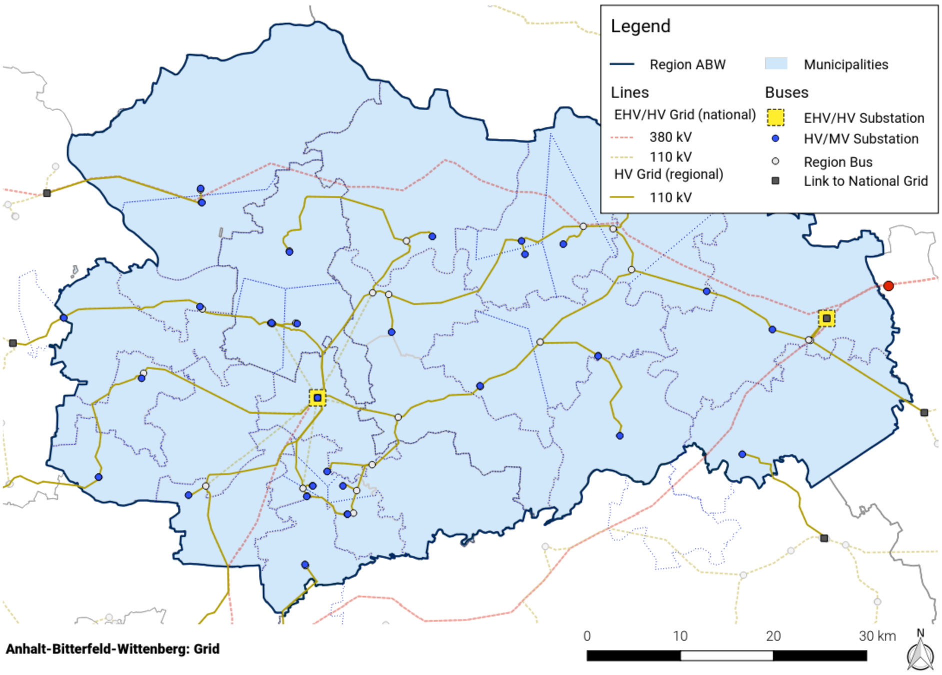


Figure 3: Extra high voltage and high voltage grid of *Anhalt-Bitterfeld-Wittenberg*

The analyses are carried out using the regional energy system model *WindNODE_ABW* (Reiner Lemoine Institut, 2020b,a) that is based on the energy system modeling framework *oemof-solph*

(Hilpert et al., 2018; Oemof Developer Group, 2019). The model comprises the electricity and heat sector of ABW at municipal-level at a temporal resolution of 1 hour. It is formulated as a linear optimization problem with the objective of minimizing the cost for operation, CO_2 emission allowances and grid extension.

On the electrical generation side, wind turbines, ground-mounted, and roof-mounted PV, biogas plants, CCGT, and single-cycle gas turbine (SCGT) have been integrated as the most important technologies in the region. The heat generation includes decentralized conventional heating systems primarily based on natural gas, wood, and fuel oil. Four large district heating networks are located in the region which are fed by CCGT, CHP units, and gas boilers. The electrical and heat demand incorporates the residential, commercial, trade, services and agricultural sector; for the industrial sector, only the electricity side is included. On the flexiblity side, the model integrates households with DSM, battery storages, and power-to-heat (heat pumps and electrical boilers),

The transmission capacities between the municipalities are given by the extra high voltage and high voltage grid as shown in Figure 3; its topology and parameters were taken from Mueller et al. (2018). This allows for a realistic assessment of the intra-regional exchange and grid load as well as the identification of potential congestions on those voltage levels. Subsequently, the electrical generation and demand of the municipalities are allocated to high voltage/medium voltage transformer stations. Although the national grid is not explicitly modeled, it is used for power exchange by municipalities without direct connection to the regional grid. Imports and exports are facilitated by using virtual sources and sinks located at the cross-regional links to the national grid as shown in Fig. 3.

Scenarios that are evaluated with *WindNODE_ABW* are constructed based on two pillars: generation capacity deployment scenarios and a scenario dimension describing the market penetration of flexibility options.

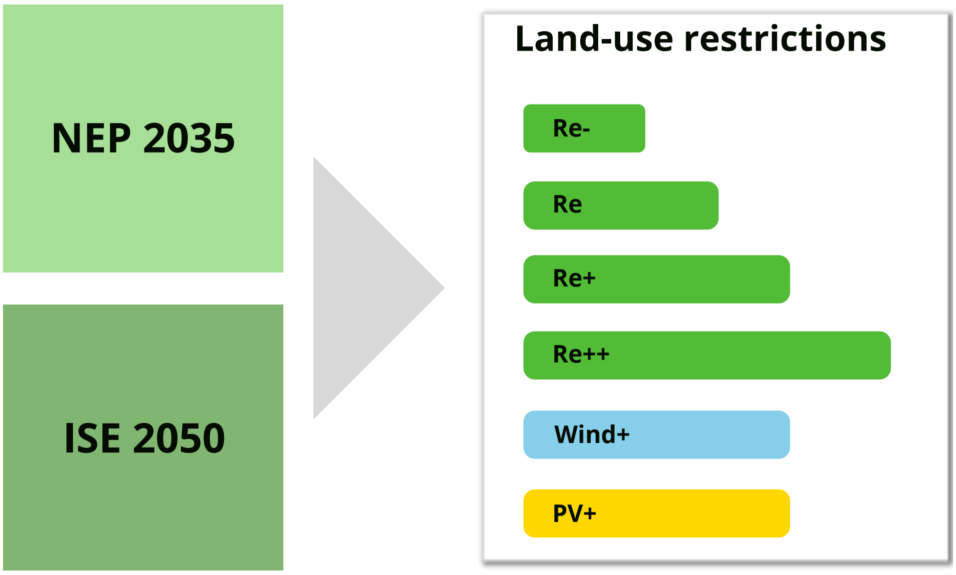
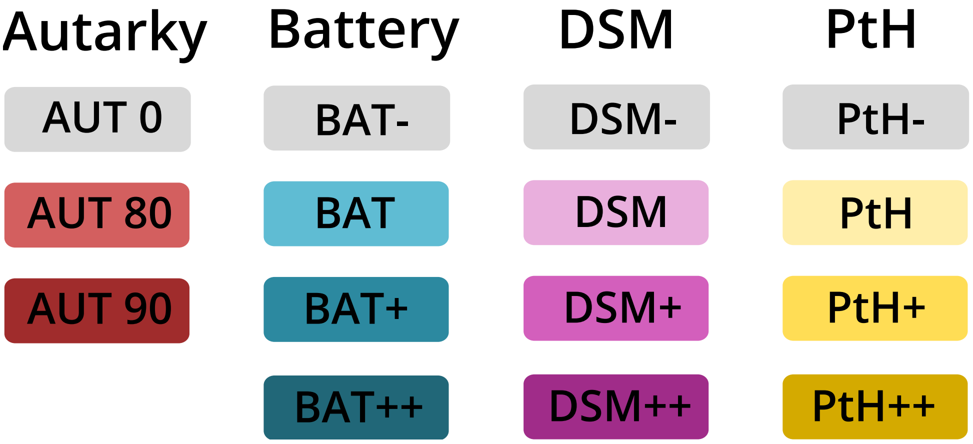


