



Regional Analysis of Potentials of Flexibility Options in the Electricity System for the Study Regions Prignitz in Brandenburg and Anhalt-Bitterfeld-Wittenberg in Saxony-Anhalt

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Cite as: Seefried, A., Müller, B., Förster, E., Regional Analysis of Potentials of Flexibility Options in the Electricity System for the Study Regions Prignitz in Brandenburg and Anhalt-Bitterfeld-Wittenberg in Saxony-Anhalt, J. sustain. dev. energy water environ. syst., 8(1), pp 162-183, 2020, DOI: <https://doi.org/10.13044/j.sdewes.d7.0277>

ABSTRACT

The electricity system is changing. Due to the climate targets, the share of fluctuating renewable energy will continue to rise in the next few years, and conventional, fossil fuels will increasingly take a back seat. This creates the challenge of balancing supply and demand in the power system and increases the need for flexibility in the electricity system. In this article flexibility in energy systems is introduced, flexibility options are categorised along existing literature and a method is explained to approach the estimation of flexibility potential by means of two example regions. Therefore, 13 flexibility options in the electricity system in four categories are analysed: flexible generators, demand side management, storage, and power-to-X. By means of the two study regions Prignitz in Brandenburg and Anhalt-Bitterfeld-Wittenberg in Saxony-Anhalt, a practicable, transferable method to quantify and compare the technical potentials of the flexibility options at a high regional level is developed.

KEYWORDS

Flexibility, Regional energy system, Potential, Case-study, Flexibility options, Electricity.

INTRODUCTION

Flexibility of supply and consumption is one big challenge in the transition of the energy system towards a higher degree of sustainability. In electricity systems with a higher share of Variable Renewable Energy Sources (VRES) the demand for flexibility will increase via two factors [1], firstly, VRES increase the temporal and spatial variability as well as uncertainty on the supply side and thus increases the need for flexibility. Secondly, VRES replace part of the flexible conventional generation capacity and thus less flexible generation units are available in the system. That's why it is a cross-cutting topic for all research projects that are investigating possible pathways for the energy transition. The analyses done for this paper are part of the project WindNODE, one of five big research projects financed by the German federal Ministry of Economics

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and Energy to show how the energy transition could work. The WindNODE project aims at “showing a network of flexible energy users who can align their electricity consumption with the fluctuating supply of wind and solar power plants” [2] (translated quote). This paper gathers basic knowledge of flexibility potentials in the energy system and applies a flexibility analysis to two regions. The approaches will be used in further works to analyse various solutions to balance regional energy demand and supply.

LITERATURE OVERVIEW

Triggered by the globally increasing share of electricity generation from Renewable Energy Sources (RES), a growing number of publications deals with the analysis of flexibility in the electricity system – with a different focus.

Great attention is being paid to the development of frameworks for defining and measuring flexibility. Metrics for measuring power system flexibility are defined Ulbig and Andersson [3]. Flexibility metrics for different degrees of complexity concerning the analysis are developed by Cochran *et al.* [4]. Furthermore, definitions concerning flexibility and the development of a mathematical model in order to measure transmissions grid flexibility is conducted [5].

Many researchers are also addressing the need for flexibility of specific power systems with increasing RES shares. Flexibility requirements in the European power system with increasing wind and Photovoltaic (PV) shares are assessed by Huber *et al.* [6]. A test system in order to evaluate the implications of an increasing share of variable renewable generation in a power system is defined and modeled by Lannoye *et al.* [7]. Further studies categorize scientific approaches to determine demand for flexibility in Germany and Europe [8]. Moreover, a review of studies examining flexibility impacts on power systems is provided [9].

To balance the fluctuating feed-in of RES, there are various flexibility options, i.e. technological options with the ability to bring in line power generation and electricity consumption [10]. Hence, another highly regarded field of research is the analysis of options for RES integration. A detailed overview of supply and demand side flexibility options for RES integration is provided by Lund *et al.* [11]. Flexibility options for power systems with increasing RES shares are also presented in Holttinen *et al.* [12]. Existing and emerging options and barriers that might hinder its development are reviewed by Cruz *et al.* [13]. Other studies focus on demand response technologies in smart electricity grids [14, 15]. A focus on storage technologies is provided by Koochi-Kamali *et al.* [16]. A further analysis evaluate both demand side and storage options with a focus on wind power integration [17].

Various studies deal with a quantification of the potentials of flexibility options and determine potentials using historical data, estimates or energy system models. An estimation of the potentials of flexibility options available today and future potentials until 2050 in Germany is conducted by Bauknecht *et al.* [18]. Another approach that quantifies potentials of flexibility options until 2030 for Germany is presented in Krzikalla *et al.* [19]. A linear programming model in order to measure the capacity of different flexibility options is developed by Alemany *et al.* [20] with the conclusion that potentials are highest for demand response and virtual power plants.

Potentials of a broad range of flexibility options in selected European countries are illustrated in Lund *et al.* [11]. Estimations of flexibility potentials of demand side options in northern European countries are summarized in Söder *et al.* [21]. Demand response potentials on a national level in Germany are modelled by Müller and Möst [22]. Another study focuses on the power-to-gas technology in a German model region [23]. A review of power-to-gas real-life projects, system modelling studies and economic assessments is provided by Quarton and Samsatli [24]. Potentials for industrial load management in Germany are examined by [25]. A further analysis evaluates the role of

batteries for stability enhancement of a power system containing high RES shares in Japan in different scenarios [26].

A regional approach is conducted by another study determining optimal design of RES-based systems including case studies in Austria with a focus on the optimization of resource-technology-demand networks and ecological efficiency [27]. RES systems in specific regions in Korea are analyzed and the optimal design and economic implications based on theoretical equations are derived in Chung *et al.* [28].

