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Position Paper

Flexibility concepts for the German power supply in 2050

Ensuring stability in the age of renewable energies

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Ensuring stability in the age of renewable energies

Foreword

The power supply in 2050 will be dominated by renewable energies, in Germany, above all by the fluctuating feed-in from wind power and photovoltaics. Since power generation must at all times equal power consumption, we will require technologies capable of reliably establishing this equilibrium. For instance, while flexibly regulatable power plants must step in if power generation from wind and photovoltaics is insufficient, batteries can be loaded during occurrences of electricity surplus.

Technically, this would seem to be feasible. However, it remains to be defined what technologies should actually be employed, how they can usefully and efficiently interact with the system and what economic costs they will entail. Since political and social framework conditions have a major influence on the future "flexibility mix", today, the public will have to agree on the priorities for the future.

This position paper describes and compares different ways of ensuring a stable power supply in the age of renewable energies. The academies thereby seek to create momentum for the important debate evolving around the advantages and disadvantages of different design options for the energy system of the future.

This position paper was drawn up by the ad hoc working group "Flexibility Concepts" in the Academies' Project "Energy Systems of the Future". Over one hundred specialists from science and industry have contributed their expertise. We would like to express our sincere thanks to those who contributed to the development of this paper, as well as to the reviewers for their commentaries.

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Contents

Abbreviations

CCS	Carbon Capture and Storage
CSP	Concentrated Solar Power
DSM	Demand-Side Management
RES	Renewable Energy Sources
FRES	Fluctuating Renewable Energy Sources (wind and photovoltaics)
CCGT	Combined-Cycle Gas Turbine (power plant)
GT	Gas Turbine
CHP	Combined Heat and Power
PV	Photovoltaics
EGS	Enhanced Geothermal Systems

Units

GW	Gigawatt (equivalent to 1 million kilowatts, or approximately the power-output of a nuclear power plant)
GWh	Gigawatt hour (equivalent to 1 million kilowatt hours, approximately the annual power consumption of 250 households)
TWh	Terawatt hour (equivalent to 1,000 gigawatt hours or 1 billion kilowatt hours; Germany’s total power consumption amounts to approximately 600 TWh)

Abstract

By increasingly shifting energy generation toward renewable energy sources, Germany can use its power system as an important lever for a significant reduction in carbon dioxide (CO_2) emissions. However, since the feed-in from wind and photovoltaic systems varies with the weather, the power system will need to react much more flexibly in the future than it does today: Insufficient power feed-in due to the absence of wind and solar radiation makes it necessary, for instance, to activate additional power plants or to throttle the power consumption in industrial processes. Any excess electricity can be dealt with by reducing the power generated by power plants, or by using electricity for heat or gas generation. Also, storage devices can take in surplus power and release it on demand. This balance between fluctuating generation and consumption defines the **flexibility requirements** of a power system.

The technologies necessary to make the power system more flexible are either already available or can achieve commercial viability through research and development by 2050. This position paper considers various possibilities of what a low-emissions power supply system could look like in 2050, and the specific features and extent of the flexibility technologies it relies on.

Modelling techniques and working methods

Based on current energy scenarios depicting different designs of future energy systems, an ad hoc working group of the Academy Project "Energy Systems of the Future" (ESYS) has identified and evaluated the respective flexibility requirements. In a first step, the most important technologies for the provision of flexibility were subjected to a standardised interdisciplinary review. The results served as a basis for model calculations: The portfolio of flexibility technologies was computed based on the respective share of wind and photovoltaics and the power consumption in each energy scenario. The calculations assumed certain basic conditions largely supported by the German public (for example, certain carbon reduction targets, or a high or low acceptance of technologies and generation sites) and were designed to keep the respective average electricity generation costs as low as possible. The electricity generation costs include the costs for the construction and operation of the power plant portfolio, for fuels, and for the necessary emissions allowances.

The development and selection of the calculation method involved simplifications regarding the architecture of the model and the system boundaries. For instance, the model calculations are limited to Germany; any possible flexibility provision in neighbouring countries is not taken into consideration. Likewise, the analysis is focused on the power system; flexibility potential in the heating sector will be considered only to the extent that it is linked to perennial heat consumption (e.g. industrial process heat). The flexibility provision in electric vehicle batteries is taken into account as part of the demand-side management potential.

The calculations are based on the greenfield approach, assuming that all plants will be newly built by 2050. The

technical and economic progress that is assumed to have taken place by 2050 for most technologies (for example, efficiency increases or cost reductions) requires their steady evolution as of today. The costs of this systemic transformation cannot, however, be taken into account in the chosen approach.

The model calculations enable the comparison of different cost-effective options for the design of the power system. In this policy paper, the results were used to design options for the following energy policy issues:

- What impact do the emissions reduction targets have on the flexibility requirements?
- How could a power system based on 100 per cent renewable energy sources present itself?
- Centralised vs. decentralised generation – how does it affect the energy system?
- What role does storage play in the future?
- What uses could be made of power surpluses?
- How does a lower dependency on the import of energy sources affect the power system?

Results

In all of the energy scenarios we considered, **wind and photovoltaics** will play a crucial role for the power supply in 2050. Assuming that the price of emissions allowances in 2050 will significantly surpass its current level, a power generation system boasting a high percentage of wind and photovoltaics will, as a rule, come cheaper than a system dominated by fossil fuel power plants.

Simple as well as combined-cycle gas turbine power plants are the backbone of a secure and reliable power supply. Depending on the technical, social and political conditions, they are operated with natural gas, biogas or – as part of gas storage systems – with hydrogen or methane. If engineered with variable gas firing, these plants constitute a robust option for the power supply of the future for different development paths; there are (as yet) few alternatives to this option.

Flexibility will constitute a key feature of the future electricity system. If the power supply is to be fully covered with renewable energy, the fluctuating generation from renewable energy sources (RES) will be supplemented by storage systems, demand-side management and controllable energy technologies such as biogas plants. In the case of lower percentages of wind and photovoltaics, trans-European power grids would enable the use of solar thermal power plants with integrated heat storage (Concentrated Solar Power, CSP) in southern Europe or North Africa. If, on the other hand, more wind and photovoltaic systems are installed than are needed to meet demand, the use of bioenergy can be drastically reduced at only minor additional cost.

Decentralised power supply should be accompanied by particularly high levels of wind energy and photovoltaics. Whether the power system should indeed be organised at the local, decentralised level or whether a predominantly centralised supply structure is preferable should be determined on the basis of a comprehensive assessment of the cost differences. It also largely depends on the level of public acceptance for the different variants.

The most cost-efficient way of meeting the **short-term energy storage demand** is demand-side management measures (flexible power consumption control). In 2050, the bulk of the potential will probably be provided by thermal

storage units and battery storage in electric vehicles, and photovoltaic systems in households.

Longer periods with little wind and solar radiation (“dark and windless periods”) can be technically bridged, either with **long-term energy storage devices** or with **flexible producers** (gas-fired plants, for example). On the whole, it is becoming clear that the more flexibility options are available and the lower climate protection requirements there are, the less long-term energy storage systems are used. If emissions reductions do not exceed 80 per cent compared to 1990, long-term storage is not required to a relevant extent. If, however, the import of natural gas is restricted or the usable potential for bioenergy is rather low, long-term storage plays a major role. With high proportions of fluctuating RE, long-term storage devices can be installed in order to reduce the demand for natural gas imports. The use of lignite in combination with **Carbon Capture and Storage** (CCS) is likewise an option to reduce energy imports. Currently, however, public support for this technology is unlikely.

Research & development and expanding the installed capacity are vital to realise any **cost-cutting potential**. Together with technological evolution, systemic integration is likewise of great significance.

This position paper indicates that there are a number of options for the design of a future power supply system that feature a relatively similar level of electricity generation costs. As a rule, a strategic decision against individual technologies for technical, political or social reasons can be compensated at relatively low additional cost by resorting to alternative generation technologies. This, however, requires early decisions in order to avoid unnecessary investments. A cost-effective technology portfolio composed of the two categories “fluctuating producers” (wind and photovoltaics) and “flexibility technologies”, and ranging within the boundaries of the respective framework conditions is the key to a sustainable, secure and cost-effective power supply system.

1 Introduction

Germany has agreed on ambitious national goals in order to contribute to global climate protection: By 2050, German greenhouse gas emissions are to be reduced by at least 80 per cent. This transformation of a major industrial country can also serve as a possible road map toward a low carbon economy. The power supply is to play a significant role in obtaining achieving the carbon emissions reduction goal while invariably remaining reliable, as cost-effective as possible and backed by a broad public consensus. Against this background, it is generally recognised that the future German supply system will largely build upon energy from renewable sources. Here, wind power and photovoltaics will play a crucial role.

For the future power system, this implies that unlike today, power generation will no longer be composed of the typical base load, medium load and peak load power plants[1]. It will, instead, be dominated by the strongly fluctuating electricity generation from wind and photovoltaics (PV). In addition, so-called flexibility technologies will ensure that power generation can, at all times, match the load.

But what flexibility technologies will actually be needed in 2050? How do the various potential systems differ in terms of cost? How do basic sociopolitical conditions affect the structure of the flexibility technologies portfolio? This position paper attempts to answer these questions, thus providing design options for the power supply system of the future. The methodology is described in chapter 2, followed by the basic characteristics of the power system in 2050 in chapter 3. This includes an overview of the potential flexibility technologies used for the model calculations. Findings from the research into the mechanisms of public acceptance are used to assess the political feasibility of the respective technologies. On this basis, chapter 4 outlines design options for a choice of long-term energy policy challenges.

> In the electricity grid, power generation must, at all times meet the demand. Any disequilibrium between generation and consumption requires measures to restore the balance.

The results for the year in question, 2050, can serve as guidelines for present-day decisions. They can, for instance, provide indications as to what investments and strategic decisions for technological developments are required today in order to achieve the goals set for 2050. The economic costs of these programmes would have to be considered in the political decision-making processes and carefully weighed against the cost savings the technological developments achieved by these programmes would bring about.

1 Today, baseload power plants are permanently operated with about 7,000 to 8,000 full-load hours per annum. Medium load power plants compensate periodic fluctuations occurring in the course of the day with 4,000 to 5,000 full load hours per annum (e.g. differences between daytime and nighttime consumption). Peak load power plants cover the additional peak demand in 1,500-2,000 hours per annum.

2 Methodology

Technical and economic modelling is an important tool to explore how energy systems work. Usually, such models centre on scenarios showing how the power supply structures can be transformed and restructured on the basis of renewable energy sources, and how this will affect carbon emissions and costs.

The desire to produce a realistic representation of existing energy systems with all of the important correlations and systemic interconnections has led to the development of more and more elaborate calculation models. The computation time of these often highly complex models amounts to several days or even weeks, limiting the number of calculations that can reasonably be carried out as the basis for a study.

Different studies of the energy system employ a wide range of modelling approaches and assumptions. This makes a comparison of the results very difficult. The authors of a recent study[2] provided a comprehensive overview of the existing studies in the field of energy storage and flexibility provision, coming to the conclusion that "a comparative interpretation of the range of results may only be carried out among the scenarios of the same studies". The typically small number of comparable scenarios makes it difficult to identify correlations and interdependencies in the energy system. And this is precisely the starting point of the examinations this position paper is based on:

2 BMWI 2014-2.

A method[3] was developed that enables the rough calculation of a power supply-design within a few minutes. It was used to sketch a large number of alternative constellations for a future system. These are presumed to satisfactorily cover the range of possible developments of the power supply system. This allows for a comparison of differently structured power systems and an assessment of the influence of different framework conditions.

To obtain a valid and conclusive database for the model calculations, the relevant technologies were assessed by over one hundred experts[4] from science and industry in ten working groups focused on different technologies. The resources required were likewise considered, along with social issues such as public acceptance.

The parallel expert group "Energy Scenarios" examined the flexibility requirements of potential energy systems in 2050. The so-called residual load (the load that exceeds the possible feed-in from fluctuating sources and therefore remains to be covered by dispatchable plants) was identified as the pivotal parameter for these scenarios.

A specially developed algorithm was then used to construct a cost-effective portfolio of flexibility technologies for the residual loads of these illustrative scenarios, ensuring that their power demand

3 The methodology has been described in detail in an analysis by Elsner et al. 2015. Also, an in-depth article is to be published in a relevant journal.

4 For a complete list of contributors, cf. Elsner et al. 2015.

is covered at any hour of the year. In order to take the various uncertainties and political preferences into account, these calculations were carried out for several parameter variations (e.g. limited technology availability, limited grid expansion and low / high carbon reduction targets). This allows for a comparison of differently designed power systems and the deduction of options for energy policy-relevant questions.

Figure 1 illustrates the working processes of the ad hoc working group "Flexibility Concepts".

2.1 Assessing the flexibility options

It can be assumed that the power supply in 2050 will be mainly based on refined versions of technologies either already established or in the test period today. In order to assess their potential role in a future system, a realistic estimation of features like efficiency levels and costs in 2050 is necessary. For this purpose, more than 100 experts from academia and industry took part in a broad consultation process, analysing the different technologies and quantitatively assessing them according to a standardized benchmark. The basic technical characteristics and cost data used in the model calculations were jointly adopted by the expert groups.