Figure 4: Generation capacity deployment scenarios.

Two studies that analyze electricity/energy supply in Germany provide the basis for the scenario construction. The *Netzentwicklungsplan 2035 (2021)* (*NEP 2035*) (Nahmmacher et al., 2020) investigated grid extension needs until 2035 and therefore provides a reliable scenario basis. The second study, *Wege zu einem klimaneutralen Energiesystem* (*ISE 2050*) (Sterchele et al., 2020), looks at a climate-neutral sector-integrated energy supply for the year 2050. Both

studies are used to determine available generation capacity derived from national numbers. In a second step, land-use restrictions with six variations are applied and might reduce deployable generation capacity within the region ABW in certain scenarios. Aside from generation capacity, other parameters such as electricity demand, heat demand, and methane share are aligned with these studies. Moreover, for each target year, assumptions on technical parameters such as cost, efficiencies and emissions are applied.
The second pillar for the scenario construction comprises the degree of autarky and three different resources for power system flexibility (see Fig.5). These are considered in three to four variations each.



Autarky	Battery	DSM	PtH
AUT 0	BAT-	DSM-	PtH-
AUT 80	BAT	DSM	PtH
AUT 90	BAT+	DSM+	PtH+
	BAT++	DSM++	PtH++

Figure 5: Autarky and flexibility options variations. Autarky: restricted electricity imports from national grid; Battery: different battery storage capacity for large and small battery storage; market penetration of DSM; PtH and associated thermal storage capacity. The top (gray) variation is considered in the default case.

A detailed description of the model and the scenarios can be found in Reiner Lemoine Institut (2020a).

2.2 Qualitative comparison

The two studies analyzing flexibility options in regional energy systems are compared in a qualitative manner. The qualitative comparison of the named studies is founded on a comparison along challenges to decarbonize the energy sector.
Papadis and Tsatsaronis (2020) identified four challenges for the decarbonization of the energy sector: environmental sustainability, security of electricity supply, economic stability, and social aspects of transition and dilemmas. Key aspects of each of these challenges are shown in Table 1.

Table 1: Key aspects of challenges for decarbonizing the energy sector described by Papadis and Tsatsaronis (2020).

	Key aspects
Environmental sustainability	• Reduction of CO_2 emissions • Investments into clean energy technologies • Increasing energy efficiency • Change in market design covering requirements of new flexibiliy options • Investments in devoloping countries

Security of electricity supply	• Balancing supply and demand is increasingly challenging due to intermittent generation by RES • Decreasing load-following capacity from conventional power plants must be replaced by new flexibility options • Missing incentives for investments into new flexibility options • Long planning horizons for energy infrastructure urge to act early
Economic stability	• Energy supply at affordable cost according to SDG 7 • Security of supply is important for the economy • Political barriers and dependencies may be a risk • High energy prices may leave people dissatisfied with the energy transition
Social aspects of transition and dilemmas	• Fair energy transition ensuring social, and economic justice • Public acceptance • Public acceptance can be increased by participation, education and transparent information • Empowered communities by decentralized energy supply

We were inspired by Wiese et al. (2018) on how to conduct a qualitative evaluation in the research field energy systems research. They developed a conceptual framework to evaluate fitness for energy system modeling frameworks for addressing 21st century energy system modeling challenges described by Pfenninger et al. (2014). We build upon this idea and discuss main findings of the two studies along the aspects of each challenge described by Papadis and Tsatsaronis (2020). As part of the comparison, first, we explain to what extent each of the challenges is reflected in each of the named studies. Then, we discuss how and to what extent the flexibility options can contribute overcoming these challenges.

3 RESULTS FROM THE CASE STUDIES

Results of both case studies are presented very briefly in separate sections.

3.1 Case study 1: Curtailed wind energy in the Uckermark

The analysis of 63 scenarios showed that there is no profitable business case for making use of otherwise curtailed wind energy considering the current regulatory framework. Assuming regulation according to the SINTEG-VO would create a case for PtH in 2050, while reducing around 8 % of CO_2 emissions. The regulations of the *FlexFriendly* scenario – which makes very broad assumptions regarding CO_2 taxation – provides the conditions to create business cases for new flexibility options. Already today, PtH could make use of a certain amount of curtailed wind energy. By 2050, it could create savings of 71 % of CO_2 emissions compared to the case without flexibility options.

Among the considered flexibility options, only PtH and PtG could create profitable business cases. The largest potential for cost-competitive levelized cost of heating (LCOH) at low CO_2 emissions was identified for PtH in combination with heat storage. Table 2 shows the installable capacity of PtH and heat storage for scenarios with competitive LCOH.