In order to assess if an electricity system possesses enough flexibility options to balance electricity generation and demand at any time in the status quo and in future scenarios with increasing RES shares, energy system models are an essential tool and widely applied. Furthermore, they provide information on how the system can be modified to increase its flexibility [7]. However, energy system simulations are often based on exogenous assumptions concerning future expansionary trajectories [8] or potentials of flexibility options are determined by a greenfield approach supposing that a complete electricity system is build up new (e.g. as in Elsner *et al.* [29]). Agora Energiewende discuss in their 2018 publication [30] about when would be the right time to provide storages for excess energy and state that in the beginning of a „massive roll-out of renewables, there will be excess electricity only on a few days per year – if at all (in Germany, there has not been a single day with excess power from renewables)“ and that „storages would be much more expensive than just dumping the excess energy“. This results from a countrywide view. At the same time, some regions with a lot of renewables had local excess energy that they had to cut of because of grid restrictions (according to [31], in the last three months of 2017, 5.144 GWh had to be dumped). That is the reason why a lot of projects already address flexibility options (including storages) and why especially the local view on the subject is important. Agora describes in that study situations when very high gradients of load changing were reached and could be handled through to flexibility options.

A broad review of studies concerning the future role of flexibility options in the context of country-specific criteria of electricity systems with a focus on Europe is provided by Zöphel *et al.* [32]. They conclude that firstly, it is not possible to meet flexibility demand with one option but an optimal portfolio of flexibility options is required. This conclusion supported by the modelling results of Alemany *et al.* [20] recommending a diverse set of options to balance. Secondly, the optimal mix of flexibility options that should be used and is realizable and cost-effective in a specific region, is largely dependent on the local energy system characteristics such as on site availability, resource availability, historical development of generation facilities and network deployment situation [33]. Thus, it is essential to consider and analyze flexibility options and interdependencies between them in a regional context considering the prevalent electricity system in a region [32].

Consequently, the determination of the potentials of different flexibility options in a specific region is a crucial input for a realistic illustration of a regional electricity system in a model. It helps to determine for which options and to what extent an integration into the model for the study regions is reasonable.

So far potentials of flexibility options and the need for flexibility have either been quantified with a focus on a broader regional context (e.g. Germany or Europe, see [8] for an overview of research on this topic), on the basis of a fictitious test region (see [7]) or with a more narrow range focusing on particular technologies and often based on exogenous assumptions such as in Söder *et al.* [21].

This study tries to determine in detail potentials of available flexibility options in a specific regional context. In doing so, it focuses on options that are able to provide mid-term flexibility. Mid-term flexibility denotes periods from a few minutes to a few days.

By means of the two study regions Prignitz in Brandenburg and Anhalt-Bitterfeld-Wittenberg (ABW) in Saxony-Anhalt, a practicable method to quantify the technical potentials of the flexibility options at a high spatial resolution is developed. The developed methodology can be applied throughout Germany to other regions in order to determine flexibility potentials and compare potentials across different regions.

Flexibility options in the electricity system

Flexibility options can be divided into five different categories.

Flexible generation. Supply side flexibility options include conventional power plants (coal, gas, oil, nuclear), biogas plants, Combined Heat and Power plants (CHP plants) and flexibility provided through the curtailment of VRES such as PV systems and wind power plants.

In this analysis, the flexible generation category includes gas-fired power plants, biogas plants, CHP plants and curtailment of VRES. Among the fossil power plants, only gas power plants are considered, which, in contrast to other fossil power plants, are also suitable for a 100% RES scenario when operated with RES gas. Nuclear power plants are not considered due to the moratorium in Germany for the year 2022.

Concerning the flexibilization of biogas plants, no electricity is stored, but the source of energy (biogas). Thus, its flexibility can be increased by increasing the capacity of the biogas storage. A further flexibilization can be achieved by expanding the CHP capacity, enabling a reduction in full-load hours and needs-based operation according to schedule. Beyond that, a variation of biogas production through the use of various temporary feedstock is possible. This flexible form of biogas production also enables seasonal shifts [34].

CHP plants can be operated either electricity-led or heat-led. As a flexibility option for the electricity sector, only electricity-led CHP plants are relevant that can also produce electricity when there is no heat demand. In order to make CHP plants more flexible, electricity and heat supply have to be decoupled via the installation of heat storage systems, so that excess heat can be stored in times of high electricity demand.

This analysis includes biomass plants (solid biomass) as well as CHP plants that are operated with waste, gas or oil. For gas-fired CHP plants, as for gas-fired power plants, currently used natural gas can be replaced by RES gas without any technological changes. The difference to gas-fired power plants is the integrated waste heat recovery. For oil-fired plants an operation with biodiesel is possible. Due to the premise of suitability for a 100% RES scenario, coal-fired plants are outside the scope of the investigation.

VRES curtailment refers to the adjustment of the production of a VRES plant (wind power or PV) in order to balance electricity demand and supply or for congestion management in electricity grids. Reducing peak loads via a small amount of peak capping can reduce the need for additional grid and storage capacity [35]. However, the curtailment of VRES should always be used as the last option for providing flexibility, as available energy will be unused.

Demand-Side Management (DSM). DSM is becoming increasingly important and benefits from the progressing digitization of the energy industry, which opens up new possibilities for communication and control [12]. Opportunities are opening up in both the energy-intensive industry, the commercial sector, through smart home applications in the household sector and by the electrification of the transport sector.

In the industrial sector, in processes with temporally movable energy performance or material or heat buffers, flexibility can be created through load shifting or temporary

shutdown. In particular, the five energy-intensive sectors of steel, cement, paper, aluminum, and chemicals are suitable for this purpose [36].

In the commercial sector the following areas offer DSM potentials due to flexible power consumption: horticulture, waterworks, cold stores, air-conditioning in offices, hotels, hotels and sports facilities and refrigeration in food retailing and production. In addition, ventilation systems and pumps of municipal sewage treatment plants as large consumers of electricity provide potentials [37]. The flexibility arises either due to a process-related interval operation (lighting in greenhouses, stirrers and circulation pumps in sewage treatment plants, feed pumps in waterworks) or from permissible temperature intervals in the thermal storage of energy (air conditioning, refrigeration in cold stores, electric cooling in food production and retailing) [18].

In households, load-shifting potential exists especially in heating or cooling processes for room heating, hot water processing, refrigerators, freezers and air conditioning.

Electric vehicles as mobile electricity storage devices can offer potentials for load shifting or store surplus electricity. In the future, the Vehicle-to-Grid (V2G) technology could enable a re-feeding of the energy stored in the batteries of electric cars into the grid during times of high load via special charging stations. In this analysis, only arising load-shifting potentials (controlled charging) are considered, because at present it is hardly predictable which role the V2G technology will play in the future due to missing infrastructure and the high cost of bidirectional charging and communication technology [18].