The study covers all power generation technologies based on fossil and renewable primary energy sources that are deemed relevant for 2050, along with the crucial storage technologies, de-

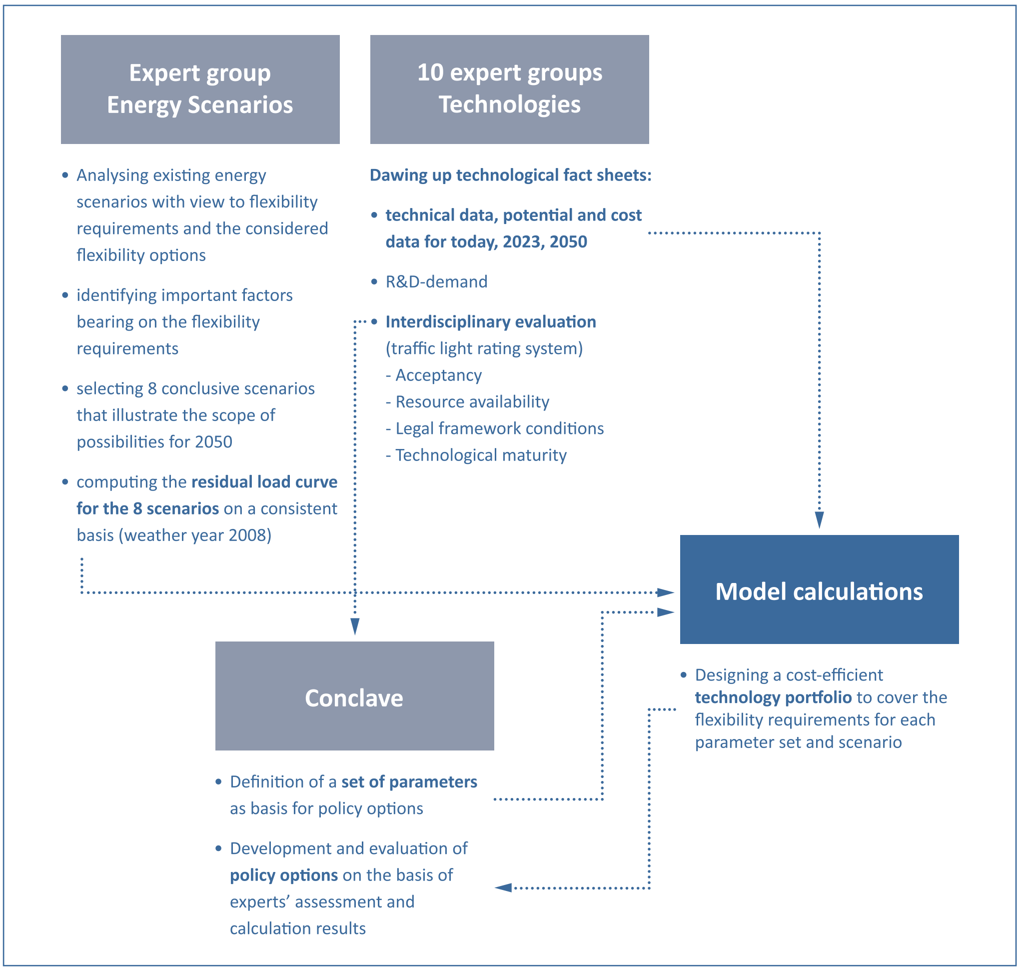

Figure 1: Diagram of the working processes of the ad hoc working group "Flexibility Concepts"

mand-side management potential, transmission grids and power-to-X technologies.[5]

Experts analysed and evaluated the existing technologies and the prospects for their development by 2050, focusing on the technical possibilities and the costs of a flexible application. Technologies that have not yet reached the stage of commercial trials were not taken into account.

The assumptions for the model calculations were determined on the basis of expert estimates as to efficiency improvements and cost reductions possible by 2050.[6] One condition applies to almost all technologies: The assumed technical and economic progress can only be achieved if the technologies are continuously developed and if the continued construction of the respective plants results in economies of scale.

The working group has likewise assessed the specific research and development requirements as well as questions of public acceptance, the availability of materials and legal barriers that might impede the implementation of the different technologies. The different framework conditions for the model calculations were determined on the basis of these appraisals. For instance, specific model calculations were conducted with a view to the public preference for small, decentralised technical solutions, and the widespread scepticism about the construction of power lines[7]. Variants considered included a very limited expansion of the transmission grids or the exclusive use of minor, decentralised power generation plants.

2.2 Energy scenarios and flexibility requirements

The comparative scenario analysis was used to determine key factors influencing the flexibility requirements and to identify so-called robust lines of development. The term robustness describes a development that remains unaffected by the differences in various power system designs. In a first step, eight scenarios were selected from the variety of energy scenarios currently available for Germany. This choice is assumed to cover the scope of developments of the future energy system as broadly as possible. The selection includes the following scenarios:

- S1 – Trend scenario[8], 57 per cent of fluctuating renewable energy sources (FRES)
- S2 – Climate Protection Plan NRW – B CCS[9], 45 per cent FRES
- S3 – Target scenario[10], 67 per cent FRES
- S4 – Energy target in 2050 – Regional alliance[11], 95 per cent FRES
- S5 – Paths to 100 % renewable power supply – scenario 2.1.a[12], 91 per cent FRES
- S6 – Germany’s power system in 2050 – the reference scenario[13], 83 per cent FRES
- S7 – Scenarios for Germany‘s energy supply – SZEN 100[14], 68 per cent FRES
- S8 – Climate protection scenario 2050 – climate protection scenario 90[15], 79 per cent FRES

5 Power generation based on nuclear fission was ruled out with view to the German Federal Government’s decision to phase out nuclear energy – a resolution which is backed by broad public support. However, even assuming the power generation costs currently presumed in the United Kingdom in a feed-in law for new nuclear power plants, this technology would, for economic reasons, still be ruled out. Power generation by means of nuclear fusion was not considered an option, as experts agree unanimously that even by 2050, no fusion power plant will have reached technical and economical operability.

6 For a complete list of the technology and cost parameters used in the model calculations, cf. the appendix to Elsner et al. 2015.

7 Ohlhorst 2009; Wüste 2012.

8 BMWi 2014-1.

9 WI 2014.

10 BMWi 2014-1.

11 UBA 2010.

12 SRU 2011.

13 Fh-ISE 2013.

14 BEE 2014.

15 BMUB 2014.

Each scenario is representative of a specific (illustrative) line of development, which is especially relevant for the estimation of the flexibility requirements. The scenarios differ mainly regarding the climate protection goals assumed (continuation of the current trend versus climate protection according to the federal government's objectives or beyond), the use of specific technologies (e.g. Carbon Capture and Storage (CCS)) and, in particular, the share of fluctuating power generation from renewable energy sources (FRES).

A further scenario considered in this position paper assumes a power system where the power generation potential from wind and photovoltaics exceeds consumption (installed FRES -overcapacity with 136 per cent FRES).[16]

In the illustrative scenarios, the annual electricity demand varies between 450 and 750 terawatt hours. A comparison with Germany's current generation of around 600 terawatt hours will help to assess the dimensions correctly. The feed-in from the fluctuating renewable sources wind and photovoltaics accounts for about 15 per cent of total power generation today, whereas the proportion ranges between 45 and 95 per cent in the scenarios for 2050. This high variability is the result of different assumptions as to the extent to which efficiency measures will affect power consumption or whether an increasing electrification of the heating and transport sector is assumed. The latter would lead to a rising demand from a new category of power consumers, such as electric mobility or electric heat pumps. The production of synthetic gas or fuels by means of electricity is likewise a prominent feature in some scenarios.

To limit the complexity of the analysis and ensure a degree of comparability for the subsequent calculation steps, the following simplifications were made:

- Only the annual electricity demand and the generation from run-of-river, photovoltaics and on- and offshore wind turbines were obtained from the scenarios and used as set values. Thus, the scenarios delineate the development corridor for the fluctuating feed-in and the power demand. The additional power plants or the storage devices figuring in the scenarios were not considered.
- Standardised technical parameters were used for the fluctuating generation plants and uniform assumptions made as to the geographical distribution of wind and photovoltaic installations across Germany. [17]

The temporal characteristics of power generation from wind and photovoltaics assumed in the calculations are based on weather data from 2008. That weather year witnessed two longish dark and windless periods, making it a rather challenging basis for the design of a system. However, due to the exceptional economic situation (economic crisis) of that year, the load curve, i.e. the hourly values of electricity demand, is not representative. Therefore, the load characteristics of 2010 were applied. It was adapted by scaling the respective power requirements of the scenarios.

16 The particularity of this scenario compared to the other eight consists in the assumption and design of wind and photovoltaic capacities capable of generating about one third more electricity than is necessary to meet power demand. Thus, significant amounts of energy can be stored in long-term storage systems even with the losses factored in. This scenario serves as a benchmark for approaches aiming not only at a carbon-free power supply, but a system that relies almost completely on wind and photovoltaic systems. This scenario is not included in the analysis by Elsner et al. 2015.

17 It is partly owing to this simplification that the share of fluctuating renewables slightly deviates from the underlying studies.

For each scenario, the residual load was calculated on the basis of hourly values, i.e. for 8,760 hours per annum. The residual load describes the amount of power required in addition to the fluctuating electricity provided by wind and sun (positive), or else the amount of possible power surpluses (negative). This difference between electricity demand and consumption determines the respective flexibility requirement.

Dark and windless periods

The result of the model calculations largely depends on the weather data used. The longest period with no or only little power generation from wind and photovoltaics is decisive for the structure of the respective power supply system. Such periods are referred to as dark and windless periods. These periods are critical once their duration begins to impact the charge levels of the storage systems and the flexibility potential from demand-side management has been fully realised. In order to ensure supply security, sufficient additional power generation capacity and energy sources must therefore be kept available for the longest dark and windless period that can reasonably be assumed. This capacity may be provided in the form of coal, natural gas or biomass, as well as water in large reservoirs or gas produced with renewable energies (power-to-gas).

The results presented in this positions paper are based on the weather conditions in 2008. As that year contained two comparatively long dark and windless periods, it provides a rather challenging weather scenario. Nevertheless, we cannot exclude the occurrence of occasional, even longer periods without sun and wind. In such an event, even more stored energy would be required. Basically, however, a mix of wind power plants and photovoltaic systems helps to mitigate the impact of extreme weather events.

Residual load

The residual load is equivalent to the difference between the total power demand of all electricity consumers and the total amount of power generated from fluctuating renewable energies. It is imperative that the residual load be kept at zero at all times. This is achieved by means of flexibility technologies.

A positive residual load signifies that the feed-in from wind and photovoltaics is not sufficient to meet the demand. Here, two courses of action are possible: Either additional power is provided, for instance from flexible power plants (e.g. natural gas, coal, or bioenergy plants) or storage devices, or else consumption is reduced by switching off flexible consumers (demand-side management). A negative residual load occurs when power generation from wind and photovoltaics exceeds the demand at a certain point in time.

In this case, the excess power can be used to fill up storage systems, operate flexible consumers or convert power into other forms of energy or energy sources (for example, power-to-heat or power-to-gas). As an alternative, wind power or photovoltaic capacities could be switched off. Thus, the continuous necessity of balancing the load defines the flexibility a power system requires.

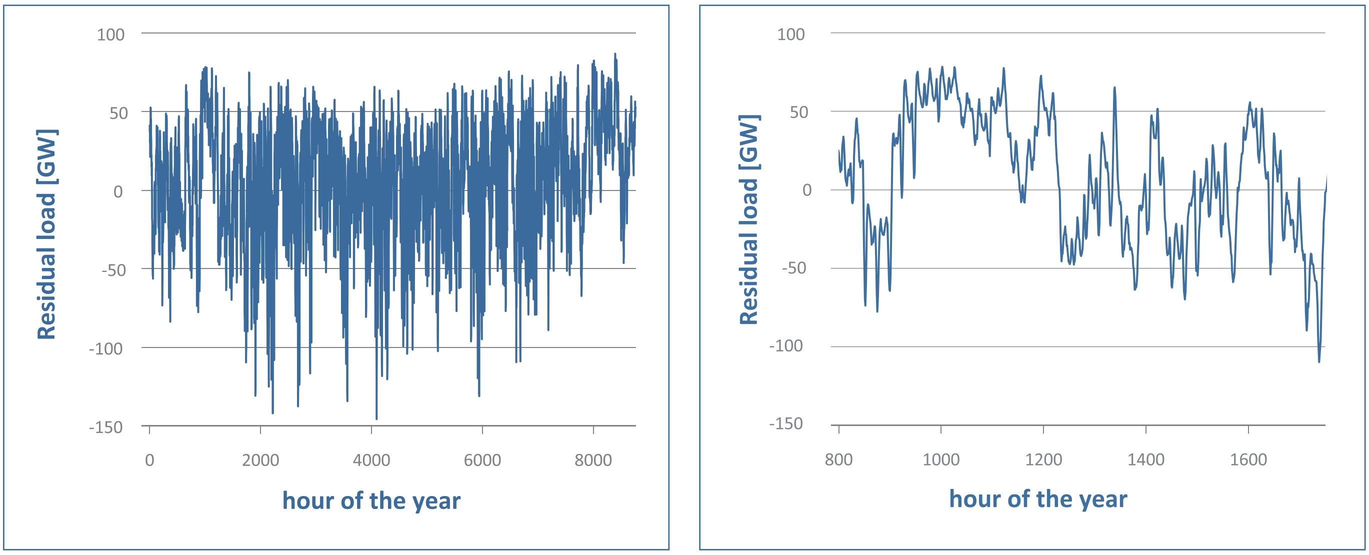

Figure 2: Residual load for scenario S6 (for definition c.f. e.g. figure 3) for the entire year (left) and for a section of that year of a little over a month (right)

Figure 2 shows the temporal curve of the residual power demand on the basis of the data from exemplary weather year 2008. The effect of prolonged weather phenomena is clearly visible: around the hours 900 to 1,200, there is a two-week period, and around hour 8,000, a three-week period featuring constantly high positive residual loads. During these times, a particularly large number of regulatable power plants (coal, gas, biogas, etc.) or long-term storage systems will have to meet the demand. This is due to a very low power supply from photovoltaic and wind power plants (dark and windless period). Such extreme situations are pivotal for the definition of the absolute amount of reliably available power required (necessary capacity) and the appropriate mix of flexibility options.

Figure 3 shows the annual fluctuating feed-in from wind and photovoltaics, as well as the residual load for each of the scenarios contemplated. In some scenarios, wind and photovoltaics meet the demand almost completely (S4, S5); in Scenario S9, the energy generated over the year even exceeds the demand. In other scenarios, however, still more than half of the electricity demand is covered by other generation technologies such as conventional power plants, geothermal plants and biomass power plants. While storage systems or demand-side management can shift a part of the electricity demand to other times, they cannot make any direct contribution to power generation. If in times of power surpluses the fluctuating feed-in is curtailed, i.e. wind and solar plants are taken offline, the required amount of additional power generation will increase.

2.3 Model calculations

On the basis of the identified residual loads, the model calculations aimed at settling two issues: They were to determine the most cost-effective mix of flexibility technologies to meet the power demand in each scenario and to establish when to employ what technologies over the course of a year. To this end, a new calculation method was developed on the following framework conditions and assumptions:

- The subject of the analysis is technologies assumed to be relevant for providing flexibility in 2050.
- The model calculations are limited to Germany; any possible flexibility provision by neighbouring countries is not taken into consideration.
- The focus is on the power sector. The heating market, the gas market and electric mobility will only be considered in terms of their potential for providing flexibility or utilising power surpluses (negative residual load).