		StatusQuo			SINTEG			FlexFriendly		
		2016	2035	2050	2016	2035	2050	2016	2035	2050
Prenzlau	PtH	-	-	-	-	-	1	6	3	3
	Storage	-	-	-	-	-	0	30	15	15
Schwedt	PtH	-	-	-	-	-	3	12	6	8
	Storage	-	-	-	-	-	20	60	40	40

Table 2: Profitably installable power of PtH (MW) respectively capacity of heat storage (MWh) along scenario dimensions regulatory framework and target year.

With smaller capacity and fewer scenarios with a viable business case, PtG is the second flexibility option that can be considered for absorbing otherwise curtailed wind energy. With the assumed cost reductions and efficiency increases, PtG is expected to become competitive in 2050. Similar CO_2 reductions as with the PtH option can be achieved. However, the cost-competitive capacity totals to 8 MW rated electrical power (see Table 3). This is due to investment costs that are expected to be still relatively high in 2050.

	StatusQuo			SINTEG			FlexFriendly		
	2016	2035	2050	2016	2035	2050	2016	2035	2050
Prenzlau	-	-	-	-	-	-	-	-	2
Schwedt	-	-	-	-	-	-	-	-	6

Table 3: Profitably installable power of PtG in MW along scenario dimensions regulatory framework and target year.

Although the largest cost reduction potential is expected for battery storages, this resource of flexibility cannot be used to absorb curtailed wind energy cost-effectively. With the evaluated business case for arbitrage trading at the day-ahead market, there is no profit to earn.

Even in the scenarios in which curtailed wind energy is used at large scale for feeding district heating grids by PtH, only a share of at maximum 5 % of the total otherwise curtailed wind energy can be used.

3.2 Case study 2: Regional energy supply in Anhalt-Bitterfeld-Wittenberg

The analysis of the available area for wind and PV installations (cf. Section 2.1.2) already reveals important insights regarding stated research questions. Figure 6 presents installable capacity of wind and PV for the four land-use restriction scenarios (*Wind+* and *PV+* are integrated into *RE+*) and for each target year.

On the left hand side, the scenario assuming the lowest capacity installations (*RE-*) reflects the current regulatory status quo. In this comparatively restrictive scenario, the available area for wind turbines and ground-mounted PV is entirely used and serves as a reference for the relative land use in the other scenarios. For realizing wind turbine capacity as assumed in *RE* (reflects capacity of *NEP 2035*), 165 % of the available area under current legislation would be required. This could already be achieved by wind installations in 10 % of not restricted forestal areas. In order to achieve installations according to *ISE 2050*, it would be necessary to reduce the minimum required distance of wind turbines from settlements to 500 m. It further becomes

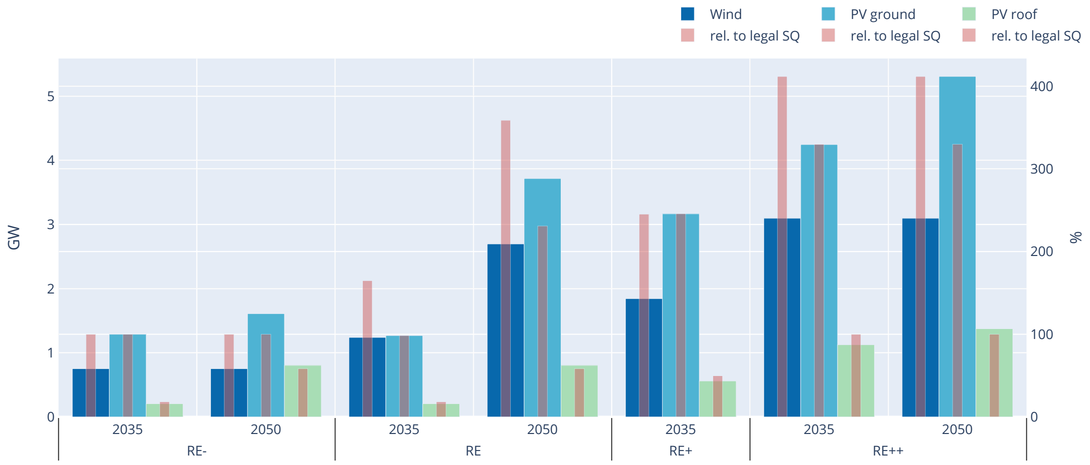


Figure 6: Installable capacity for wind and PV considering four land-use scenarios. Capacity is given in GW (wide bars, left axis) and relative to the installable capacity under consideration of the current legal status quo (narrow bars, right axis), which is applied to determine the capacity for *RE-* scenarios.

clear, that in *RE*, there is sufficient space to realize the required ground-mounted PV power of *NEP 2035* but not for the targets of *ISE 2050* where the available area it is exceeded by 130 %. For the more ambitious land use restriction scenarios *RE+* and *RE++*, the areas necessary for wind and ground-mounted PV strongly exceed the designated areas in 2035 as well as in 2050. In all land use scenarios, the capacity of roof-mounted PV is lower than or equal to the available potential. To sum up, it can be said that even in the regulatory status quo, the region has space to increase the amount of RES to a certain extent, but to reach a deep decarbonization, the designation of further areas is essential.

For answering the question “to what extent can the region ABW can be supplied by RES?”, we look at the RES share (local RES generation divide by demand) shown in Fig. 7. Although the required area for wind and PV ground-mounted matches the current available area in *RE-* scenarios, on an annual balance, the regional energy demand can be met by domestic generation in all scenarios. At least 160 % of regional electricity demand is covered locally by RES. For scenarios considering more RES, capacity this share can go up to above 500 %. In all of the analyzed scenarios, the connection points to the national transmission grid (high voltage lines and extra-high voltage transformers) are still capable of transporting large-scale electricity exports. Cost varies significantly. At higher RES shares, with more capacity being installed, the cost tends to decrease. This is more distinct for LCOE than for LCOH.