Electricity storage. Storage refers to technologies that can charge and off-load electrical power. There are a variety of storage technologies differing in storage duration. Short term electricity storage options store electricity from seconds up to 15 minutes. These include double-layer capacitors, flywheels, supraconductors and batteries. Medium-term storage means minutes to day storage. For this storage duration pumped storage, Compressed Air Energy Storage (CAES) and batteries are considered. Long-term storage options can store energy for several days and weeks up to months, a whole season and years. Here, large pumped storage power plants are suitable and also power-to-gas belongs to this category of storages.

Power-to-X (PtX). PtX refers to the use of excess electricity from renewable sources to generate heat [Power-to-Heat (PtH)] or gas [Power-to-Gas (PtG)]. Due to various possible uses of renewable electricity in the electricity, heating and transport sector, PtX is also referred to as sector coupling [38].

PtH means the transformation of electrical energy in useful heat, which is easier storable than electricity [11]. Technology options for PtH are heating elements or heating cartridges at a decentralized level as well as the use of electric boilers or electrode boilers for large-scale deployment. In addition, heat pumps of all sizes can be used. PtG is the use of (surplus) electricity for fuel gas production, which can be burned in conventional gas power plants. The process consists of two stages [39]: in hydrogen electrolysis, electrical energy is used to split water into hydrogen and oxygen and can be chemically stored in the form of hydrogen gas. The hydrogen is methanized in the second stage by adding carbon dioxide (CO₂). Thus, the gases produced can be used not only in the electricity sector, but also in the heat and the transport sector.

Compared to hydrogen, methane can be easily transported and stored as it is the main component of natural gas and therefore can be fed into the existing natural gas infrastructure (grids and storage facilities). The huge storage capacity of the natural gas grid (in Germany approx. 400 TWh) can then be used as a medium or long-term storage option. Hydrogen, in contrast to methane, can only be injected in small amounts of approx. 5% into the natural gas grid [39]. PtG creates the perspective, by storing excess

energy in the gas network and the possibility of re-conversion into electricity in times of low VRES production to feed the power system by 100% via RES.

As a future technology, the synthesis of hydrogen with carbon monoxide or dioxide to hydrocarbons and subsequent treatment to liquid fuels such as gasoline or kerosene [Power-to-Liquid (PtL)] and use in the transport sector might play a role. However, the PtL technology is only just at the beginning of marketable implementation and there are no commercial PtL systems yet. Currently several pilot plants are operated in Germany [40]. Another option is to use surplus electricity to produce basic chemicals for the chemical industry [Power-to-Chemicals (PtC)]. This technology is also in the development stage.

Electricity grids. Transmission and distribution grids are a key tool for providing flexibility. Network expansion, i.e. increasing transmission capacities and thus avoiding network congestion, reduces the variability of VRES by balancing variations across larger geographic areas and creating spatial flexibility [11]. It is shown that in a fully RES-based European power system, a robust, Europe-wide transmission network structure can significantly reduce residual load [41]. In addition, there are flexibility options in the operation of the networks by the installation of power flow control devices, such as phase-shifting transformers or flexible three-phase transmission systems to control or redirect the power flow [42].

This paper focuses on the analysis of flexibility options of the first four categories described (flexible generation, DSM, electricity storage and PtX), as their flexibility potential can be quantified by the underlying technologies. The potentials of grid based options are case-specific and depend on the regional network deployment situation, which makes quantification more difficult [43]. Thus, the network infrastructure and the current electricity market design are assumed to be given in the quantitative part of this analysis.

The temporal dimension of flexibility

In addition to the key technological characteristics, the temporal dimension must be considered for each flexibility option [7]. The above-mentioned options can provide electricity for a few seconds up to a full season, depending on their technological characteristics and economical limitations. They are, therefore, suitable for offering flexibility in different timeframes, according to which they can be differentiated (see Figure 1).

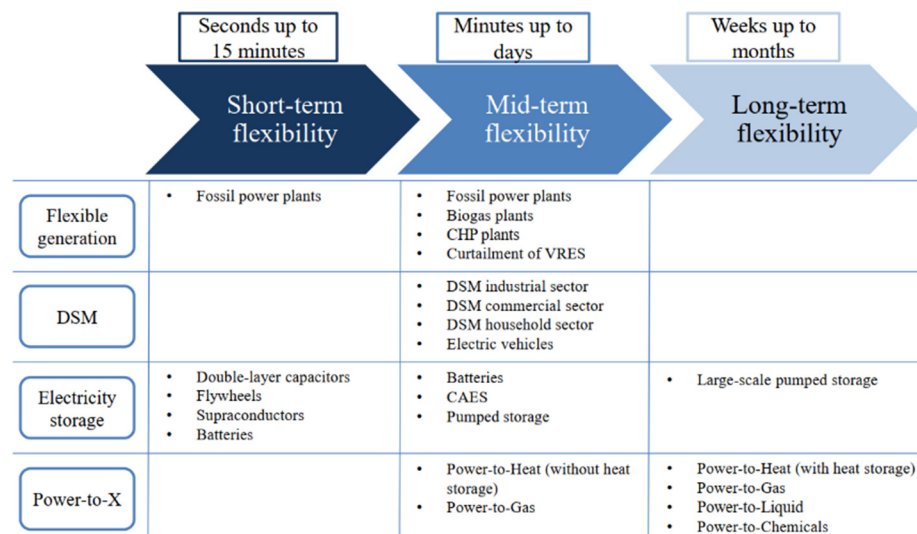


Figure 1. Categorization of flexibility options

Short-term flexibility is needed primarily for frequency and voltage regulation and has traditionally been provided by conventional power plants [1].

Medium-term flexibility describes periods of a few minutes up to a few days. For this need the greatest variety of technologies is available. Both flexible generation, demand-side management and several storage technologies (batteries, compressed air storage, pumped storage), the PtH as well as the PtG technology can offer medium-term flexibility [1].

To cover the need for long-term flexibility for periods from one week up to months or an entire season, the options are more limited. Here especially pumped storage power plants with very large water reservoirs, PtH in combination with large heat storages or the electrolysis or methanization of electricity (PtG) and storage in caverns or in the existing gas grid come into consideration [44].