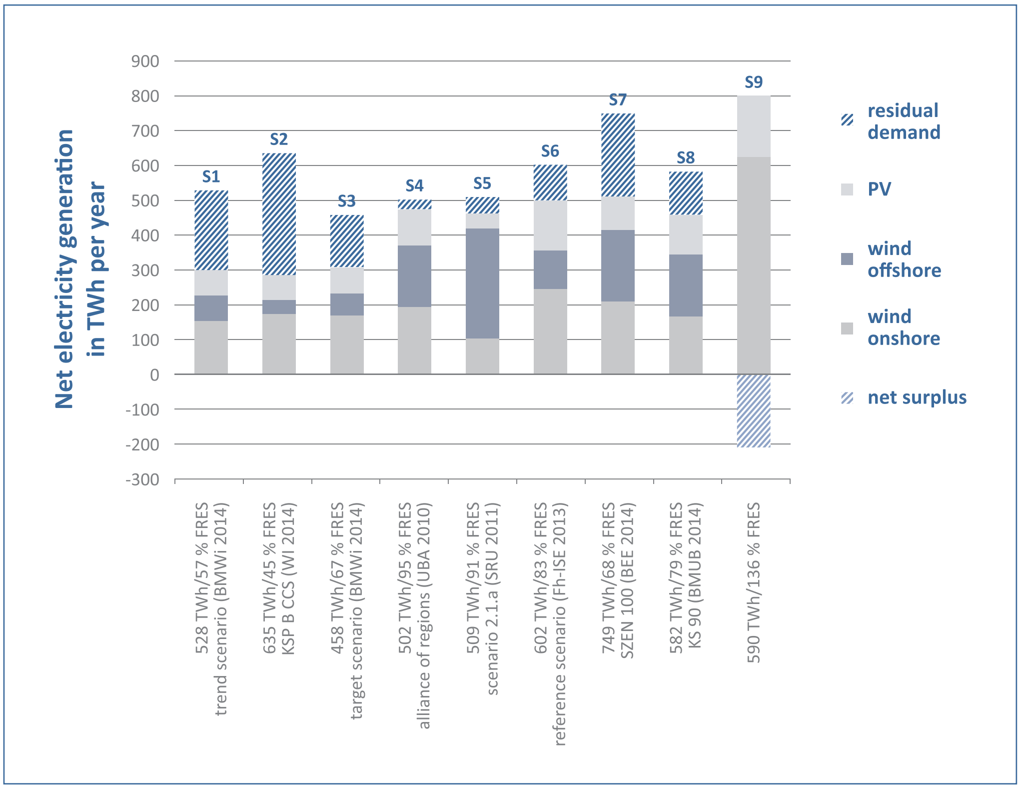

Figure 3: Net electricity generation from wind and photovoltaics in the nine scenarios selected. The percentages of wind and photovoltaics ascribed to each scenario are based on the net electricity demand[18] and represent maximum shares, assuming no curtailment of fluctuating generation takes place.

- The design of the technology portfolio is based on economic considerations: Power generation costs are minimised with regard to the investment and operating costs of the plants. Management interests or specific market models are not considered.
- The analysis is structured in reference to the base year. For methodological reasons it is assumed that all plants are newly built in 2050 ("greenfield" approach). Therefore, the analysis does not trace the development of the plant portfolio from the current status up to the year 2050. For the sake of simplification, it is assumed that a completely new portfolio of power plants will be built. The grid infrastructure, on the other hand, is assumed to be uniformly and perfectly developed ("copper plate").
- The calculations are based on data from weather year 2008. That year provides a rather challenging basis with regard to the provision of energy from fluctuating renewable energy sources (due to e.g. long dark and windless periods).
- The entire year will be split into hourly values, allowing the identification and use of only those storage systems that still contain sufficient energy from previous charging phases.
- The share of wind and photovoltaics is predetermined by the scenarios. The economically optimal share of wind and photovoltaics was not calculated; however, the costs of wind and photovoltaic power plants are considered according to their respective development status. In other words, only the portfolio of flexible technologies is optimised, not the entire power supply system. In return, the comparison of several scenarios allows for the inclusion of a wide range of possible development scenarios for wind power and photovoltaics.

18 Unlike the gross electricity demand, the net electricity demand includes neither the power required to run the plant nor the occurring transmission losses. This accounts for certain divergences from the data in the underlying studies.

- The data for fuel prices and emissions allowance costs for 2050 are taken from the German Federal Government's 2014 energy reference prognosis[19].
- All calculations are carried out on the 2014 price level without taking into account the effects of inflation.

The model calculations yield the following results: the installed capacity[20] required for all flexibility technologies, the annual power generation of each technology, the annual carbon emissions of the electricity sector and the total cost of the power system (excluding grid costs). This data, in turn, was used to compute the electricity generation costs in the various differently-designed power systems (generation and flexibility technologies). As a macro-economic approach was chosen, these costs do not include taxes, levies or concession fees.

The scope of application of this calculation method being limited, it does not show all operational optimisation potential. Naturally, inaccuracies occur. However, with a view to the aim of this study – i.e. the comparison of differently designed power generation systems – these inaccuracies are considered to be of little significance. Moreover, as the assumptions underlying the scenarios reach 35 years into the future, they are, in any case, subject to high uncertainties.

Nevertheless, the findings from this study can support policy decisions – the advantage of this calculation method being that a wide sensitivity analysis allows for the consideration of a variety of technical and social factors. Thus, a large scope of possibilities can be covered.

The calculation takes only a few minutes on a standard PC. The ad hoc working group took advantage of this in order to calculate numerous variants for each scenario. Based on the interdisciplinary reviews of the expert groups, various framework conditions were determined for the design of the flexibility portfolio. These basic conditions show a range of characteristic paths the development of the power system could take. They include:

- high and low carbon saving levels
- the greatest reasonably assumable cost reduction for CSP, geothermal energy, photovoltaics and wind power
- a system with and without energy imports
- a system with and without CCS
- 100 per cent renewable energy
- a system with solely decentralised generation plants and reduced grid expansion[21]

All in all, some 140 possible designs for a future power supply system ("system variants") were calculated. They are presumed to realistically cover the range of possible developments of the power supply. Thus, many possible power system configurations can be outlined and compared. Also, the influence of different framework conditions such as political decisions for or against specific technologies can be analysed.

A system variant based on the wind and photovoltaic shares and the electricity demand figuring in the federal government's target scenario serves as reference scenario. It appears in chapter 4 as a benchmark for various configurations of the power system.

19 BMWi 2014-1; for instance, the prognosis assumes a gas price of 33.1 euros per megawatt hour (thermally, i.e. referring to the heat energy contained) and a carbon allowance price of 76 euros per tonne.

20 The installed capacity indicates the plants' maximum output. Because the operation of the system is dynamic, the maximum output is only achieved at certain times.

21 A complete list of the model calculations can be found in the analysis "Flexibility concepts for a sustainable power supply in 2050" (Elsner et al. 2015).

The reference scenario (based on the federal government's 2014 target scenario[22])

The energy reference forecast drawn up for the Federal Ministry for Economic Affairs and Energy contains a target scenario aimed at the fulfilment of the German climate protection goals. It identifies the interim results required to meet the targets of the federal government's energy concept. The concept assumes that with the consistent implementation of efficiency measures, an incremental reduction in gross electricity consumption can be achieved: from 553 TWh in 2020 to 509 terawatt hours by 2030, and eventually 475 terawatt hours by 2050. However, new fields of application for electricity such as electric mobility or heat generation with electric heat pumps somewhat counteract the reduction in power demand. A possible production of gas and chemical upstream products with electricity, which would further increase the power demand, was not taken into account in the target scenario. At the same time, the share of renewables[23] in gross electricity consumption[24] increases from 46 per cent in 2020 to above 62 per cent in 2030, to an eventual 79 per cent in 2050.

For the purposes of this position paper, a power system featuring the renewable share (67 per cent) and the net electricity demand (458 terawatt hours in 2050) from the German Federal Government's target scenario is used as reference scenario. The respective flexibility portfolio is calculated by means of the method used for all variants. With a view to the risks their implementation might cause, the reference scenario excludes both the lignite CCS technologies and solar thermal power generation; it also stipulates a carbon reduction target of 90 per cent compared to the 1990 level. The resulting flexibility portfolio is shown in figure 6.

22 BMWi 2014-1.

23 Including not only wind and photovoltaics, but also other renewable energies such as biomass.

24 Unlike the net electricity demand, the gross electricity demand includes both the power required to run the plants and the occurring transmission losses.

3 The power supply in 2050

From the scenarios, we can derive some basic features of the 2050-power supply system. This chapter presents the available flexibility technologies, including the framework conditions relevant for the model calculations and the requirements from research and development. Besides the technological development, public acceptance plays an important role in their implementation.

In order to actually realise the potential of a flexible power system in 2050, significant research and development progress is still necessary in some areas.

3.1 Flexibility technologies – an overview

The power supply system in 2050 will consist of a mix of fluctuating generators and flexibility technologies. A combination of these two technology groups must ensure the balance between generation and consumption necessary for the safe operation of the electricity grid at all times.

Flexibility technologies are defined as units able to perform one of the following on demand: increase or decrease the feed-in of electricity (flexible power generators), postpone the electricity demand to a later period in time (flexible loads) or shift surpluses for use in other times (storage). Electricity grids are capable of balancing loads across spatial distance and can therefore complement the aforementioned technologies. In order to keep the analysis manageable, the technology portfolio was restricted to the most important technologies (cf. figure 3).[25]

25 For a detailed description of each technology and of the assumptions the model calculation are based upon cf. the analysis by Elsner et al. as well as the technology fact sheets drawn up by expert groups (available for download at http://www.acatech.de/flexibilitaetskonzepte-2050).

Fluctuating Renewables[1)]	Flexible Producers	Storage Systems Flexible Loads	Grids[14)]
wind onshore, offshore	**biomass** gas turbines und CCGT-plants[2)], wood-fired power plants	**storage** hydrogen[7)], methane (GT), methane (CCGT), compressed air[8)], pumped storage, battery[9)]	
PV	**solar thermal energy**[3)]	**DSM in the energy market**[10)] household sector, commerce, trade and services, industry	
	geothermal energy[4)]	**DSM in the heat market** thermal storage systems[11)]	
	conventional power plants bituminous coal, lignite[5)], lignite with CCS, gas turbine, CCGT, motor, industrial CHP[6)]	**power-to-X** power-to-heat[12)], power-to-gas[13)]	

Figure 4: Technology portfolio figuring in the model calculations[26]

1) The amounts of energy generated are determined by the scenarios. For photovoltaic systems, a mix of rooftop and open space installations was assumed.

2) Powered with biomethane fed into the natural gas grid; this assumption was made to simplify the model and is not intended to exclude other technologies for biomass power generation. The potential is not assumed to exceed double the biomass currently used for power generation.

3) Solar thermal power plant sited in Morocco; optionally equipped with thermal storage and an additional combustion unit for natural gas.

4) Enhanced Geothermal Systems (Hot-Dry-Rock-Method), cf. geothermal power generation; the assumed potential reaches a maximum of 30 GW installed electrical capacity.

5) The amount of the possible lignite mining was limited to the present level.

6) Only systems with a steady heat demand over the year were considered (potential: 2.4 GW installed electric capacity).

7) In the case of hydrogen storage systems, only gas turbines were considered as a means of reconversion. In principle, fuel cells could likewise be used. Should, for instance, a mass market for fuel cells emerge in the automotive sector resulting in massive cost reductions and a longer life time for fuel cells, they might eventually come cheaper than gas turbine systems, especially in the case of plants with lower load factors.

8) Adiabatic CAES (compressed air energy storage with integrated heat recovery)

9) This does not refer to any specific battery technology; rather, a generic type is used, summarising potential developments by 2050.

10) Assumed overall potential for positive balancing energy, i.e. power supply: household sector (including the use of PV-battery systems and electric vehicle batteries): 65 GW; commerce, trade and services: 1 GW; industry: 3.4 GW.

11) Only systems with a steady heat demand over the year were considered, mostly hot water systems.

12) Heat generation by electrode boilers for steady heat loads (base load) throughout the year in the fields of district heating and industry (assumed potential: 9 GW electric power); the credits for costs and carbon emissions coming with the heat generated reflect the costs and emissions avoided by not using natural gas.

13) Synthetic methane produced by electrolysis and methanation; the credits for costs and carbon emissions coming with the methane generated reflect the costs and emissions avoided by not using natural gas.

14) High-voltage DC transmission (considered in the context of power transport from CSP plants and of transmission grids for regional interconnection)

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26 The provision of electricity from run-of-river-power is, in principle, also subject to fluctuations, but to a far smaller degree than in the case of wind and PV. While its current installed capacity is roughly taken into account for the estimation of the residual load, it is not included in the proportion of fluctuating renewables. The costs of run-of-river-power are neglected. Since the amount of energy from run-of-river-plants is about the same in all scenarios, this does not distort the cost comparison between the different variants of the power system we present in this paper.

Technology	Research and development requirements
photovoltaics	• cheaper production methods • increased efficiency • development and innovation, e.g. by using new materials • intelligent systems solutions, for instance, highly integrated inverter battery systems
wind power	• modelling of wind conditions and effects of aerodynamic phenomena on the wind turbine • increasing grid-stabilising properties (short-term predictions, voltage and frequency stability) to improve system integration • new materials and supporting structures / anchors • more economic manufacturing processes • ecological impacts of offshore wind power
biomass	• conversion technologies, e.g. gasification of solid fuels • making generation plants more flexible • technologies to utilise biogenic residues and by-products • quantifying the potential
solar thermal energy	• increasing process temperature by more powerfully concentrating collector systems (increasing efficiency) • alternative heat carrier fluids and storage systems for the application range from 600 to 1,200 ° C to increase efficiency and reduce the volume of storage devices • integration of high-temperature circuits (e.g. gas turbines) • more economic high-temperature heat storage materials
geothermal energy	• cost-efficient, minimally invasive techniques for exploratory drilling • technical components for a hot, corrosive environment • optimising the methods for deliberate creation of hydraulic fissures • long-term studies on the usability of drillings
conventional power plants	• dynamic simulation of power plants for a better quantification of the impacts of flexible operation modes • integration of storage systems into the power plant process to improve flexibility • further development of Carbon Capture and Usage (CCU) and coal gasification • materials adapted to a flexible mode of operation
storage systems	• improvements or fundamental innovations of processes, materials, electrolytes and system components • cost-effective, innovative materials and manufacturing processes reusing and avoiding rare elements • increasing efficiency and operational safety • optimising the integration into the overall energy system
DSM electricity	• economic models for the analysis of the entire energy value chain • technical requirements for hardware and software DSM components • design of equipment and processes according to DSM requirements; standardisation, development and testing of intelligent methods to control and regulate the interaction of a large number of decentralised units in the power system • systematic field studies on the active acceptance of DSM on the basis of large samples, in particular in the fields of electric mobility and PV storage devices
DSM heat	• coupling the heat and electricity markets • tariff models effectively encouraging the use of flexibility potential • intelligent regulatory concepts considering ancillary services for balancing the electricity grid • further optimisation of hybrid systems, e.g. hybrid heat pumps operable with electricity and / or natural gas
power-to-X	• reduction in investment costs • technologies for the electrical generation of high-temperature heat (power-to-heat) in the industrial sector • electrical production of syngases as raw materials for the chemical industry
grids	• intermeshed operation of DC grids and DC and AC hybrid grids • methods for the automation of grids across several voltage levels, including the provision of ancillary services from the distribution grid • technological innovations in the field of power electronics equipment and transmission technologies • cost-effective measures to minimise field exposure, as stated in the German Federal Emmission Control Act

Table 1: Research and development requirements for flexibility technologies

3.2 Acceptance of specific flexibility technologies

After the phase-out of nuclear energy, public attention is now focussed on protests against certain technological and infrastructural features related to the energy transition.