It was asked “to what degree is autarkic supply realizable within ABW?” and “How do new flexibility options support the integration of RES?”. Figure 8 shows autark supplied hours and energy shifted by flexibility options. Throughout all analyzed scenarios, more than 58 % and up to 84 % of the time, the demand in the region ABW is supplied by locally produced electricity. In absolute numbers, heat storages in district and decentral heating systems shift the largest amounts of energy, although total shifted energy varies significantly. Shifted energy by heat storages is particularly high for scenarios with limited electricity imports from the national transmission grid (*AUTx* scenarios) and for scenarios with high flexibility penetration and/or large RES generation capacity. DSM is being used at around 60 % of its theoretical potential in scenarios where DSM is considered. In absolute numbers, battery storage is used more

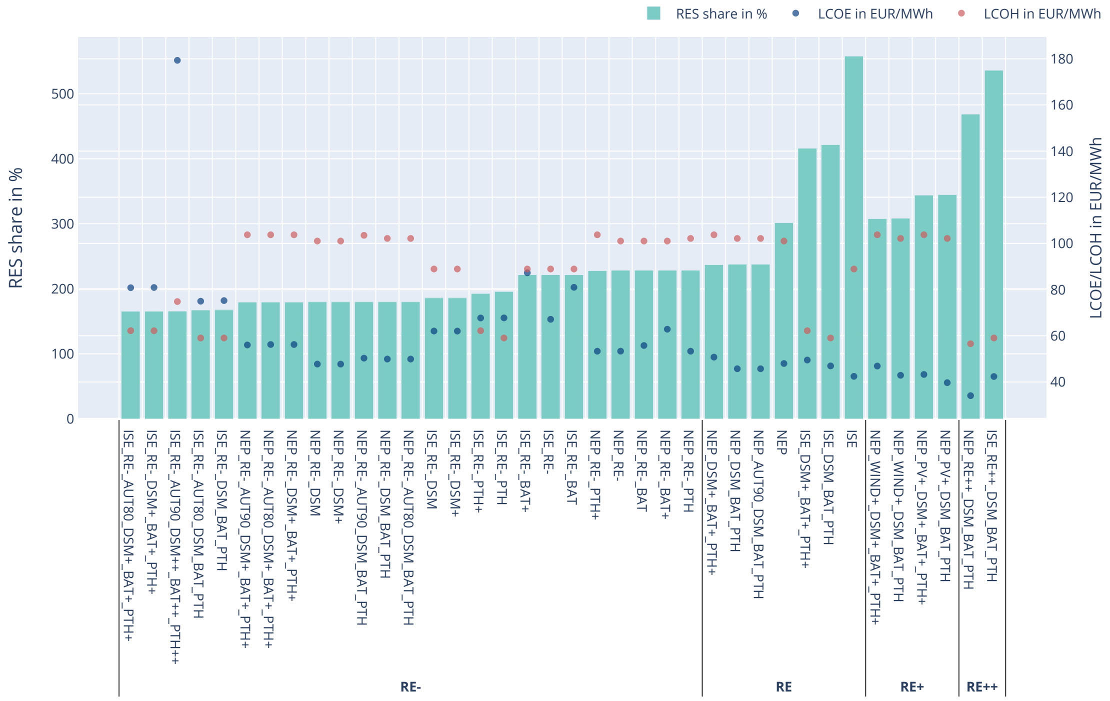


Figure 7: RES share (green bars, left axis) and LCOE/LCOH (dots, right axis) for all scenarios grouped by land-use restriction scenario.

to what

than DSM in scenarios where flexibility potential by DSM is not sufficient to eliminate all imbalances. Otherwise, the use of battery storage systems is relatively low.
Although the utilization rate of flexibility options is quite low in some scenarios (see Figure 11) – in particular for battery and heat storages –, these balancing capacities are needed to realize deep decarbonization with local generation above 80 % in relation to the demand. For one scenario with relatively low RES capacity, moderate capacity of flexibility options, and a cap of electricity imports (*ISE_RE-_AUT90_DSM_BAT_PTH*, not shown in the figure), we could not find a feasible solution. Despite large variations of specific CO_2 emissions across the scenarios, we can show net emission neutral energy supply is possible.

4 QUALITATIVE EVALUATION

For comparing main findings from the both studies in Section 4.2, we make use of the conceptual framework of challenges for decarbonizing energy supply by Papadis and Tsatsaronis (2020). For a better understanding of the comparison of findings, we first explain which aspects of each challenge is considered in each study (see Section 4.1).

4.1 Challenges reflected

In addition to the model descriptions in Section 2, essential properties of each study are explained along the challenges for decarbonizing the energy supply.