Markets for flexibility

The three time windows are reflected in different markets where flexibility is traded in Germany. Energy to compensate for fluctuations in the power grid frequency is called control energy and traded on the control energy market. These are periods of a few seconds (primary control power), 5 minutes to about 15 minutes (secondary control power) or a maximum of one hour (minute control power) [43]. Market for medium-term flexibility in addition to the control energy market is the spot market. There, day-ahead and intraday products are traded (short-term trades up to 30 minutes before delivery) [45]. Long-term flexibility can be traded on the futures market up to three years in advance. These contracts are based on the estimated variable production costs plus a risk premium. VRES cannot participate in this market unless they are backed by conventional power plants or storage options [43].

With an increasing share of VRES, the need for medium-term flexibility to compensate for variations in the daily and weekly course of wind power and PV systems is increasing. However, in the long run, more long-term flexibility will be needed in order to balance the seasonal fluctuations of VRES [1]. A major challenge is the bridging of so-called „dark doldrums“, i.e. weather periods in which wind turbines and PV systems produce little or no electricity due to wind storms, short daylength and fog, and at the same time there is a high electricity demand. Such weather conditions typically extend up to three weeks and occur especially in late autumn and winter [44].

In this work, the focus is on the analysis of flexibility options offering medium-term flexibility. Options for frequency and voltage control as well as long-term options and the underlying technologies are therefore outside the scope of the investigation. In addition, only technologies that are eligible for a 100% RES scenario will be analyzed, as a complete conversion of the electricity system to RES as a long-term goal is assumed and according to Child *et al.* [46] as well technologically as economically feasible.

Concept of potential

In order to determine the potentials of flexibility options, the term potential must be differentiated [8]. A classification often used in the literature distinguishes between theoretical, technical, economical and ascertainable potential [47, 48]. In this analysis, the technically available or technically installable potentials of the flexibility options are determined. The term technical potential is defined as the proportion of the theoretical potential (theoretically usable physical offer in a certain period of time in a defined geographical area) taking into account the technical status (e.g. efficiency) and insurmountable restrictions (e.g. restrictions on use in national parks). Social acceptance problems, energy policy framework conditions as well as economic limitations are not taken into account.

METHODS AND MATERIALS

The aim of this quantitative analysis is to develop a feasible method for quantifying the technical potential of flexibility options in specific regional contexts, which is transferable to other regions in Germany.

Indicators for quantification of flexibility potentials

A common definition of flexibility and indicators for measuring flexibility does not exist [12]. Rather, different indicators are not mutually exclusive as different aspects of the electricity system can be analyzed [11].

In order to quantify flexibility in the power system, analytic procedures are continuously being developed and improved. Potentials of flexibility options in a specific region at a determined point in time can be quantified via simulations, estimation or using appropriate historical data [12]. A large number of assessments is based on multitemporal simulations, which is required for a detailed analysis of the flexibility of an electricity system [49]. A MatLab tool for flexibility assessment is provided by Capasso *et al.* [5]. A time series model is used by Lannoye *et al.* [7]. Another analysis uses a flexibility index in order to quantify short term power system flexibility [50]. Furthermore, a linear programming model to evaluate the most important power grid flexibility options available in Germany nowadays is developed by Alemany *et al.* [20].

However, according to Ma *et al.* [49], also the development of indicators to measure flexibility potentials „offline“, without the need of a simulation is of great importance as it enables comparisons across different regions.

Following Ulbig and Andersson [3], the most important indicators for measuring technically available flexibility (in addition to the ramp-rate capacity in MW/min) are the available power provision capacity in MW and the available energy provision capacity in MWh. The quantification of installed capacities is recommended as a first step in measuring flexibility potentials in the status quo. This procedure is particularly suitable for comparative analyses [4].

In this study, for each analyzed flexibility options the goal was to determine its capacity in MW and its energy provision capacity in MWh. However, for some flexibility options, only either capacity or power provision capacity are a limiting factor regarding its flexibility potential. Furthermore, especially for DSM available data was limited. Thus, for some options it was either not meaningful or not possible to characterize its potential both by capacity and energy. In the following, it is described which parameter was chosen for each option and which database was used.

For the flexible generation plants, the installed capacity in MW is determined as it constitutes the limiting factor for its technical flexibility potential as theoretically the plants are always able to produce energy or reduce its production and provide negative flexibility and thus capacity but not energy provision is crucial. The data concerning capacity of flexible generation plants was obtained from four sources: Firstly, the power plant list of the German Federal Network Agency provides data on all existing power plants in Germany with an electrical capacity of at least 10 MW and thus capacities of larger gas power and CHP plants can be determined [51]. Secondly, the installation register of German Federal Network Agency was used, where since 2014 all new installations of renewable energy plants that are funded under the Erneuerbare-Energien-Gesetz (Renewable Energy Law) (EEG) are obliged to be registered [52] and thus capacities of biomass, PV and wind power plants according to locations are documented. Furthermore, a geographical database provided by the environmental information system of the state of Brandenburg [53] listing CHP plants and providing data on their heating output was considered complementing the data on CHP plants from the Federal Network Agency by plants with a capacity of less than

10 MW. The heating output was converted into electrical capacity assuming an efficiency of 36%. Further data on biogas, PV and wind plants was obtained from the open energy platform OpenEnergy Platform (OEP) providing geographical point data of renewable energy plants [54]. Joining the different databases it was possible to determine installed capacities of gas, CHP, biomass, PV and wind power plants according to its geographical location.

In the category of DSM, both capacity and power provision capacity are limiting factors for the determination of flexibility potentials. However, due to the poor data availability and as actual potentials of DSM depend to a large extent on non-technical factors such as market conditions and individual user behavior [55], an exact determination is only possible via collection of company or household-sensitive data which was not possible in the scope of this study. Thus, a rough estimation of the DSM potentials was carried out based on data available in secondary literature.

For the industry sector, load management potentials for suitable energy-intensive production processes at the county level, using data on energy consumption of individual companies, are determined by [56] and are used as an indicator for the total potential for load shifting in the energy-intensive industry in MW in this paper. However, especially in the industry sector it is crucial in which time frames and for how long flexibility can be provided and thus in addition to load-shifting capacity, available energy provision capacity should also be determined constituting a need for further research.

For the household sector, data on potentials for load-shifting capacities were not available. Though, according to the results of the practice-based projects „Modellstadt Mannheim“ [57] and „MeRegio“ [58], field tests concerning load shifting potentials for 1,000 household customers revealed switchable loads of 5-15% in households. By multiplying this share by electricity consumption in the household sector it was possible to determine the flexibilizable share of household electricity consumption per year in GWh. To do so, freely available, geographically high-resolution data on electricity consumption in Germany on the county level on the OpenEnergy Database (OEDB) [59] served as a database.