According to surveys and scientific studies, the majority of the Germany public agrees with the Federal Government's environmental and climate protection targets, as well as with the decision to phase out nuclear energy. Of all energy technologies, renewable energy plants meet with the greatest public approval. Amongst the various RE technologies, however, biogas plants are regarded as significantly more critical than solar and wind power plants.[27] The majority of respondents prefer small, decentralised power plants to large and more centralised systems.[28]

The attitude toward coal as an energy source is largely negative: barely a quarter of the population supports its use in Germany. The use of conventional natural gas, on the other hand, meets with the approval of around half of the population.[29] There is enormous scepticism toward large-scale technologies such as CCS.[30] Electricity grids and storage systems are regarded with a wary eye, particularly where it is feared that they are built to transport and store energy from coal power plants rather than from renewable energy plants.[31]

It is becoming clear in current debates, e.g. about the construction of the power line SuedLink[32], that it is difficult to introduce new technologies against resistance from within the population. In order to assess the chances of the implementation of specific technologies, we consulted surveys[33] on their respective likelihood of acceptance. Certain technologies classified as critical were excluded from most model calculations[34], but were admitted as possible options in selected variants, allowing for an estimate of their impact.

There is usually a comparatively high level of **passive acceptance** for locally employed flexibility technologies such as electric mobility, photovoltaics or demand-side management. In other words, in principle their use is supported.[35] However, the flexibility contribution they can make largely depends on **active acceptance**.[36] This reaches well beyond tolerance and refers to the willingness to actively use a technology and, as the case may be, even to actually buy it. The problem is that there is hardly any empirical data to suggest whether citizens would actually permit the "outside" control of their electric devices in a system of demand-side management. Knowledge in the field of social acceptability needs to be expanded by further scientific studies.

3.3 Characteristics of the future power system

The residual loads computed for the individual scenarios can be represented as a load duration curve for the year 2050 (Figure 5).

The load duration curve shows the number of hours during which the residual load is positive or negative over the course of a year. The x-intersect (0-

27 AEE 2012.

28 Ohlhorst 2009; Wüste 2012.

29 IEK-STE 2014.

30 Pietzner/Schuhmann 2012.

31 Hübner/Hahn 2013; Bruns et al. 2012.

32 Cf. e.g. Balser 2015.

33 E.g. Hübner et al. 2012; TNS 2012; TNS 2013.

34 However, studies on the acceptability of overall systems, including the entire technology portfolio as well as questions of power generation, storage, grids and DSM are, as yet, pending.

35 Demski et al. 2013; TNS 2012.

36 Dethloff 2004.

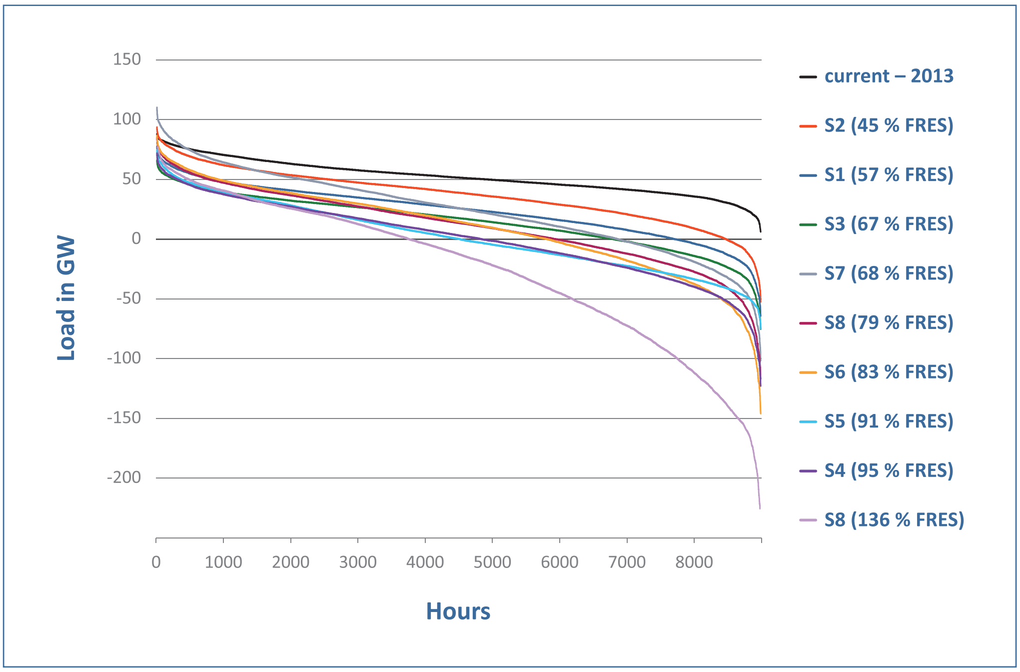


Figure 5: Load duration curve of the residual load for 2050

line) indicates the number of hours per annum, in which power demand exceeds the feed-in from fluctuating renewables. Starting from the current load duration curve (current state 2013, black line), the line drops as the fluctuating feed-in increases. This means that the number of hours with positive residual load decreases, i.e. there are steadily fewer hours per year in which wind and photovoltaics cannot meet the assumed power demand; at the same time, the potential for the use of power surpluses increases. Thus, in the scenarios assuming that wind and photovoltaics cover around 90 per cent of power consumption, additional electricity generation is required in only about 50 per cent of the hours per annum; in the remaining time, a power surplus is generated.

Accordingly, the annual operating hours for power plants decreases with the increase in fluctuating feed-in. None of the scenarios contemplated requires continuously running power plants[37]. Further analyses also show that a significant increase in the load gradient (the rate of change of the load) is to be expected. Consequently, if a high proportion of renewables is the aim, the generation portfolio in 2050 will have to be much more flexible than it is at present in order to ensure system stability.

37 Plant downtimes for maintenance purposes were not considered.

4 Design options for the power system in 2050

The following chapter is dedicated to the examination of selected energy policy issues on the basis of the results we achieved. After a brief introduction to each question, different options for solutions are presented (wherever possible), followed by a description of their respective consequences.

4.1 How do the emissions reduction targets affect flexibility requirements?

The federal government aims to reduce carbon emissions by at least 80 per cent by 2050. Many current energy scenarios assume that it is easier or at least quicker to decarbonise the electricity sector than the heat or transportation sector, let alone industry.[38] For that reason, we have contrasted a power system with an emissions reduction of 80 per cent with system variants aiming at a disproportionate reduction in greenhouse gas emissions in the power sector (90 and 100 per cent). The effects are reflected both in the structure of the power plant portfolio and in the resulting power generation costs. Figure 6 shows an example of how carbon reduction targets and the structure of the power plant portfolio are connected.

1) Carbon reduction target of 80 per cent

In order to ensure a flexible power system with 80 per cent carbon reduction, natural gas power plants are a viable option. Natural gas power plants account for more than four fifths of the installed flexibility power in the portfolio of flexibility options. The use of conventional lignite power plants is also still possible with this emissions reduction target (cf. system variant S3 with lignite in figure 6). Usually, the reduction in excess wind and photovoltaic power combined with additional power generation from natural gas is economically more cost-efficient than the storage of electricity surpluses. For this reason, long-term storage systems are rarely used in scenarios with a residual emissions rate of 20 per cent.

2) Carbon reduction target of 90 per cent

This ambitious reduction target can be achieved with several differently designed power systems: In the reference scenario, where two thirds of the energy demand is covered by wind and photovoltaics, bioenergy replaces the flexible lignite power generation (system variant S3 with bioenergy – reference scenario in figure 6). Alternatively, lignite power plants could be equipped with CCS technology units (system variant S3 lignite CCS). In this case, the use of natural gas in combined-cycle power plants (CCGT) likewise decreases. This is illustrated in figure 7, which shows the installed capacities for each technology as well as the amount of electricity it provides.

With higher proportions of wind and photovoltaics, long-term storage devices such as hydrogen storage systems play an important role, as under these conditions they are less expensive than a combination of flexible generation facilities and the reduction of excess power (cf. S4 FRES and storage systems in figure 6). This is due to the fact that with a high

38 SRU 2011.

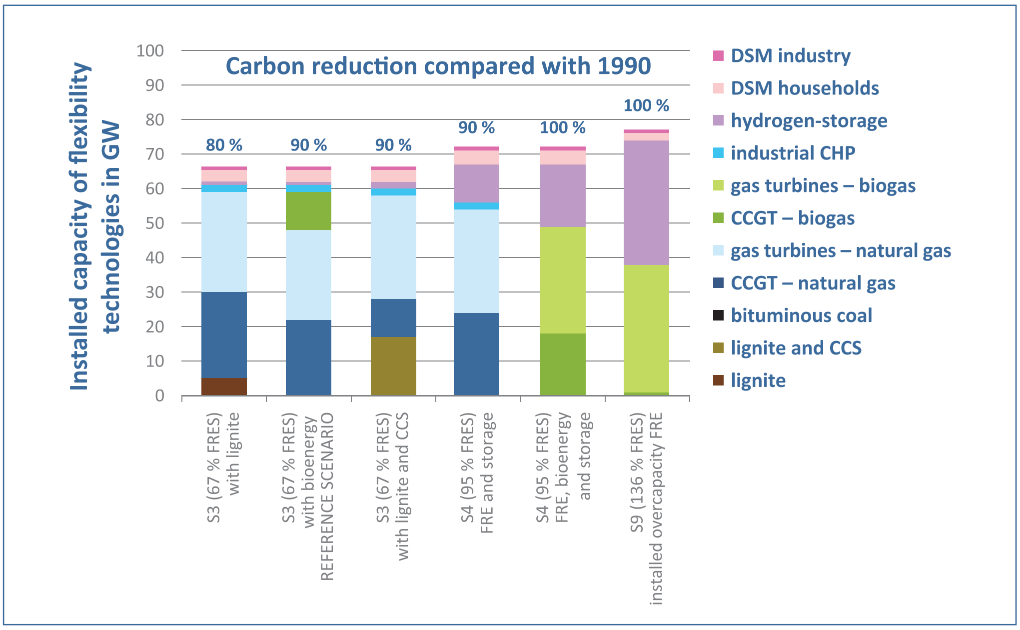


Figure 6: Design examples of power systems (without PV- and wind turbine-outputs) with emissions reduction targets of 80 per cent, 90 per cent and 100 per cent, respectively. Behind the scenario number, the respective proportions of uncurtailed feed-in of fluctuating renewables (FRES) and the main characteristics are indicated. The differences in the total installed capacity are due to the varying power requirements in the different scenarios.

Gas turbine and combined-cycle gas turbine power plants

Gas turbine (GT) and combined-cycle gas turbine (CCGT) power plants have significantly lower investment costs and carbon emissions than bituminous coal or lignite power plants. The possible fuels, however – natural gas, methane, biogas, hydrogen – are considerably more expensive than various types of coal. Hence, GT and CCGT power plants are used wherever utilisation is low or when the use of coal-fired plants is partly or totally impossible for reasons of emissions reduction.

Experts estimate that in 2050, GT and CCGT power plants will be able to reach efficiency rates of 45 and over 60 per cent, respectively. The higher efficiency of CCGT plants results from a combination of gas and steam turbines, which, however, also entails higher investment. Accordingly, GT power plants are used when very low load factors are expected, whereas CCGT plants are used when a higher number of full load hours is required.

As the basic mechanism of the power plants does not vary in terms of essentials for different fuels, they can be used very flexibly. GT power plants, in particular, can be ramped up very quickly.

proportion of fluctuating feed-in, flexible generation plants would only operate at a low utilisation rate. At the same time, the power surpluses generated in times of strong wind and solar radiation amply secure a sufficient utilisation of long-term storage systems.

A common point of all power systems with an emissions reduction of 80 or 90 per cent is the extensive use of natural gas power plants: About 90 per cent of the maximum residual load can be covered by gas turbines and combined-cycle plants. In total, however, these plants only contribute 15 to 35 per cent to the total energy provision (cf. figure 7). In other words, the plant's main objective is to reliably secure the power supply, rather than to regularly provide energy on a large scale.

3) Reduction target of 100 per cent

For the reasons mentioned above, long-term storage systems play a central role in a completely emissions-free power sector. Significantly more hydrogen storage devices are required than for less ambitious reduction targets (cf. S4 FRES, bioenergy and storage in figure 6).[39] Biomethane, in turn, replaces natural gas as fuel for gas power plants and combined-cycle power plants. The installed capacity amounts to about 50 gigawatts, which equals around 70 per cent of the total installed capacity of flexibility technologies. However, the amount of electricity actually provided by bioenergy is a comparatively moderate 65 TWh (about 15 per cent of the electricity demand) (cf. figure 6). Nevertheless, the use of biogas is projected to be about twice as high as today. Whether biomass should be used to that extent for the power sector would have to be determined on the basis of a national biomass strategy and taking the regional and global consequences into account.