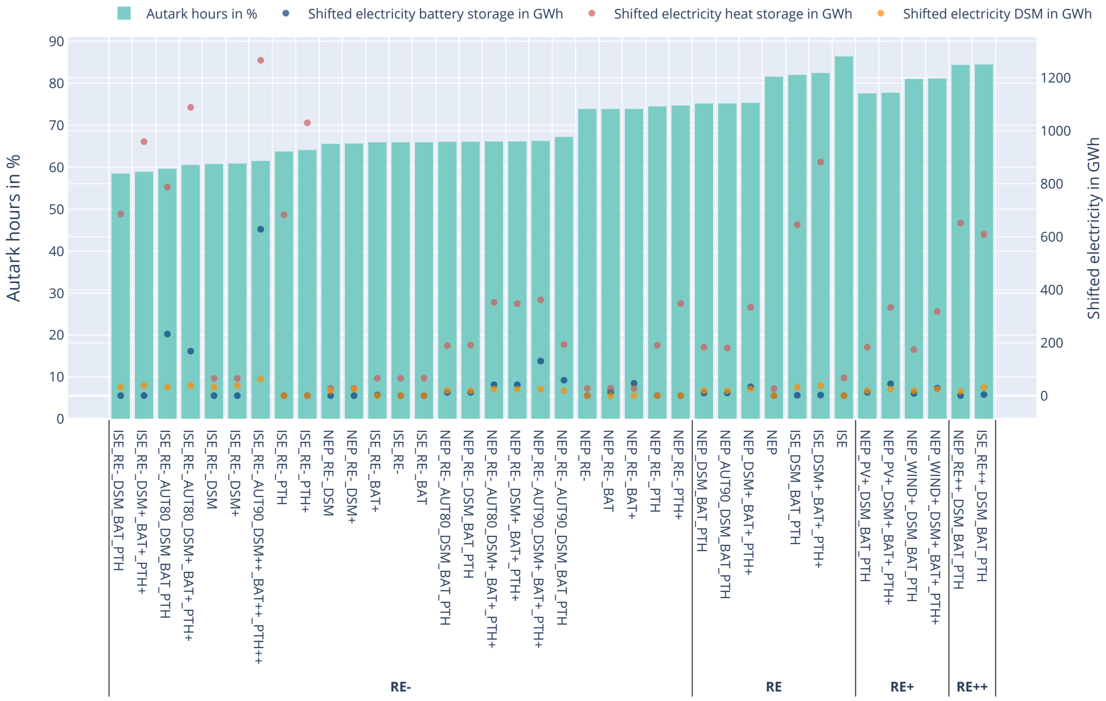


Figure 8: Autark hours which are defined by $supply_t \geq demand_t$ (green bars, left axis) and energy shifted by flexibility options (dots, right axis) for all scenarios grouped by land-use restriction scenario.

4.1.1 Environmental sustainability

Today, environmental sustainability in energy supply directly refers to lowering CO_2 emissions (Papadis and Tsatsaronis, 2020). Both studies seek for options to supply electricity and heat demand from sustainable sources. While the optimization in both studies drives towards lowest dispatch costs, CO_2 emissions are a key parameter for comparing scenarios. In addition, in *WindNODE_ABW*, cost for CO_2 emission allowance is considered as part of the operational cost and might have an influence on the dispatch of a unit.

4.1.2 Security of electricity supply

In a nutshell, the challenge *security of electricity supply* describes the task of balancing demand and supply in every moment. Due to the intermittent supply of RES, this becomes increasingly interesting. In both underlying studies, security of supply is investigated as a crucial aspect in terms of RES-based energy supply. Balancing mismatches between intermittent generation by RES and electricity and heat demand is at the core of the analyses, but treated differently. Whereas in *WindNODE_KWUM* the focus lies on using otherwise curtailed wind energy, *WindNODE_ABW* models the entire electricity and heat supply sector. Hence, different balancing options (conventional power plants, new flexibility options, electricity grid) are considered in the model. Both studies have in common that they assess the balancing demand on an hourly level, neglecting sub-hourly ancillary services such as frequency regulation and spinning reserve.

4.1.3 Economic stability

The case studies reflect the dimension of economic stability by using operational cost of energy supply as an optimization criterion and using total cost as key parameter for the scenario analysis. Investments into energy conversion systems are assessed via the analysis of many scenarios that define the capacity for each technology. One exception is made in *WindNODE_ABW*: investments into grid extension are endogenously assessed. Furthermore, in *WindNODE_ABW*, cost for CO_2 emission allowance is considered as part of the operational cost.
Scenarios carried out in the studies do not address the aspect of political barriers in terms of economic stability. The use of natural gas, which is a globally traded good, decreases in most scenarios. In consequence, international dependencies are reduced as well.

4.1.4 Social aspects of transition and dilemmas

Social aspects of the energy transition are not essentially part of the two conducted studies. But indirectly, these aspects are considered in the studies. While *WindNODE_KWUM* analyzes options to make use of curtailed wind energy, it touches public acceptance. In *WindNODE_ABW*, public acceptance is influenced by the concentration of RES, which is represented by different land use scenarios. Furthermore, the aspect of local energy supply is considered, which might increase public acceptance as well.

4.2 Comparison of findings

Despite the different perspectives each study takes, both share some common findings regarding the integration of RES and the use of flexibility options. Main findings from both studies are presented along the challenges for decarbonizing energy supply in Table 4.

Table 4: Comparison of main findings along challenges described by Papadis and Tsatsaronis (2020).

	WindNODE_KWUM	WindNODE_ABW
Environtmental sustainability	• Enough space is available for required wind and PV installations to serve at least regional demand with RES	
	• Regulatory framework inhibits use of curtailed wind energy • CO_2 pricing can increase profitability of flexibility options	• High potential for energy exports, depending on land use restrictions • Land use restrictions need to be revised for accessing large-scale RES potential
Security of electricity supply	• Flexibility options can help to avoid curtailment • Curtailment can not be entirely avoided, grid extension might be necessary	• Climate neutral scenarios can technically work, even with a high degree of autarky by using flexibility options • Rather small amount of regional demand is served from national grid

Economic stability	• Compensation payments for curtailed wind energy cannot effectively be eliminated • Introducing a common CO_2 price for all energy sectors would increase profitability of new flexibility options and would create business cases	• Regional LCOE drop with increasing share of renewables • Region ABW can create benefits from exporting electricity
Social aspects of transition and dilemmas	• Regional energy supply is appreciated	
	• Public acceptance may be at risk because wind energy needs to be curtailed	• Economic benefits of electricity exports may increase public acceptance

Regarding the challenge environmental sustainability, we learn from both studies that in rural, rather sparsely populated areas, enough space is available to generate more energy than the local energy demand requires. Depending on the further development of land use regulations, an enormous potential for RES-based electricity generation and large-scale exports exists. Flexibility options help to make use of the intermittent and sometimes mismatching electricity. But without a fundamental revision of the current regulatory framework for grid- or market-oriented application of flexibility options, a rather large portion of this potential is wasted.

Despite the value of flexibility for harvesting more of the RES-generated electricity, grid extensions might be still beneficial to increase utilization of RES-based electricity. Regional energy supply, using predominantly domestic generation, is feasible. Under consideration of economic aspects exchange with the national transmission grid is still valuable. Serving small fractions of the local electricity demand with imports keeps cost at an affordable level. In addition, the demand for flexibility might decrease with increased electricity exports.