The quantification for electromobility was based on a time series model according to [60]. This model was used in a modified form to calculate flexibility potentials through flexible charging. The load profiles of the vehicles in the model were determined by Arnold *et al.* [60], based on data regarding average driving distance (14,000 km/year), purpose of journey and related travel times, speed, distance, etc. [61]. Furthermore, a consumption of 14 kWh/100 km was used for the calculations. Charging infrastructure was assumed to be available at 80% of all trips terminating at home, 30% of all trips terminating at workplace and 10% of all trips terminating elsewhere. The model assumes that all electric cars connected to the grid form a combined storage. Cars that are connected to the grid for charging increase the battery capacity and the charging power, while departing vehicles reduce these sizes [60]. The difference between the upper and lower charging levels of the combined storage per hour is available as flexibility.

The flexibility potentials for different degrees of temporal flexibility and varying charging power are calculated by Arnold *et al.* [60]. In this work, a „medium-flexible“ scenario was considered supposing that there is the option to not charge a vehicle connected to the grid during the first four hours, as long as it is fully charged at departure and thus offer flexibility in these four hours. Furthermore, a currently average charging power (3.7 kW at home and 50 kW at a public charging station) was assumed.

As at present, the penetration of electric vehicles in Germany is still very low, the potential range of flexibility offered by electric vehicles was calculated for the year 2030. According to [62], it was assumed that 7 million electric cars will be used throughout

Germany by 2030. On the basis of the amount of the current vehicle stock according to data of the Federal Motor Transport Authority [Kraftfahrtbundesamt (KBA)] [63] this number was scaled to the study regions. Thus, a time series could be generated for electric vehicles indicating the potentially available flexibility per hour in the year 2030 in MW in the study regions. V2G was not considered. From the time series data a range in MW was derived indicating the minimum and maximum available hourly potential which was used as the indicator quantifying flexibility potentials for electric cars in this study (see Figure 2).

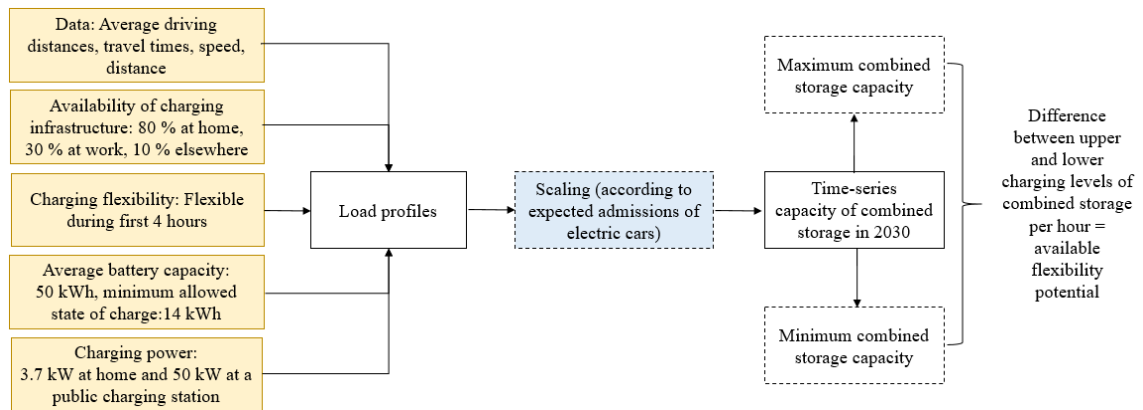


Figure 2. Approach for calculation of flexibility potentials due to flexible charging of electric vehicles according to Arnold *et al.* [60]

For the category storage, both power capacity in MW and storage capacity in GWh constitute limiting factors for the determination of flexibility potentials. For this analysis, potentials are determined by the evaluation of potential studies and thus depend on the data availability. For pumped storage, potential studies focus on capacities in MW of existing and planned pumped storages [38, 64].

Concerning CAES, so far there are only two active CAES systems worldwide, one of them with a capacity of 320 MW in Huntorf in Germany [44]. Potential future locations are mainly in northern Germany [44]. However, the concrete potential of these locations is still not completely discovered and thus cannot be quantified yet.

For the use of battery technologies, no specific local site requirements must be met [44]. Therefore, for batteries a theoretically infinite technical potential is assumed both in terms of capacity and energy.

For PtX, the limiting factor for flexibility potentials differs across the regarded technologies. In this study, two technologies are considered: PtH and PtG. Since PtG is a future technology, in contrast to PtH, not available but installable potentials are determined.

For PtH, the theoretical potential is huge, as heat accounts for around 50% of final energy consumption in Germany [65]. However, neither technologically nor economically it is meaningful to cover total heat demand by PtH. Thus, in this study, PtH potentials are determined via excess electricity supply side potentials using excess electricity in GWh per year in the status quo as indicator. The theoretical excess electricity potential results if energy generated by PV plants and wind power plants exceeds electricity demand in a region and was calculated on the basis of an energy system model based on the open source framework Open Energy Modeling Framework (OEMOF) according to Figure 3. As input, data on existing powerplants taken from [54] was merged with weather data from Geyer and Rockel [66] to generate a time-series on electricity feed-in. Production was then compared with electricity demand derived from

data on electricity demand from [59]. If production exceeds demand, excess electricity is generated which is used for an estimation of PtG potentials.

For PtG, in this analysis, only the direct production of natural gas (methanization) is considered, because in order to quantify the potentials of hydrogen use, more accurate analyzes of the future hydrogen demand and the necessary infrastructure would be required, which are not yet available [29]. PtL and PtC as future-oriented technologies are also not taken into account. The limiting factor for the PtG flexibility potential is installed capacity of PtG plants, as the German gas grid offers sufficient capacity for storage of gas generated by methanization of excess electricity and thus produced energy is not constraining potentials.