The extreme case of a system generating more power with wind and photovoltaic plants than is altogether required (S9 with installed FRES -overcapacity) is shown in figures 5 and 6. In such a scenario, combined-cycle power plants with biogas combustion are only rarely employed, as utilisation rates are low and the ensuing costs high. Instead, around 35 gigawatts worth of gas turbines are required in each case for biogas combustion and for hydrogen. The output of around 15 terawatt

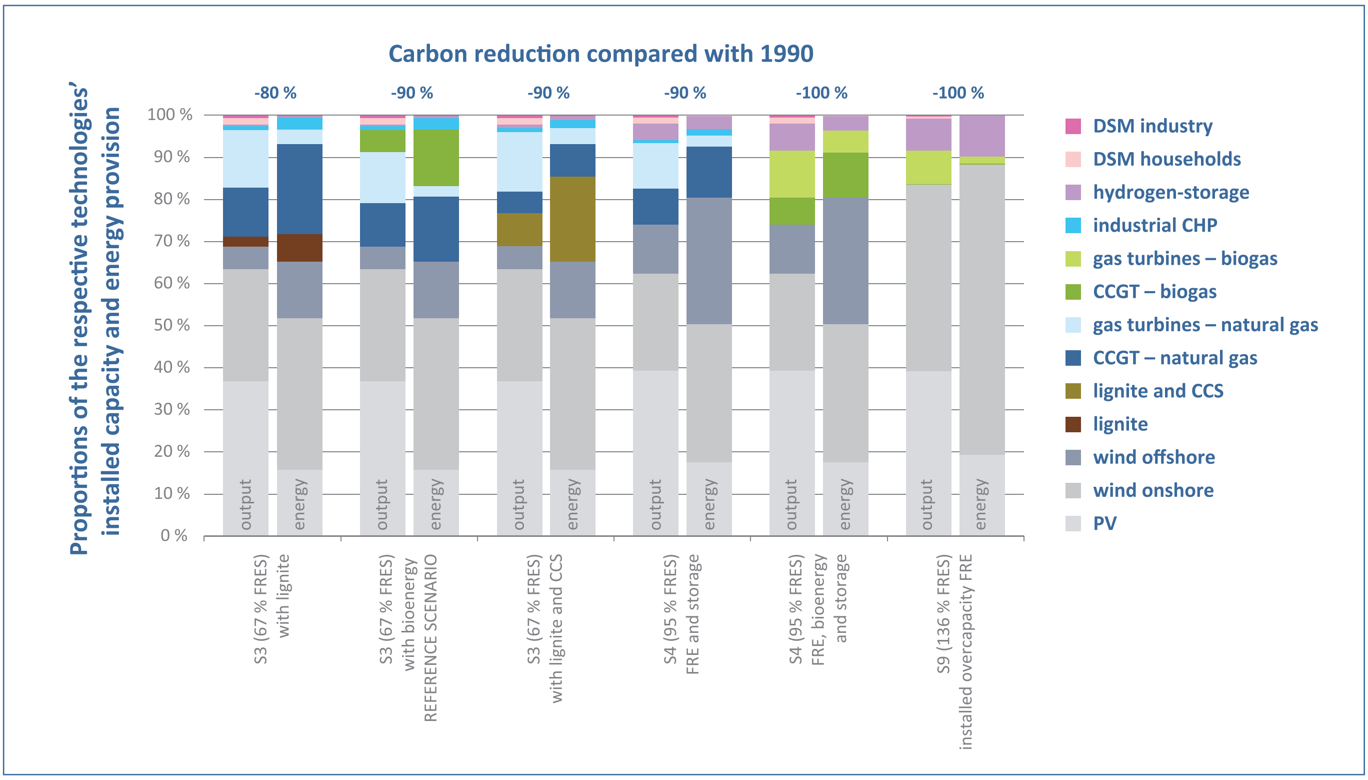


Figure 7: Exemplary distribution of the installed capacity and electricity generation shares in the technology portfolio (including FRES) assuming emissions reduction targets of 80, 90 and 100 per cent. Every constellation is exemplified by one scenario, the basic conditions of which are specified; the output shares are shown in reference to the installed peak power, the energy shares in reference to the total energy supply of the portfolio.

39 Further possible variants of an emissions-free power system are described in section 4.2.

Frozen Scenario

The *Frozen Scenario* takes the power plant portfolio in the BMWi-trend scenario (2014) forecasts for 2025 and "freezes" it for use in the period beyond that time. In other words, it designs the case that the power supply system remains unchanged after the nuclear phase-out in 2023 and does not undergo any further transformations.

For the sake of comparability, this power generation portfolio was evaluated on the basis of the costs assumed for the year 2050. This implies electricity generation costs in the amount of 67 euros per megawatt hour[40], excluding costs for emissions certificates. If emissions certificate costs of 76 euros per tonne of CO_2 are included, the power generation costs rise to 96 euros per megawatt hour. In the Frozen Scenario, the generation of one megawatt hour of electricity produces 0.380 tonnes of carbon emissions. This is a reduction of about 50 per cent compared to 1990.

hours of electricity from biomass amounts to only about a third of the power currently generated from biomass. In short, this scenario achieves not only independence from energy imports of all kinds, but also a very low use of biomass, reducing carbon emissions in the energy sector to zero.

Figure 8 allows for a comparison between the Frozen Scenario and the different power systems regarding the respective relation of additional costs and carbon savings. Costs are presented without emissions certificate costs, as well as with emissions certificate costs of 76 euros per tonne of CO_2.

It becomes clear that, assuming an emissions allowance price of 76 euros per tonne, a complete decarbonisation of the electricity sector is in almost all cases more cost-efficient than maintaining the power generation portfolio of 2025. Even the installation of an overcapacity of wind and photovoltaics, which would make the electricity sector independent of imported energy while requiring very little use of bio-energy, could then be effected without any additional costs compared to the Frozen Scenario.

This is due to the fact that, under the cost assumptions made for 2050, fluctuating renewable energy sources can provide power at comparatively low costs and emissions. At the same time, the high expenses for emission allowances increase the costs of a system with low carbon savings as assumed in the Frozen Scenario. An emissions reduction by 90 per cent compared to 1990 hardly entails any additional costs compared with 50 per cent compared to 1990. A further reduction from 90 to 100 per cent will, in most system variants, increase costs by 10 or 15 euros per megawatt hour. The absolute electricity generation costs are, however, still below those of the Frozen Scenario.[41] Additional relevant costs will only arise in systems with low shares of wind and photovoltaics, where more expensive generation technologies such as geothermal energy are used.

40 This is about twice the current price at the energy exchange in Germany. The difference results from the fact that current trading only partly reflects the investment costs: Basically, the trade price for power only covers the operating and fuel costs (i.e. the so-called short run marginal costs). Since new investments cannot be refinanced (the long-run marginal costs are not covered), the current price level is insufficient as far as maintaining a stable energy supply in the long-term is concerned.

41 Disruptive developments in the field of fossil fuels (e.g. a greater price increase than expected) that do, indeed, appear possible, were not considered. Such developments would further increase costs in the Frozen Scenario.

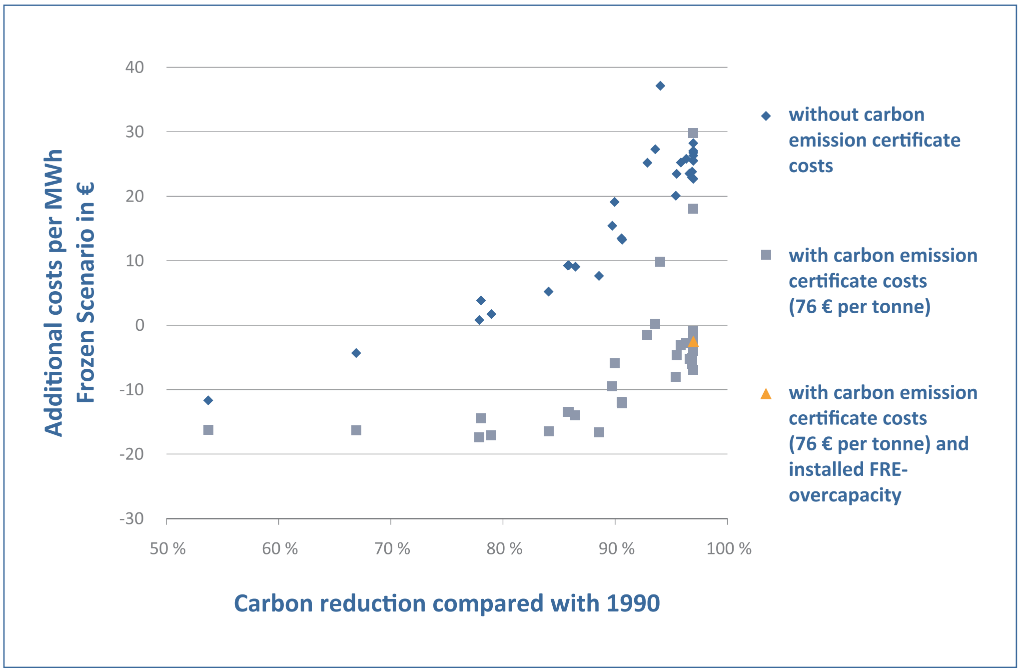


Figure 8: Additional costs per megawatt hour compared to the Frozen Scenario for different carbon reduction levels and, respectively, with and without consideration of emission certificate costs

Conclusion

The model calculations suggest that an early definition of the long-term emissions reduction target for the power sector is vital if we wish to avoid investing in the wrong technologies. It shows that gas turbine technology in all of its system variants is being used to a great extent. It is true that, independent of the carbon reduction target, the installed capacities of gas plants and combined-cycle plants equal a relatively similar level in the different scenarios. However, the carbon reduction targets and the share of fluctuating renewable energy sources determine whether the plants in question are powered by natural gas, biogas or hydrogen. Consequently, if in the near future we are successful in designing new gas power plants that can be flexibly operated with natural gas, biogas and hydrogen, robust development paths toward a carbon-free power supply system open up. This enables a successive transition to low-carbon fuels in step with continuously more ambitious carbon reduction targets. Eventually, this could allow for mixtures with higher hydrogen concentrations or even the use of virtually pure hydrogen.

A fully decarbonised power system could, for instance, be achieved by means of a functioning emissions trading system. For with a price of 76 euros per tonne of CO_2, it is cheaper to reduce carbon emissions in the power sector to zero than to maintain the power plant portfolio of 2025 (Frozen Scenario). Without resorting to emissions allowances, carbon emissions cannot be reduced by more than 80 per cent compared to the 1990 level without incurring additional costs compared to the Frozen Scenario.

4.2 Possible features of a power supply system with 100 per cent renewables

An emission-free power supply can only be achieved if it is based entirely on renewable energy sources (e.g. photovoltaics, wind, biogas, geothermal and solar energy).[42] In all scenarios contemplated here, the power is largely generated by wind and photovoltaic systems.

42 Theoretically, carbon-free power generation is possible with the use of CCS. However, concerning the residual emissions that usually accrue on the order of about ten per cent, this case was not considered here.

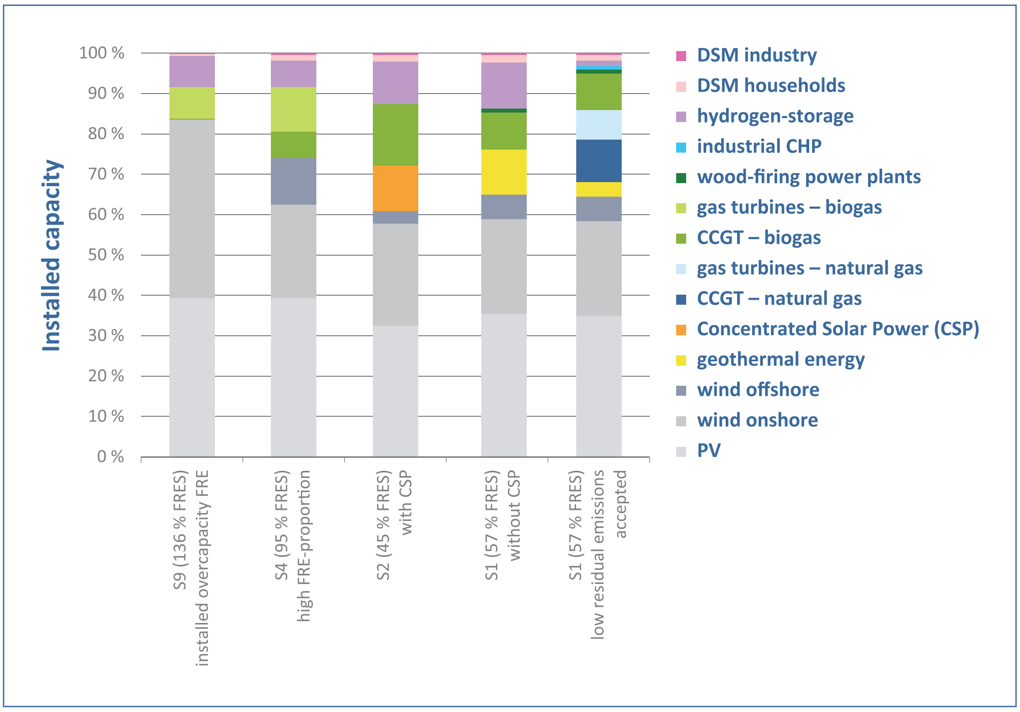


Figure 9: Technology portfolios for possible power systems with 100 per cent emissions reduction or very low residual emissions (about four per cent)

Since this type of energy generation is subject to fluctuations, it cannot by itself ensure a full supply of electricity at all times. It must therefore be complemented with flexibility technologies such as storage systems or demand-side management and dispatchable energy technologies like biogas plants or solar thermal power plants with integrated heat storage.

In a first step, we will first be considering four design options for a completely carbon-free power system. This is followed by a fifth option, exemplifying a power system where a low level of residual emissions persists. Figure 9 shows examples of possible technology portfolios for the five respective power systems.

1) Zero carbon emissions with installed overcapacity of fluctuating renewables

It turns out that long-term flexibility requirements can be completely met with gas turbines fuelled by biogas and hydrogen from long-term storage systems. Such a power system design requires around 70 gigawatts worth of installed gas turbine capacity. Their output amounts to about 90 terawatt hours of electricity from hydrogen in long-term storage systems and a good 15 terawatt hours from biomass. Consequently, in this variant of the power system, the biogas consumption is significantly lower than today[43], amounting to only about 40 terawatt hours (thermal) per annum. Due to the high energy surpluses from fluctuating wind and photovoltaics, the load factor of the hydrogen storage devices is significantly (between 150 and 200 per cent) higher than in systems with less than 100 per cent FRES.