Regarding the economic dimension of challenges for decarbonizing energy supply, the analyzed studies find that compensation cost for curtailed electricity from RES cannot be eliminated entirely by flexibility options. They remain as an unwanted side-effect of introducing RES at large-scale while not extending grid capacity at the required pace. But at the same time, large-scale RES electricity production allows for electricity supply at lower cost. Here again, the regulatory framework introduces most of the barriers for the effective application of flexibility options.

Social aspects of the transition and resulting dilemmas are not directly included in the studies, but treated indirectly. In the Uckermark, often-curtailed wind energy units may be a risk for public acceptance. Inhabitants of this region are affected more than people of other regions in Germany, due to change in the landscape. Wind energy converters that are not operating during windy times might support criticism about feasibility and effectiveness of the energy transition. In the region ABW, an agreement needs to be found regarding how much of the available area can be used for RES installations.

5 DISCUSSION

Due to the different focus of the studies, only a partial overlap of findings can be observed. Whereas in *WindNODE_ABW* it was found that the region ABW can benefit from large-scale electricity exports, impossible electricity exports due to grid congestions are the starting point in *WindNODE_KWUM*. This contrast may be a result of a different representation of grid congestions in the surrounding transmission grid or due to different boundary conditions of both regions. In addition, the scope of the studies is different. While in *WindNODE_KWUM* the focus lies on analyzing the effects of different regulatory frameworks on the use of flexibility options, the model in *WindNODE_ABW* looks from an techno-economic angle on the use of flexbility for integrating RES. This makes the studies partially difficult to compare.

Nevertheless, in context of recent literature on this topic, the findings seem plausible and can underpin findings of other researches. Hilpert (2020) found that flexibly operated heat pumps with thermal energy storage can replace some of the required short-term balancing capacity from battery storages. Furthermore, he reports that the effect on decreasing total system cost by using heat pumps as a flexbility option for the electricity system is small. With our findings, we agree on both. Heat pumps can provide relatively inexpensive storage capacity that can be used to provide flexibility for the power systems. Increased PtH capacity does not decrease total cost significantly. With the findings from *WindNODE_KWUM*, we can confirm that surcharges on electricity is the main barrier for using curtailed wind energy in PtH applications as already reported by Gerhardt et al. (2014) in 2014.

Our findings regarding the value of DSM are in line with results in the study of Brouwer et al. (2016). DSM is a great source for cost-efficient flexibility, but it needs to be complemented by other flexibility options for sufficient balancing capacity for very high RES scenarios.

Like in Figgener et al. (2020), we see use cases for battery storages in balancing demand and supply mismatches. But at the same time, we cannot find viable business cases beyond PV home storage and primary control reserve considering the current regulatory framework.

Autarky ranges between 60 % and 80 % in most scenarios in *WindNODE_ABW*, which underpins the findings by Möller (2020) that degrees of autarky above 80 % are difficult to achieve. Nevertheless, in context of the study, in stakeholder workshops, we have learned that people see a non-tangible value in local energy supply.

Despite the valuable findings in this paper, limitation are associated with this study, respectively the underlying studies. We discuss the most important. *WindNODE_ABW* assumes new RES installations, that are expected to be installed in Germany, will be spatially uniformly allocated. This leads to net RES-based electricity exports, even in scenario with the lowest expected RES installations for 2035. Besides exports, it also affects utilization of flexibility options. With more demand being covered directly, less flexibility is needed which is only true if no grid congestion occur.

A large methodical drawback in both studies is the representation of the national transmission grid and the electricity market. While *WindNODE_KWUM* inherently considers transmission grid bottlenecks, it relies on historic price data for representing the electricity market. This does not anticipate a potential change of price patterns, likely imposed by the progressing energy transition and might assume incorrect price signals. In *WindNODE_ABW*, the electricity market is entirely neglected. Potentially sold electricity is rated with a fixed price. The national transmission grid is represented through the capacity of high voltage lines and transformers to the extra-high voltage level. There, no major congestions could be identified, but it is not studied how it affects the entire national grid. Neither it is studied how the transmission system could be operated if many other regions would act similarly. Hence, taking the results as a blue print for a Germany-wide roll-out is not possible.

6 CONCLUSIONS

We have analyzed RES-based energy supply in two different regional contexts. We focused on challenges associated with the integration of RES and investigated the potential of different flexibility options for tackling these challenges. For the individual analysis of regional energy supply, we used energy system models built upon *oemof-solph*. The final result of this paper is the qualitative comparison of findings from both studies with regard to challenges to decarbonize energy supply.

From comparing these two case studies, we find that sparsely populated regions – as both of the analyzed are – have the potential to exceed the local energy demand with RES. This allows to export electricity for supplying demand in other region with less RES potential and high demand. This might create economic benefits for the exporting regions. Furthermore we have found that autarkic supply is possible in at least 60 % of the hours of the year. Flexibility options are required to achieve deep decarbonization. A single technology might not provide enough flexibility potential to cover all relevant mismatches. A combination of different technologies is advantageous according to our analysis.

In both case studies, it became obvious that the regulatory framework is crucial for the successful progress of the energy transition. At first, regulations regarding land use need to be adapted to allow for enough RES installations to supply the increasing demand, for example from sector coupling. Second, taxes and levies for using electricity in applications providing flexibility need to be revised fundamentally. As already stated by Schluzy (2019), a level playing field across energy sectors is needed to enable cross-sectoral flexibility provision.

ACKNOWLEDGEMENTS

We acknowledge the generous funding for this research project (grant number: 03SIN525) provided by the German Federal Ministry for Economic Affairs and Energy within the research programm SINTEG. We thank Miriam Leich for very helpful language corrections.

SUPPLEMENTARY MATERIAL

The input data and the developed source code used in this work have been published online under open source licenses (Reiner Lemoine Institut, 2020b,d). A comprehensive documentation can be found in (Reiner Lemoine Institut, 2020a,c).