The quantification of the potentially installable PtG power in MW was carried out according to Schneider and Kötter [23], in the form of a spatial location analysis for PtG plants which was automated and applied to the two study regions. For the calculation, a PtG efficiency of 60% was used according to various studies evaluating flexibility options (such as [19, 29, 67, 68]). For the calculation, 4,000 full load hours were assumed for PtG plants following [23]. The approach is illustrated in Figure 4. In a first step, suitable sources of CO₂ in the study area are determined, as for methanization of hydrogen CO₂ is needed. Thus, the availability of CO₂ sources is a fundamental prerequisite and the limiting factor for the methanization potential [23]. Suitable CO₂ sources are biogenic sources and industrial plants. Among the biogenic sources are biogas, sewage gas and landfill gas plants, as the fermentation of biogenic substances produces a high concentration of CO₂. Data on the location of those plants can be obtained from [54]. In a second step, it is verified if identified CO₂ sources are located in an restrictive area for the construction of a PtG plant. Among the restrictive areas are nature, flood and water protection areas as well as areas with unsuitable slope and already used areas. Relevant geographical data can be obtained from offices for environment of German federal states (such as from [53]). Next, the proximity to the gas network is next checked which is needed for feed-in of produced gas. If the CO₂ source is more than 5 km away from the existing gas network, it is classified as only limited suitable. Lastly, the proximity to VRES plants is checked, as locations in close proximity (< 1 km) are particularly suitable for construction of PtG plants and methanization of excess electricity. Finally, the actual PtG potential in MW can be calculated on the basis of CO₂ volumes of suitable sources. A more detailed description of the approach for the calculation is available in Schneider and Kötter [23]. Also, the used script, a documentation and metadata for the datasets are provided open source [69]. In this analysis, for the PtG potential particularly suitable, suitable and limited suitable potentials are considered.

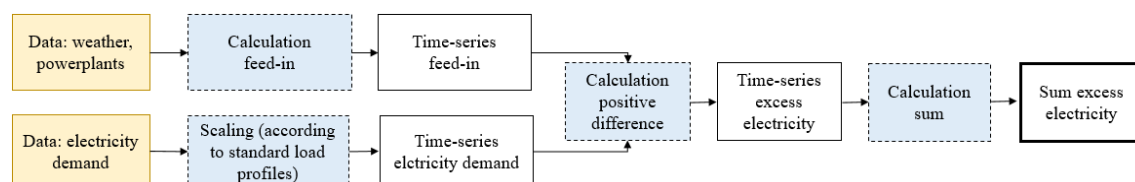


Figure 3. Approach for calculation of excess electricity potential for PtH

Table 1 presents all used indicators for quantifying the potential of medium-term flexibility options. For flexible generation, most DSM options and PtH potentials in the status quo are calculated. However, for future technologies (flexible charging of electric vehicles and PtG) future respectively installable potentials are considered. For storage, as well current as installable potentials have to be considered.

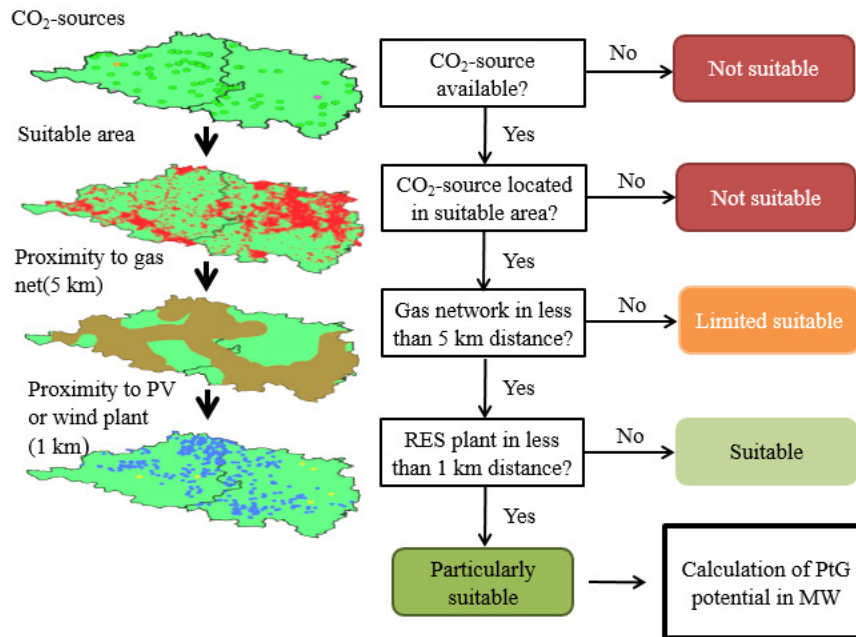


Figure 4. Approach for geographic analysis of regional PtG potentials according to Schneider and Kötter [23]

Table 1. Indicators for quantifying flexibility potentials

Category	Flexibility option	Limiting factor	Indicator used in this study	Unit
Flexible generation	All	Capacity	Installed capacity	[MW]
DSM	DSM industry	Capacity/energy	Load shifting potential in energy-intensive industry	[MW]
	DSM commercial sector	Capacity/energy	No data available	-
	DSM households	Capacity/energy	Flexible share of annual electricity consumption	[GWh]
	Electric vehicles	Capacity/energy	Flexibility per hour in 2030	[MW]
Electricity storage	All	Capacity/energy	(Installable) storage capacity	[GWh]
PtX	PtH	Energy	Excess electricity	[GWh]
	PtG	Capacity	Installable capacity	[MW]

The study regions

For this article, two study regions are analyzed: Prignitz in Brandenburg and ABW in Saxony-Anhalt (see Figure 5).

The study region Prignitz is located in the Northwest of the state of Brandenburg. It includes the two municipalities of Prignitz and Ostprignitz-Ruppin. Its area is 4,665 km² and corresponds to 1.3% of the area of the Federal Republic of Germany. In total, around 185,000 people live in the region (0.2% of the German population). The region is rural and ranks with on average 38 inhabitants/km² among the most sparsely populated areas of Germany. Significantly, more renewable electricity is generated in the Prignitz than consumed (271% in the Prignitz district and 125% in the Ostprignitz-Ruppin district) [70] (national average: 32% [71]).

The study region ABW is situated in the Southeastern part of the federal state of Saxony-Anhalt. It consists of the districts of Anhalt-Bitterfeld and Wittenberg as well as

the administratively independent city of Dessau-Roßlau. Its area amounts to 3,629 km² and makes up 1% of the area of the Federal Republic of Germany. The area is partly low and partly medium densely populated with on average 104 inhabitants/km² and there are about 375,000 inhabitants in the region (0.5% of the German population). Compared to Prignitz, in the ABW region, the proportion of renewable energy production is much lower (7% in Dessau-Roßlau, 65% in Anhalt-Bitterfeld and 57% in Wittenberg) [70].