2) Zero carbon emissions with more than 80 per cent of fluctuating renewables

In an emissions-free power system with wind and photovoltaic shares of more than 80 percent, the remaining electricity demand can be met with bioenergy. This would require approximately 200 terawatt hours (thermal) worth of biogas, about twice the current amount. Such a system would largely rely on generation

43 Current consumption is an estimated 100 terawatt hours (thermal).

Solar thermal electricity (Concentrated Solar Power, CSP)

Solar thermal plants concentrate solar rays by means of lenses or mirrors to generate high temperature heat. This heat energy is then converted into electrical energy by the means of steam turbines. Thermal storage units upstream from the steam generation process allow for the decoupling of solar radiation and power generation. This is a significant advantage of CSP systems: They are able to provide flexibility and are therefore not counted among the fluctuating renewable power producers.

Since only direct sunlight can be focused, an adequate generation site requires a high average of cloudless sunshine hours per annum. Therefore, this position paper assumes that such plants would have to be built in European and African countries on the Mediterranean. The power could be transferred to Germany through high-voltage direct current transmission grids. The costs of such additional grids have been considered in the electricity generation costs.

technologies already established today (wind and photovoltaics), complemented by hydrogen storage devices with an installed capacity of about 20 gigawatts.[44] This technology is likewise already being tested in demonstration plants. Several issues in the field of gas, i.e. gas storage, the development of gas production and its large-scale use still require significant research and development efforts.

Should the amount of available biomass not suffice for its use in the power sector, the use of long-term storage systems could be extended, storing more surpluses from wind and photovoltaics. In the power system illustrated in figure 9 (FRES-share above 80 per cent), almost ten per cent of the power from wind and photovoltaics is curtailed. More long-term storage devices would, however, increase the costs of power generation.

3) Zero carbon emissions with CSP and a small share of fluctuating renewables

If only half of the necessary electricity were generated by wind and photovoltaics, the picture becomes somewhat different. In this case, the supply gap could be filled primarily with electricity from solar thermal plants (Concentrated Solar Power, or CSP) in the Mediterranean. Since solar thermal energy can be stored as heat, it is both calculable and flexible. In the case presented, the required installed capacity of solar thermal plants lies somewhere between 10 and 30 gigawatts.

Increasing proportions of wind and photovoltaics would induce a corresponding reduction in the output of the solar thermal plants. This would, however, entail higher electricity generation costs because solar thermal plants can be operated more viably as base load plants than with low utilisation rates.

Whether and to what extent an extensive importation of solar thermal power from abroad could actually be realised is, however, uncertain. A precondition is that the countries generating the power as well as the states affected by the transit create the political and legal conditions necessary for the safe transmission of electricity. It also remains to be clarified whether and how the transport can be cost-efficiently organised via the European transmission grid the EU is considering. The feasibility of this option thus largely depends on certain conditions, i.e. the public acceptance of grid expansion

44 This refers to the discharging capacity (installed capacity of gas turbines) of hydrogen storage units. In this case, the charging capacity (electrolyser capacity) is about twice as high.

and the development of a single European energy market or, indeed, the inclusion of the North African region into such a market.

4) Zero carbon emissions without CSP and with a small proportion of fluctuating renewables

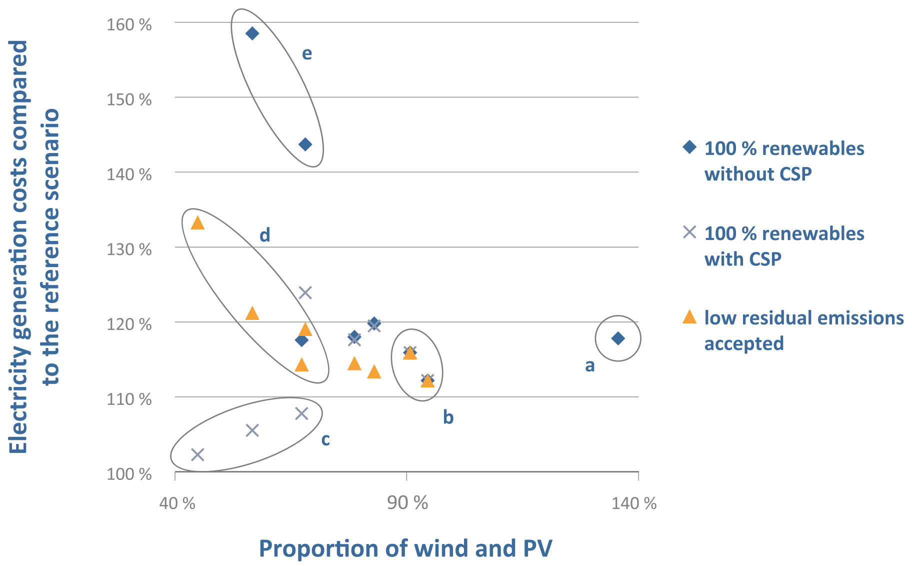
If wind and photovoltaics account for around 50 per cent of electricity generation and solar thermal energy is not available, the remainder can – as far as we know today – only be covered by electricity from geothermal energy. Since the latter is significantly more expensive than power from biogas and solar thermal sources, this would increase electricity generation costs by about 50 per cent compared to a system with CSP. Nevertheless, in this variant there would be no need to resort to the import of energy or energy sources.

5) A low level of residual emissions with less than 50 per cent of fluctuating renewables

If we accept a low level of residual emissions from the power system – about four per cent compared to 1990 – and assume a share of fluctuating energies under 50 per cent, natural gas and geothermal power plants would have to make up the difference.[45] This would lead to a considerable cost reduction, as the gas power plants would largely replace the comparatively expensive hydrogen storage systems. Power surpluses could then be used for power-to-X technologies and in other energy sectors (for instance, as raw material in the chemical industry).

Conclusion

With a low share of wind and photovoltaics, power generation costs largely depend on the options that remain for



a) An installed overcapacity of fluctuating renewables can significantly reduce the use of biomass at similar costs.
b) With about 90 per cent FRES, the comparatively cost-efficient bioenergy constitutes a sufficient complement.
c) With low FRES-shares, the utilisation rates for CSP are higher, making it a cost-efficient supplement.
d) If FRE-shares are low and CSP is excluded, admitting low residual emissions (gas power plants) results in significant cost reductions.
e) If a complete decarbonisation is to be achieved with low FRES-shares and no CSP, the remaining power demand can only be covered by expensive geothermal power.

Figure 10: Costs of electricity generation with a (virtually) complete power supply from renewable energy sources with different shares of fluctuating renewables. The 100 per cent reference value was taken from the reference scenario with a carbon reduction of 90 per cent compared with 1990 levels.

45 As in option 3, it is assumed that solar thermal energy is not available as a flexibility technology.

The differences between decentralised and centralised power generation and flexibility technologies[46]

Decentralised technical solutions can be operated in small units. This includes all gas turbine power plants (natural gas, biomethane or methane storage), engine power plants, fluctuating renewable energies, wood-fired power plants, geothermal power plants, battery storage and DSM technologies. As a rule, smaller units running on the same basic technology as the large, centralised systems, incur higher specific investment and maintenance costs than the latter while being slightly less efficient.

Centralised technical solutions are characterised by the fact that they can only be economically operated in very large units (more than 100 megawatts output). Examples include steam power plants, combined-cycle plants as well as hydrogen, compressed air and pumped storage systems. Due to the necessity of transporting the electricity over very long distances, solar thermal plants are likewise classified as centralised technical solutions.

power generation. If solar thermal energy is available or if a low level of residual emissions, in other words natural gas power plants, are accepted, electricity generation becomes much more cost-effective than without these generation technologies. However, if the proportion of wind and photovoltaics surpasses 80 per cent, the cost reductions achieved by resorting to solar thermal energy and natural gas are negligible (cf. figure 10). In terms of costs, a system with an installed overcapacity of fluctuating renewables more or less equals systems with wind and photovoltaic shares of 80 to 95 per cent. However, the use of biomass is significantly lower in the case of an installed FRES overcapacity. Such a system could therefore present an interesting option should competing uses or environmental risks posed by the cultivation of energy crops reduce the availability of biomass for power generation.

4.3 The impact of centralised vs. decentralised electricity generation on the power system

For a long time, the power system was characterised by centralised generation structures: Having been generated in large power plants, the electricity was transported to the consumer passing by the different grid levels (transmission and distribution grids). With the progressive integration of renewables, this system is changing: Increasing numbers of small units (for instance wind and photovoltaic systems) are feeding power into the distribution grids. The power flow thus now runs in both directions. The existing locally distributed generation units can, in the future, be complemented by centralised power plants, or else by further decentralised technical solutions. What the effects of one or the other would be with a view to the power system in 2050 is an important question.

Survey results show that small, locally distributed plants meet with more public approval than large, centralised plants.[47] At

46 There being, as yet, no clear definition of decentralised and centralised power plant units, the ad hoc working group has agreed on the definition provided in this paper.

47 Ohlhorst 2009; Wüste 2012.

the same time, there is often vehement local resistance to grid expansion schemes. The decision to capitalise on a more centralised or, indeed, a decentralised system of power generation is therefore of high public relevance. Also, investors are increasingly wary of constructing central power plant units, as profitability must be guaranteed for several decades before entering into the planning stage. The refinancing risk is high, not only due to rapid technological developments, but also in view of basic energy policy conditions that are not readily predictable over such long periods. As a result, the number of large, central power plants currently in planning is negligible.

To illustrate the differences between centralised and decentralised power generation, we will now discuss two scenarios pushing the main features of the two variants to the extreme: the use of centralised technical solutions with an extensive expansion of the transmission grid on the one hand, and a system focusing on small, locally distributed generation units in combination with a very low level of transmission grid expansion on the other.

1) Centralised technical solutions and extensive transmission grid expansion

When centralised technical solutions are used, it is assumed that the transportation of electricity in the transmission grid is not restricted by limited grid capacity ("ideal transmission grid structure"). The inherent assumption is that public resistance to the expansion or indeed the planning and construction of large-scale energy systems can be overcome. A significant development of the transmission grid, for instance, enables the transportation of large quantities of offshore wind power to urban areas with high load rates in southern and western Germany. Fluctuating generation and consumption can thus be balanced over long distances. With a rather small percentage of wind and photovoltaics, power can be generated at comparatively low costs in large-scale systems such as CCGT plants. Alternatively, electricity from lignite power plants can be transported to consumers in southern Germany – provided this does not clash with the emissions reduction targets for 2050.

On the whole, those system variants containing extensive grid expansion and mainly centralised technical solutions are the most cost-effective. This is true even after factoring in the costs of the required grid expansion. In order to estimate the financial expenditure of grid expansion, we can resort to the sums indicated in the German Grid Development Plan[48]. In the most optimistic scenario with regard to the progress of RE development, the costs are estimated to be around five euros per megawatt hour. This is equivalent to approximately six to eight per cent of the electricity generation costs and shows the expansion of the grids to be a comparatively cost-effective measure.

2) Exclusive use of decentralised technical solutions and low level of transmission grid expansion

This option takes two important factors into account: firstly, the preference among the population for a decentralised energy supply based on small, locally distributed generation units in combination with a low level of transmission grid expansion; secondly, the economic uncertainty of centralised generation units with long depreciation periods. Consequently, transmission grids are not extended over long distances, and only decentralised technical solutions are being considered. The model illustrates this by splitting up Germany's power supply system into three regions (south, northeast and northwest). Hence, wind power from the north can no longer be transported to southern Germany.

48 NEP 2014.

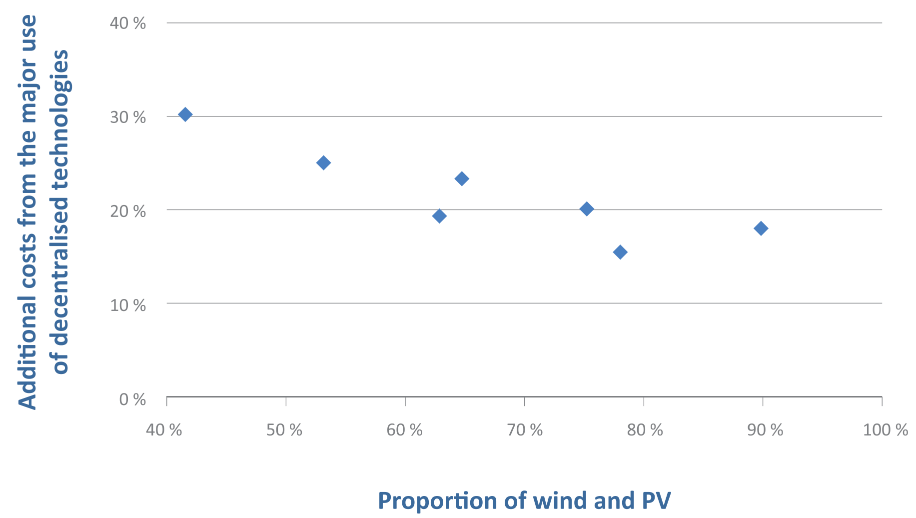


Figure 11: Additional costs of a decentralised power system with a low level of grid expansion for different rates of wind and photovoltaics, excluding grid costs. The additional costs are referenced against those of the respective rate of wind and photovoltaics combined with centralised technical solutions and an extensive expansion of the transmission grid. If the cost differences ensuing from the different degrees of grid expansion are considered, the additional costs of the decentralised systems decrease by six to eight per cent.

Figure 11 shows that the lower the share of wind and photovoltaics is in the power supply, the higher the additional costs of decentralised systems. In scenarios with low fluctuating renewables, the gap would, as described above, mainly be filled by resorting to centralised generation units. There are currently no economical decentralised alternatives. Hence, when the share of wind and photovoltaics is low, decentralised systems can only be established at high additional costs.

Conclusion

All in all, systems with an extensive expansion of the transmission grids and those resorting to both decentralised and centralised technical solutions are more cost-efficient than completely decentralised systems. A high degree of decentralisation should definitely be combined with a significant expansion of wind and photovoltaics all over Germany, particularly in urban settings with high load rates. If the expenditures of expanding the transmission grid are taken into account, the power generation costs of the two variants differ by about ten per cent. Hence, an implementation would require a comprehensive prior assessment of the cost differences and their subsequent discussion, not omitting the aspect of public acceptance.