LICENSE

NOMENCLATURE

ABW *Anhalt-Bitterfeld-Wittenberg*

CCGT combined-cycle gas turbine

DSM demand-side management

ESM energy system model

LCOE levelized cost of electricity

LCOH levelized cost of heating

MILP mixed-integer linear programming

PtG power-to-gas

PtH power-to-heat

PV photovoltaic

RES renewable energy sources

SCGT single-cycle gas turbine

APPENDIX

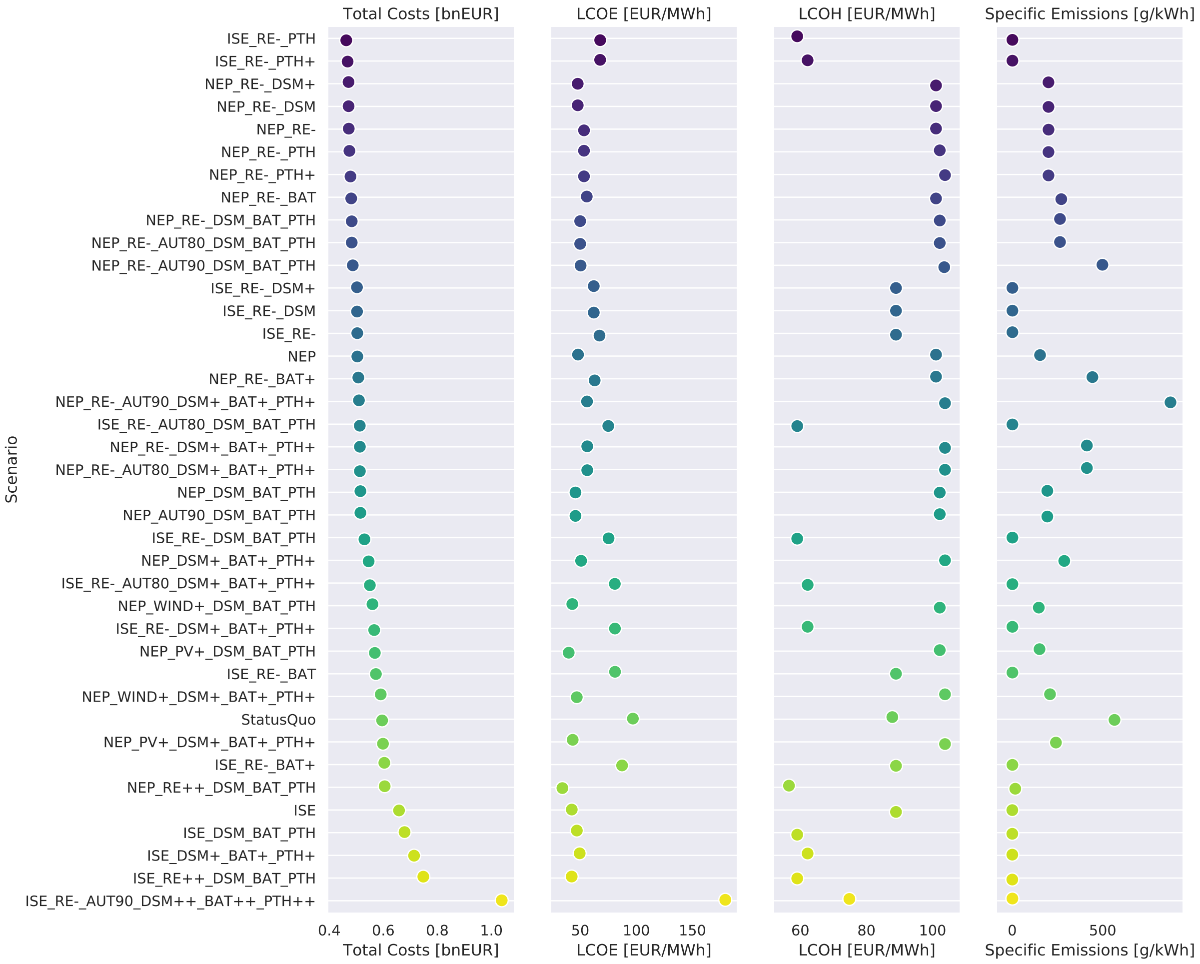


Figure 9: Key result figures for region ABW: costs and CO_2 emissions.