The Prignitz area is larger than the ABW region, yet it has less than half the population. In both regions, the population density is low compared to the nationwide average of 230 inhabitants/km² [74, 75]. It is expected that the population will continue to decrease both in Prignitz and in the ABW region [76, 77].

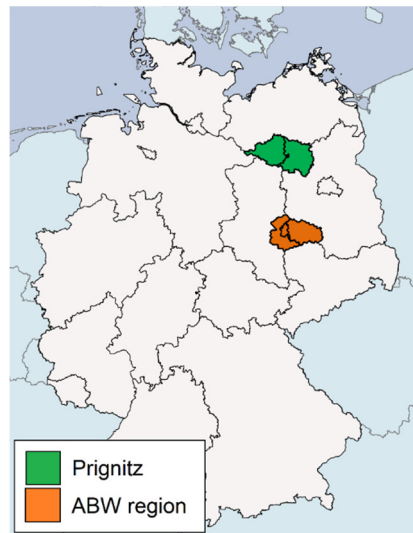


Figure 5. Placement of the study regions in Germany GeoBasis-DE[®]/BKG 2017[®] Database of Global Administrative Areas (GADM) [72, 73]

RESULTS

Table 2 summarizes the identified potentials of the flexibility options in the two study regions. Of particular relevance is whether the respective flexibility option is able to provide negative or positive flexibility [7]. Positive flexibility means an increase of production capacity or a reduction of electricity demand. In contrast, negative flexibility describes a reduction of production or an increase of demand [19].

It should be noted that by VRES curtailment and PtH only negative flexibility can be provided. PtG can in the first step only offer negative flexibility. Via the re-conversion into electricity in gas-fired power plants it can also offer positive flexibility.

Table 2. Quantifiable flexibility potentials in the study regions

	Prignitz	ABW region
(RES-) Gas power plants [MW]	+/- 0	+/- 40
Biogas plants [MW]	+/- 61	+/- 30
CHP plants [MW]	+/- 63	+/- 196
Curtailment of VRES [MW]	-1,618	-1,079
DSM energy-intensive industry [MW]	+/- 0	+/- 5-20
DSM commercial sector	Not sufficient data available	
DSM households [GWh/year]	+/- 16-31	+/- 31-66
Electric vehicles (without V2G) [MW]	+/- 0-35	+/- 0-64
Pumped storage [GWh]	+/- 0	+/- 0
CAES	Not sufficient data available	
Batteries	Independent of the location	
PtH [GWh/year]	-1,791	-184
PtG (Methanization) [MW]	-316	-155

There are clear differences regarding the potentials of the different options in the two regions. In the ABW region, there is one gas power plant with an electrical capacity of 40 MW, whereas there is none in Prignitz. On the other hand, the potential of biogas plants is with 61 MW in Prignitz twice as high as in ABW. Concerning CHP plants, in the ABW region there is much higher potential (196 MW) compared to 63 MW in Prignitz, mainly due to some currently still predominantly conventionally operated large CHP plants. This information makes no claim to completeness, as there is no mandatory plant register for CHP plants, as existing for RES plants. For curtailment of VRES, in Prignitz necessarily more potential can be found, due to a higher installed capacity of RES plants.

Concerning DSM, the potential in the ABW region is also absolutely higher in comparison to Prignitz due far more resident industrial enterprises and more than twice the number of inhabitants in the region. In the energy-intensive industry, the potential is estimated at 0 MW in Prignitz and at 5-20 MW in the ABW region according to [25]. For households in Prignitz, the moveable quantities of electricity amount to 16-31 GWh/year and for ABW to 31-66 GWh/year and for electric vehicles to 0-35 MW and 0-64 MW per hour in 2030, respectively. This means that in some hours, flexibility potential from electric cars is zero (during the early morning hours) and in some hours there is up to 35 MW (in the evening and night hours).

It should be noted that especially for DSM, the temporal availability of flexibility plays an important role where two dimensions of time have to be considered: in addition to the time availability in hours within a year, it must be taken into account how long the flexibility can be provided. In contrast to flexible generation, for example in the industrial sector, the greatest potential is in the range of five minutes to one hour of disconnectable power [25]. Thus it is better suitable to balance short term fluctuation caused by RES than provide flexibility for long time spans [22]. However, in this study no time series analysis concerning flexibility potentials was conducted which states a need for further research.

In the category of electricity storage, there are no pumped storage power plants in the study regions, nor are plants being planned according to [38, 64]. As a flexibility option, the potential in both study regions is therefore zero. For CAES, a quantification of potentials, is not yet possible as so far only possible storage sites but not its potentials have been investigated [78]. The follow-up project InSpEE-DS, which runs from 2015-2019, aims at determining potentials of the individual salt structures.

In the case of batteries, the potential is independent of the location and therefore theoretically infinitely high. However, batteries are a comparatively expensive option for flexibility when storing large amounts of energy [79].

In the PtX category, Prignitz has much higher potential. For PtH, this is due to larger VRES excess electricity amounts of 1,791 GWh/year (ABW: 184 GWh/year) if supposed that only VRES excess electricity amounts are used for PtH. It should be noted that the VRES supply and heat demand do not always correlate well, as the PV profile is contrary to heat demand and on cold days usually little wind blows as well as on windy days often mild temperatures prevail. Therefore, the use of PtH technology depends to a large extent on the availability of heat storage [19]. However, process heat in the industrial sector as well as basic heat supply are required all year round.

For PtG, the installable capacity is 316 MW in Prignitz and 155 MW in ABW (considering particularly suitable, suitable and limited suitable locations for installation of PtG plants due to available CO₂ volumes). The higher installable PtG capacity in Prignitz is caused particularly by a higher CO₂ potential of the numerous biogas plants that is essential for the methanization of excess electricity and provided mainly by biogas plants.