4.4 What role can storage devices play in the future?

Storage systems are technologies that take in power and release it again at a later time. Thus, surplus power from wind and photovoltaics can, for instance, be shifted to times of higher power demand or less fluctuating feed-in. There are numerous storage technologies (e.g. batteries, pumped storage systems, hydrogen storage systems), all of which have specific advantages in different fields of application. The main distinguishing feature is the length of the period during which energy can be stored or released. For instance, technologies with high efficiency rates and relatively high storage costs, like e.g. batteries, can store energy for several hours (short-term storage). Technologies with a low efficiency level and low capacity-related investment costs, such as hydrogen storage systems, can store energy for several weeks (long-term storage).

Demand-side management (DSM) has a similar function in the power system as short-term storage: By increasing or decreasing the power demand at certain times by switching electrical devices on or off, consumption and generation can be balanced. Flexibly schedulable power consuming appliances are then mainly used in periods with a high supply of wind and photovoltaic power. In the present calculations it is assumed that in 2050, photovoltaic systems and electric vehicles will provide a large number of battery storage devices. The capacity of DSM in charging and discharging processes is estimated at 65 gigawatts. To this we can add the potential in the industrial sector, which amounts to three gigawatts according to conservative estimates. Clearly, the bulk of the DSM potential in our study is provided by electric and thermal storage systems in households.

1) Demand-Side Management for short-term storage

In 2050, short-term storage devices may have an installed capacity of up to nearly ten gigawatts or 25 gigawatt hours of installed storage capacity, respectively. They would serve to mitigate high load peaks and to optimise the operation of conventional power plants. If storage devices are used in electric vehicles and photovoltaic systems, and further demand-side management measures are applied in various other sectors, there is no necessity to install separate battery, pumped or compressed air storage systems for these purposes. That does not, however, mean that no storage devices are used: The demand-side management potential considered in the present study largely consists of electricity storage devices in vehicles, stationary plants for a semi-autonomous self-supply, as well as of thermal storage units in heating and hot water systems in households and industry.

Exploiting this DSM potential is a comparatively cost-efficient way to meet the demand for short-term storage. However, it is easily conceivable that for different reasons, such as owing to a lack of public acceptance or for the want of technical and legal solutions to integrate many small power generation units into the electricity market, this might not be possible. In that case, the more expensive alternatives mentioned above would have to make up the difference.

With regard to the incremental transformation of the power supply system until 2050, it must, however, be noted that in the short term, the full DSM potential will not be available. It will take some time for the number of electric vehicles and storage devices in households to reach the level assumed to estimate DSM's potential. In the meantime, additional battery storage systems can certainly play an important role when it comes to limiting the expansion of the distribution grids. They can also mitigate the fluctuations the grid is subjected to using the feed-in from wind and photovoltaics. By enabling a rapid increase or reduction in the output, they can further add flexibility to older conventional power plants. In addition, battery storage devices can provide grid services, such as primary control reserves or reactive power, thus contributing to secure grid operation. In other words, due to their modular, decentralised structure and their relatively limited durability ranging between 10 and 20 years, battery systems are excellently suited as bridging technologies.

Demand-side management (DSM)

Demand-side management refers to the targeted and controlled shifting of the power demand of electrical consumers. By partly shifting power consumption to a later time, DSM can contribute to making the power system more flexible, particularly if higher proportions of fluctuating generation from renewable energy sources must be dealt with. Even today, industrial consumers – in particular large and energy-intensive companies – strive to adapt their energy consumption to current electricity prices. Their aim is to operate their own machines and technical systems flexibly enough to avoid energy-intensive processes at expensive peak load times.

In 2050, households with photovoltaic battery systems, electric vehicles and electric heating, and hot water systems combined with thermal storage units could well accommodate particularly large DSM potential. Introducing the necessary control technology will constitute one of the challenges involved. Another will be to get consumers to surrender part of their sovereignty over the control mechanisms by agreeing to have their devices “remote-controlled” from the outside.

2) Bridging dark and windless periods with long-term storage

In order to securely meet the power demand, systems must be ready to meet demand in dark and windless periods. This criterion can be fulfilled either with flexible generation units (for example, biogas- or natural gas-fuelled power plants) or by long-term storage systems. Long-term storage devices are charged over a longer period of time, mainly with surplus electricity from fluctuating generation, which is converted into hydrogen or methane. The gas is stored in underground caverns or in the gas grid and at a later time reconverted into electricity in a gas power plant. The number of long-term storage units required depends, inter alia, on how ambitious the climate protection goals are and how large the share of fluctuating renewable energies is in the power generation system.

With less ambitious climate protection goals (80 per cent carbon reduction compared with 1990), the number of long-term storage units is limited (cf. figure 12). In such cases, curtailing renewables and resorting to flexible generation is often more cost-efficient than the use of long-term storage systems.

Assuming more ambitious climate goals (90 per cent carbon reduction compared with 1990), the use of long-term storage systems depends on the share of fluctuating renewables and the availability of other low-carbon power sources. With the biomass potential and the number of natural gas power plants we assumed, a low proportion of wind and photovoltaics entails a limited use of long-term storage systems, as surpluses occur comparatively rarely. The ensuing low utilisation rate would make long-term storage units relatively expensive. With higher proportions of wind and photovoltaics, long-term storage systems achieve a higher utilisation rate, making them more cost-effective than a system based on flexible generation and the curtailment of excess generation.

In the scenario of a full coverage of power demand from renewable energy sources, however, long-term storage plays a significant role in all cases, with installed discharging capacities of up to 50 gigawatts. Since in a completely decarbonised system there are no cost-efficient flexible power generation technologies available and the biomass potential

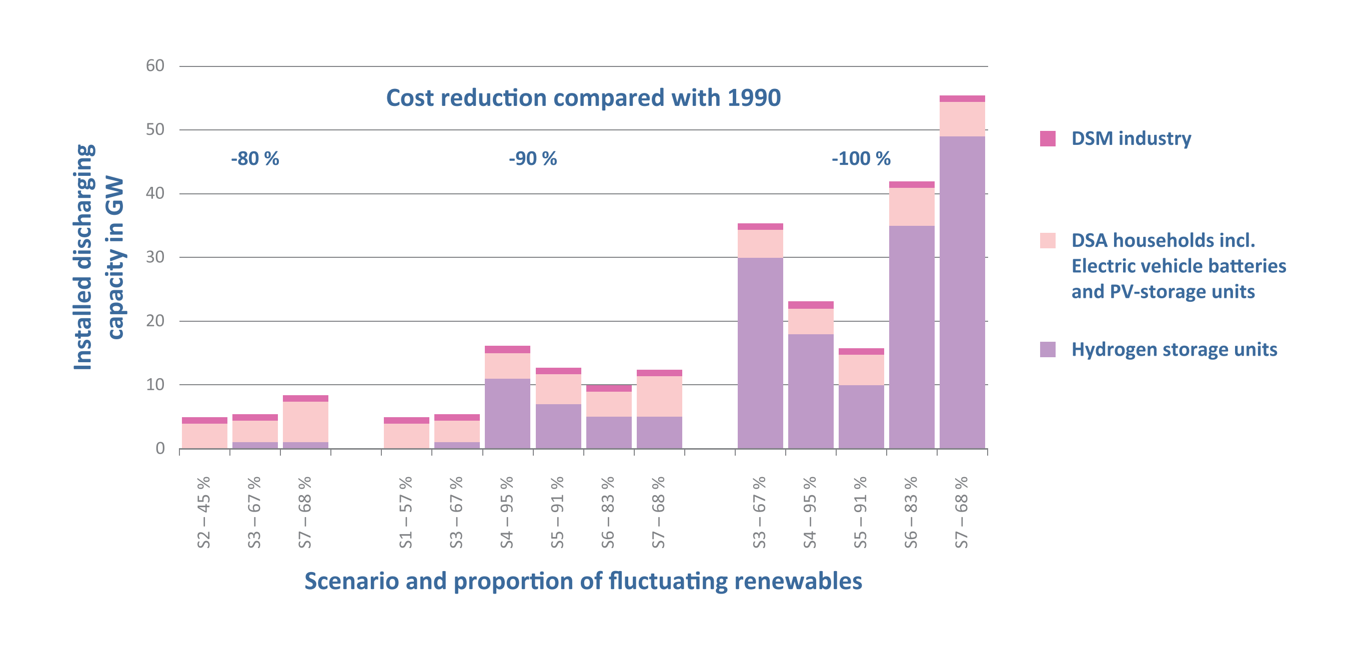


Figure 12: Correlation of long-term storage use with the proportion of fluctuating renewables and carbon reduction

is insufficient to meet the remaining demand, the storage of wind and photovoltaic power is the only alternative. With lower FRES shares, only a large-scale use of long-term storage devices can ensure a completely carbon-free system. In this case, long-term storage systems account for up to 20 per cent of the overall costs of electricity generation.

To summarise, we can state that the installed capacity of long-term storage systems strongly depends on the ability to use flexible generation. If the use of natural gas is limited by import restrictions or carbon reduction targets, or if the potential for bioenergy is confined, the importance of long-term storage increases. Whether natural gas, biogas or hydrogen is used – the electricity necessary to bridge dark and windless periods is invariably generated in gas power plants. The number of gas power plants required therefore varies very little across all scenarios.

We also see that the more decentralised the energy supply system is organised and the smaller the areas are in which output and demand must be balanced, the more storage units are required. This is one reason why the costs increase with the level of fragmentation of the power supply system. Nevertheless, there is a certain probability that the power system will evolve toward more and more decentralised structures. This is partly owing to the fact that public acceptance of such systems is high, and partly because many citizens are willing to invest private capital in such systems – something they would scarcely consider doing in the case of central power plants or large transmission grids.

4.5 How can power surpluses be used?

How surplus energy from fluctuating renewables should be dealt with is a widely discussed question. First, the short- and long-term storage units are charged from the negative residual loads – provided this is the most cost-efficient power supply option under the respective framework conditions. Under what conditions which storage system is favoured was

Power storage systems

Power storage systems convert power into another form of energy and release it again as electricity at a later time. The storage can be effected by converting power to kinetic energy (for instance, through flywheels), potential energy (e.g. pumped storage power plants), high-temperature heat or chemical energy (for example batteries and power-to-gas).

Short-term storage systems (storage time up to several hours) are highly efficient, meaning that only very little power is lost during storage. Their long life cycle allows for a high number of charging and discharging processes. Short-term storage devices include flywheels, coils, condensers and batteries of all kinds.

The full potential of *long-term storage systems* (storage time from one to several weeks) is usually only used once or twice a year. Consequently, low investment costs are necessary to ensure profitability. As long-term storage devices are rarely used, efficiency is of secondary importance. The present state of technical developments allows for only two variants: very large water or gas storage systems. As Germany has no potential for water storage units, we would have to resort to e.g. water storage systems in Scandinavia. The storage of gas (e.g. hydrogen generated by means of electrolysis), on the other hand, should be unproblematic. Germany has sufficient capacity, mainly in leached salt domes, which could be further expanded.

described in chapter 4.4. The remaining negative residual load can be freely used for all other applications or else be cut down.

For some years now, the focus of the debate has increasingly revolved around power-to-gas processes. The analyses that served as the basis for the present position paper provide clues as to the amounts of electricity potentially available for such usage. This is discussed in the following section "power-to-gas" (regarding the use of gas outside the power sector). Power-to-heat and the possibility of curtailing excess power generation are likewise being considered.

1) Power-to-Heat

For a long time to come, the use of hybrid combustion units in classical heating systems with natural gas or oil will be the most efficient way to generate heat from fluctuating renewables. In such a scenario, the combustion unit in a domestic heating system, for instance, could be complemented by an immersion heater in the hot water tank – at a very low investment cost. In the event of a power surplus, the immersion heater is activated, saving natural gas according to the amount of heat generated. Thus, the system retains large amounts of natural gas at a low investment cost and with very high efficiencies.

For the model calculations, a conservative ten gigawatts of power-to-heat potential was estimated. This potential is largely realised in most scenarios, indicating the high economic viability and the wide scope of possible applications of this technology. The high heating loads in winter times were, however, only taken into account to a small extent.[49] The industrial sector could likewise accom-

49 Among others, Heilek 2015 and Fh-ISE-2013 have examined a comprehensive coupling of the power and heat sectors based on a significantly higher and more detailed power-to-heat potential.

modate further significant potential, particularly in the high-temperature range. These applications were not considered in the present study, as we currently have neither conversion technologies nor valid estimates of the potential of electric high-temperature heat generation at our disposal. Research and development in this field could contribute to unlocking further potential.

2) Power-to-Gas

No electricity surpluses were used for power-to-gas (production of synthetic natural gas) in any of the variants of the power system that were calculated. The investment costs for power-to-gas plants are so high that the costs of gas production invariably exceed the total market value of the gas. The reason is that many types of plants only become profitable starting at 3,000 to 4,000 full load hours per year. However, 4,000 hours of load from surplus electricity from wind and photovoltaics cannot be achieved under a total FRES share of 90 per cent (cf. figure 13). As these surpluses are also used to charge storage units and to run power-to-heat plants, the surpluses available for power-to-gas plants are even lower.

The fewer the full load hours, the higher the depreciation on the plant investment per unit of gas produced. By lowering the investment costs and increasing efficiencies, this depreciation could be reduced. More full-load hours can only be achieved with additional electricity from regulatable power plants, or by building further wind and photovoltaic plants the power system does not, in fact, need. In both cases, the investment and / or fuel costs, including the expenses for emissions certificates, must be fully factored into the overall costs of the power-to-gas plants.

Due to the lower investment costs and higher potential revenues, plants limited to the production of hydrogen as a raw material for the chemical industry or other uses (for example in the transport sector) can be operated economically, even with comparatively low load factors. Consequently, profitable uses are possible even with lower FRES shares. A more exact quantification will require more detailed analyses of future hydrogen demand, of the necessary infrastructure or else the possibilities of feeding hydrogen into the gas grid, as well as an evaluation as to the scope of revenues to be achieved.