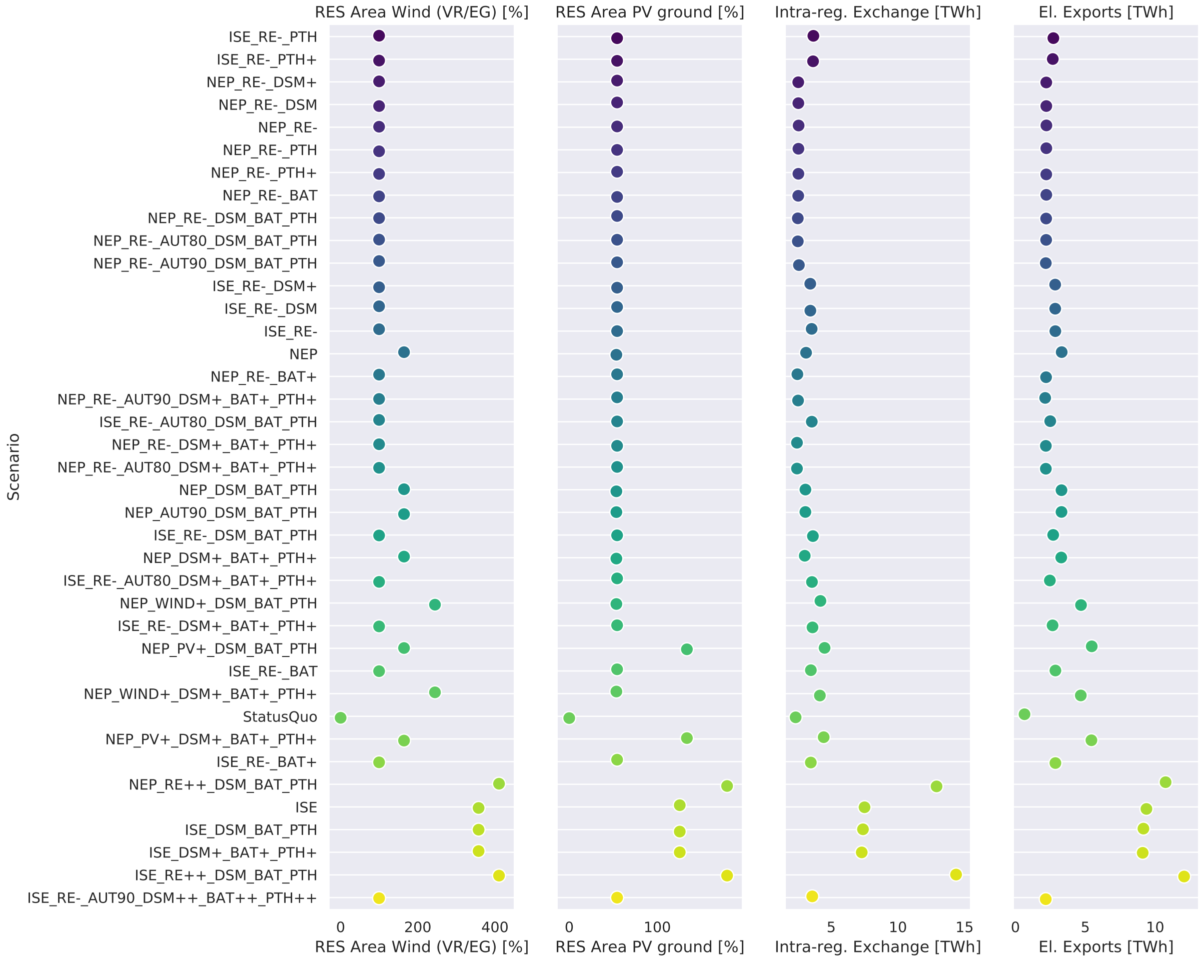


Figure 10: Key result figures for region ABW: required area RES installations and electricity exchanges.

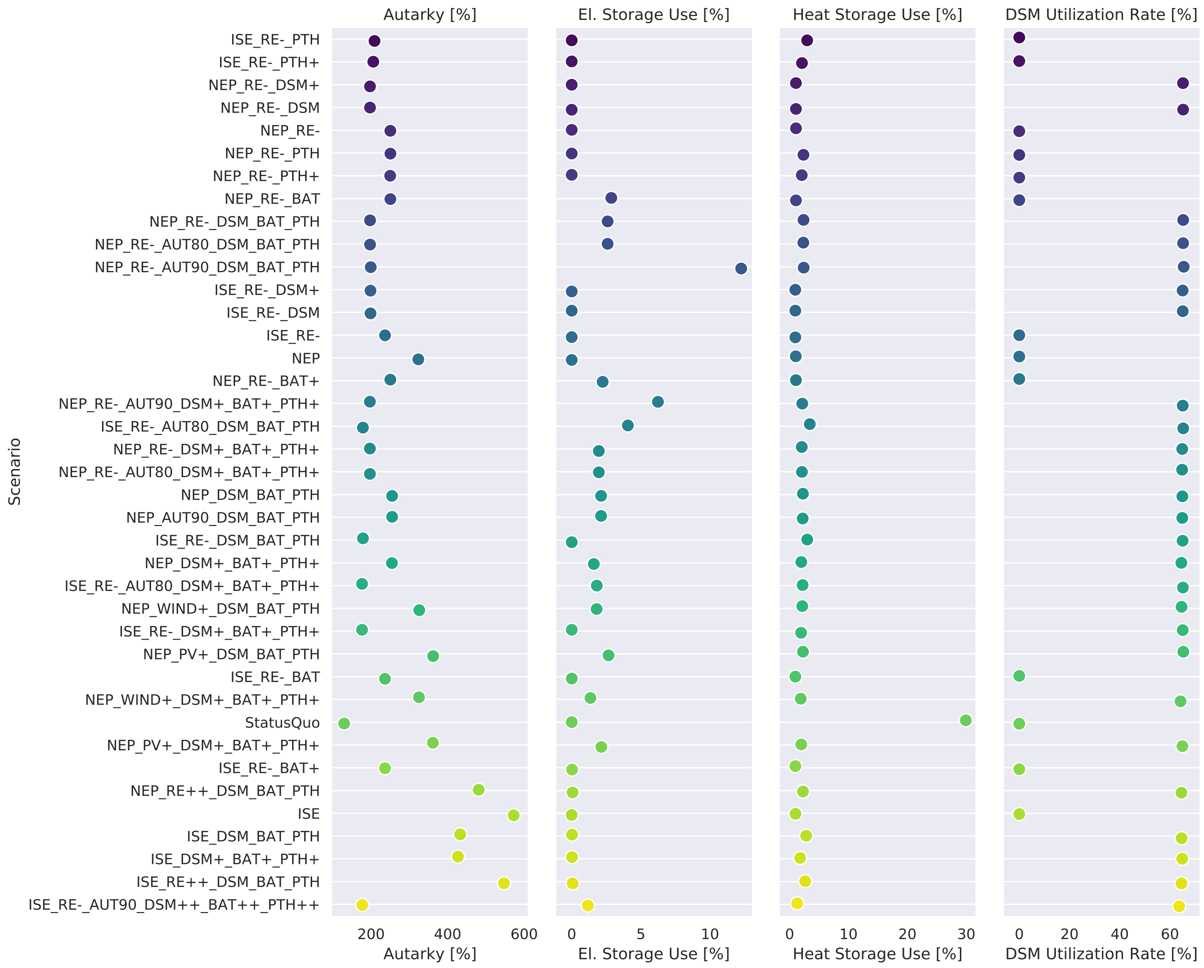


Figure 11: Key result figures for region ABW: autarky and flexibility utilization.

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