In addition, CO₂ can be extracted from industrial processes for methanization, thus contributing to CO₂ reduction [39]. Including the CO₂ potential from industrial plants calculated on the basis of emission levels in 2015, according to [80], results in a much

higher installable PtG potential of 606 MW in the ABW region, compared to 227 MW in the Prignitz region. This potential is indicated separately because for the time being it is still uncertain if this procedure will be practicable in the future. The currently existing PtG pilot plants mostly use biogas as CO₂-source [81]. Besides, annual emissions fluctuate in the industrial sector and it is unclear to what extent the underlying processes are continuous and thus suitable as CO₂-source for PtG. Also, if the CO₂ is taken from non-renewable sources, the generated methane can not be labeled as biogas according to the German Energy Act, which makes marketing more difficult.

For the ABW region, the quality of the result is reduced because no map on the course of the gas network was available, so that using the method of Schneider and Kötter [23] no final statement on particularly suitable locations for PtG can be taken. For Prignitz, a map of the gas network was available in [77].

For the PtG analysis, it should be noted that the installable potential is almost proportional to the assumed full load hours of the PtG plants. Accordingly, primarily the relation of the potentials in the study regions with each other and less the absolute values should be considered.

The potentials given in Table 2 are stated independently for each flexibility option. However, in the future, trade-offs could arise between individual flexibility options. This concerns above all the interrelation between biogas plants and the PtG technology, because biogas plants serve as an important CO₂-source for methanization. At the moment, they are mostly driven in band load operation. If flexibly operated in the future and allowing for seasonal shifts, the availability of CO₂ for methanization would also be variable in the course of the year. In turn, the availability of PtG in a 100% RES scenario affects the availability of RES gas for re-conversion into electricity in gas power plants or CHP plants. Another trade-off arises if VRES power plants are curtailed, since then there is less surplus electricity available for PtH and PtG.

CONCLUSION AND OUTLOOK

With an increasing share of VRES in the electricity system, significantly more flexibility is needed to offset temporal fluctuations and spatial imbalances. To meet this need, several technological options in four categories exist: flexible generation, DSM, storage and PtX. In this paper, the focus is on medium-term flexibility (in the timeframe of a few minutes to a few days), because with an increasing share of RES, the need for medium-term flexibility will continue to increase in the next few years.

In this analysis, a methodology was developed on the basis of two study regions in order to be able to quantify and compare potentials of different flexibility options in a high resolution according to regions. Due to different limiting factors concerning the flexibility potential for the options and limited availability of data, for each option, a specific indicator for quantification was developed. This methodology is developed to be applied throughout Germany to other regions.

The results of the quantitative analysis show that the potentials of the analyzed flexibility options are geographically bound and vary greatly from region to region depending on the local geographic and demographic conditions as well as the historical development of the production and consumption landscape. An exception is battery storage, which can be installed regardless of location and therefore has a theoretically unlimited potential.

In this analysis, the following limitations must be noted: installed or installable capacities are not proxy variables for flexibility, as other flexibility indicators such as the load change rate, the ramping rate, the maximum and minimum capacity, as well as the current market design and regulatory framework are not taken into account [4]. In addition, it can not be measured whether a power system is 'sufficiently' flexible [4].

Therefore, in a further step, the temporal dimension of flexibility should be considered by conducting a simulation with time series data [4].

Another limitation concerns the availability of data. For example, gas grid operators are not obligated to publish data concerning the course of the gas grid which is needed for the determination of the installable PtG capacity according to Schneider and Kötter [23]. Also, in Germany, the quality and amount of data available varies among the different federal states, administrative districts and municipalities.

For future flexibility technologies (in particular electromobility and PtG) that are currently still in the pilot phase, assumptions had to be taken in order to calculate forthcoming potentials. Therefore, the results presented in Table 2 are very much dependent on the assumed parameters. Factors significantly influencing the calculated potentials are for electric vehicles the degree of temporal flexibility actually available for use and for PtG the full load hours and the efficiency of the PtG plant.

By using the described technologies, VRES in the electricity system can be balanced. However, even if the options are technically available, not all are yet able to participate in the energy market because the current market conditions partly prevent the use of flexibility options [49].

To better exploit the technically available flexibility potentials, there are several proposed measures concerning the market design of the electricity market: market solutions besides technical options are presented by [11, 43, 82, 83]. A focus on possible revisions of the electricity market design and market rules in order to uncap flexibility is outlined in Orvis and Aggarwal [84]. Policy actions in order to achieve a transition towards energy systems based on 100% RES are developed in Papaefthymiou and Dragoon [42]. A framework to remove barriers for RES integration and market inefficiencies is developed in Hu *et al.* [85]. Policy recommendations concerning market design improvements to integrate high RES shares into the future European electricity system are presented by Newbery *et al.* [86].

Firstly, an expansion of its geographic market size to make more efficient use of existing flexibility options and grid capacity through spatial leveling is especially relevant for regions with different power plant parks and climatic conditions and can significantly reduce the need for flexibility in systems with high RES shares [6].

Furthermore, an adjustment of the prequalification requirements for trading on electricity markets can open the market for additional flexibility options. For example, by allowing the pooling of smaller generation units to accomplish the required minimum supply sizes of electricity, additional flexibility options such as DSM or controlled production from VRES can enter the market. This also applies for a shortening of the time blocks traded, as DSM and VRES are often only able to offer flexibility in certain time ranges.

Another measure is an approximation of the time of submission of tenders to the time of energy provision as the prediction accuracy of VRES increases over time. Lastly, real-time data communication of relevant information such as current production and purchase quantities traded on the electricity market should be published in real time allowing market participants to compensate for excess or missing amounts of electricity in real time.

Based on the methodology and results developed in this paper, the following recommendations for further investigations can be derived: for DSM more detailed studies of the potentials compared to costs involved could be undertaken since especially DSM in industrial plants can be a short-term and cost-effective flexibility option, which can often be exploited without significant investment.

A detailed regional analysis would also be useful for PtH as it can offer high short-term potentials for the utilization of excess electricity due to its high efficiency. However, the excess electricity as indicator represents only a rough estimate of the PtH

potential in a region and practical limitations such as actual demand for heat, available infrastructure for heat production, transportation and storage as well as already existing heating technologies reduce this theoretical potential. Also, there is a trade-off between usage of excess electricity for PtH and PtG.

ACKNOWLEDGMENT

The authors thank the German Federal Ministry of Economic Affairs for funding the research project WindNODE as part of the SINTEG projects (funding code: 03SIN525).

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Paper submitted: 27.09.2018
Paper revised: 17.04.2019
Paper accepted: 18.04.2019