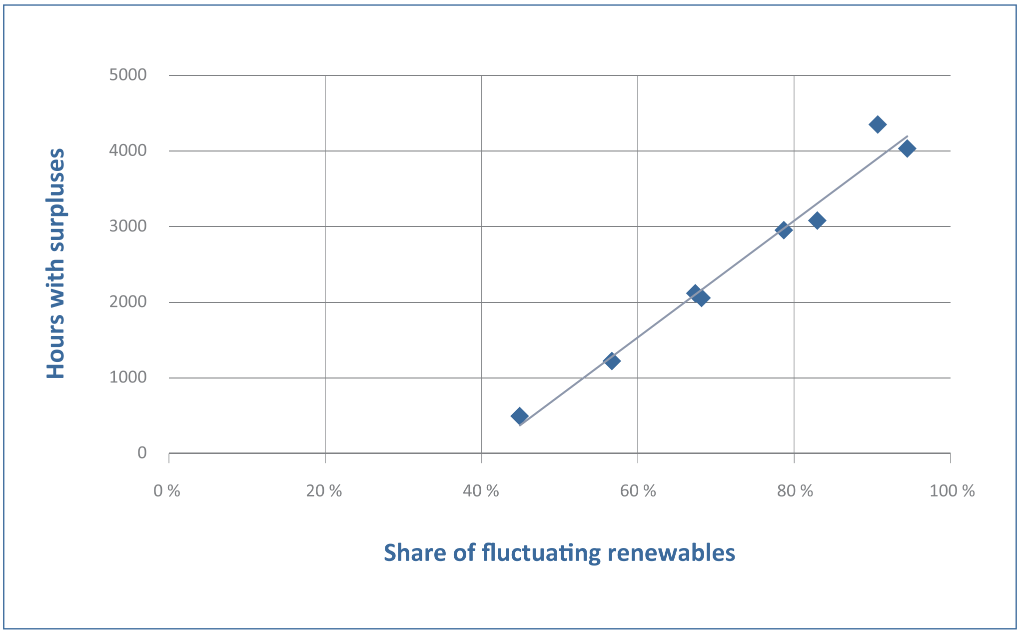


Figure 13: Ratio of annual hours with surpluses from the wind and photovoltaic shares

Power-to-Gas

With the power-to-gas technology, water is split into hydrogen and oxygen by means of electrolysis. The hydrogen can then be further transformed into methane. The model calculations invariably assume this methanation to have taken place. The gas produced can be used more or less like natural gas. It can, for instance, be transported through pipelines. At a later point in time, the gas can either be converted into electricity in gas power plants or fuel cells, or be used directly as fuel, or as an intermediate product in the chemical industry or in other sectors (e.g. transportation). If the hydrogen is processed into methane, the existing infrastructure for natural gas (pipelines, power plants) can be used. If the methanation step is skipped and pure hydrogen is produced, some new infrastructure elements would have to be constructed for storage and distribution.

At this point it is important to emphasize that this analysis primarily relates to the electricity sector, only marginally touching upon the development prospects in the heating and transport sector. However, assuming that the entire power supply will eventually have to be decarbonised, we will probably, in the medium to long term, be facing a very considerable demand for synthetic gases or fuels produced from renewable electricity. In this case, power-to-gas and power-to-fuel plants (production of liquid fuels by means of electricity) would necessarily be required – at least if the bulk of the production is realised in Germany. Power-to-X technologies would then be less intended to use virtually free surplus power, but rather power that has to be provided by additional investments. Accordingly, the interdependencies between the electricity, heat and transport sectors should be considered more closely in the long-term strategy for restructuring the energy supply. Finally, this also implies considerable research requirements.

3) Curtailment

If surpluses from fluctuating renewables cannot be economically used, power output from photovoltaic and wind power plants would be curtailed. The analyses show this to be an economical alternative to long-term storage systems – particularly in combination with less ambitious climate protection targets (cf. section 4.4). Across the range of system variants considered, between zero and ten per cent of the wind and photovoltaic power output would be curtailed.

4.6 Effects of mitigated dependence on energy import sources on the power system

In most cases, natural gas power plants provide the bulk of the flexibility, being both comparatively cost-efficient and the low-carbon alternative to coal and lignite power plants. The amount of natural gas the reference scenario (based on the federal government's target scenario) assumes for the use in electricity generation is 155 terawatt hours (thermal), which exceeds the current value by about 15 per cent.[50] In power systems featuring high power demand and only a low proportion of wind and photovoltaics, natural gas consumption is approximately twice as high as today. The corresponding installed capacities of the flexibility technologies and their energy outputs are illustrated in figure 14 and figure 15 for cases with and without energy imports, respectively.

Greater dependence on imports due to higher natural gas consumption involves risks regarding supply security in the power sector. However, most sce-

50 AGEB 2014, average 2011 to 2013.

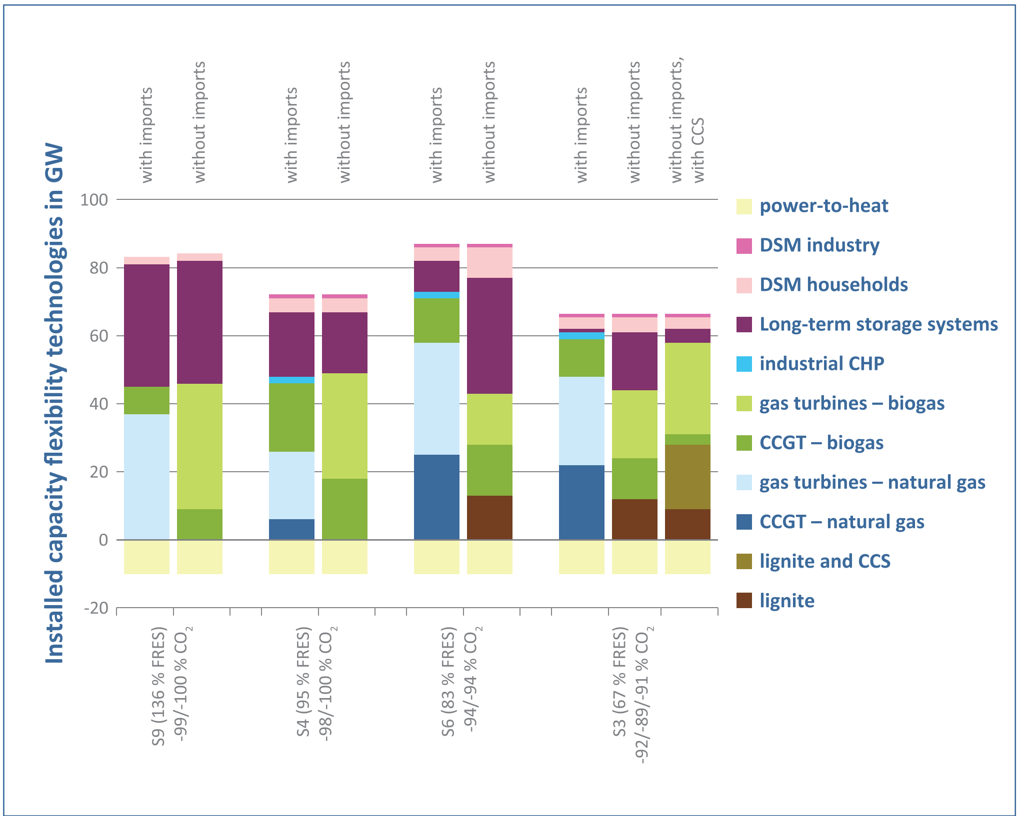


Figure 14: Influence of energy imports (particularly natural gas) on the installed capacity of flexibility technologies with different wind and photovoltaics shares and carbon reduction targets. Different levels of power demand in the different scenarios account for differences in the sum of the installed capacity.

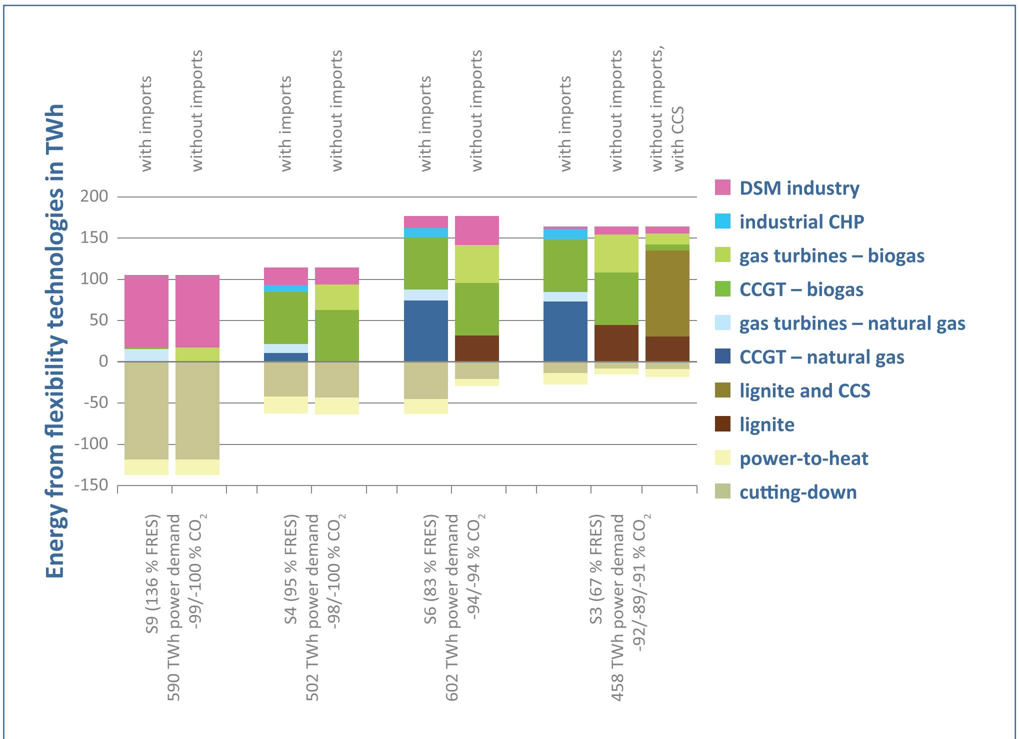


Figure 15: Influence of energy imports (particularly natural gas) on the energy provided or taken in by flexibility technologies with different wind and photovoltaic shares and carbon reduction targets

Carbon Capture and Storage (CCS)

As a by-product of processes in industrial plants, particularly in coal- and gas-fired power plants, carbon dioxide (CO_2) is usually released into the atmosphere as exhaust gas. With the carbon-capture-and-storage method, the CO_2 is first captured from the exhaust gas, then liquefied or bound in solids and finally stored, for example, in deep layers of sediment.

Building up the required infrastructure in the power plants as well as for the transportation and storage of the carbon is expensive. Consequently, CCS is only worth the investment if the technology is planned and applied for several decades. For these economic reasons, the technology does not qualify as an intermediate solution for a period of only ten to twenty years. Although a complete sequestration of carbon is theoretically possible with some CCS processes, the CCS-concepts discussed in the literature usually accept residual emissions ("slip") of about ten per cent for economic reasons. Therefore, even a power plant using CCS technology will not be completely carbon free.

An analysis of the public acceptance of CCS carried out as part of the project has revealed a very low level of acceptance indeed. Consequently, very substantial efforts and a comprehensive public debate would be necessary to have at least a chance of winning over public opinion for the implementation of CCS.

narios assume a significant drop in the demand for natural gas, especially in the heating sector.[51] Hence, the total German demand for natural gas would not necessarily exceed its present level.

The following chapter is dedicated to options that reduce or even completely avoid the importation of energy sources (natural gas, bituminous coal, electricity from CSP) for the power sector.

1) High levels of fluctuating renewable energy
With high wind and photovoltaic shares, relatively little energy is necessary to handle the positive residual load. Accordingly, the dependence on other energy sources is rather low. In scenario S4 with 95 per cent FRES – cf. figure 15 – for instance, only 50 terawatt hours (thermal) of natural gas are required. This is roughly one third of the amount currently used for electricity generation. Total independence from natural gas imports could be achieved by increasing the use of biogas. A complete withdrawal from all importing activities would require an increase by approximately 70 per cent compared to the current level. Whether this is possible and, indeed, useful, can only be assessed in a national biomass strategy that takes the competition for biomass uses into account. In theory, a system with an installed overcapacity of renewables could even work without any additional power generation at all, provided the excess power generation suffices to compensate for the losses that inevitably occur in the storage units.

2) Increased use of long-term storage devices
As shown in chapter 5.4, the use of long-term storage devices undoubtedly plays a major role in scenarios with high proportions of wind and photovoltaics. Surpluses can be more efficiently exploited, reducing the need for additional generation from natural gas or biomass. This, in turn, mitigates dependence on imports as well as possible negative environmental impacts of bioenergy use.

51 BMWi 2014-1.

However, even with lower FRES shares, long-term storage capacities can be increased in order to reduce import dependencies. Should we meet our full power demand from domestic energy sources – which would basically limit the range of complementary options to biomass, lignite or geothermal energy – the storage of surplus electricity from fluctuating renewables would, for lack of cheaper alternatives, be profitable even on a larger scale.

3) Use of lignite
As an alternative to natural gas, we could resort to lignite – within the delimitations set by the emissions reduction targets. This is particularly interesting in the case of lower proportions of wind and photovoltaics. To compensate for the high carbon emissions that lignite combustion involves, an increase in biomass-based electricity generation and installed long-term storage capacities would be required (cf. S6 without imports and S3 without imports in figure 14 and figure 15). This implies additional costs of about ten per cent compared to the use of natural gas.

By adding the option of lignite combustion with CCS, we can reduce the amount of biomass and of long-term storage capacity. While the installed capacity of the bio-energy power plants remains more or less the same, biogas is only used to cover load peaks. This reduces annual biogas consumption by about 80 per cent (S3 without imports and with CCS in figure 15). This system variant still resorts to lignite-fired plants without CCS, but to a smaller extent. Electricity generation costs drop by around ten per cent compared to the system variant prohibiting lignite CCS. However, as CCS currently meets with very little acceptance in the German public, its political implementation appears extremely doubtful for the foreseeable future.

4) Use of geothermal energy
In a scenario with lower FRES shares, lignite combustion could also be replaced by geothermal energy. However, significant research and development efforts will be necessary to realise the cost-cutting potential of geothermal energy generation. In other words: In order to make geothermal power generation an economically viable alternative, the costs would have to be reduced by a staggering 75 per cent compared to today's level. An extensive use of geothermal energy would then indeed enable a carbon-free power supply not dependent on imports – even with lower wind and photovoltaic shares.

Geothermal power generation

Geothermal power generation uses steam turbines to convert heat from deeper strata of the earth into electricity. Currently, Germany has only a very modest installed geothermal capacity, its large-scale use still being in the research stage. Since the potential of easily exploitable geothermal resources for power generation is rather small in Germany, so-called enhanced geothermal systems (EGS) must be used. The geothermal potential in Germany would suffice for the generation of about 260 terawatt hours of electrical energy per annum over a period of 500 years. The procedure for EGS is as follows: High-pressure water is injected into deep, hot layers of rock, creating cracks and fractures. With a temperature between 100 and 200 °C, these deep rock strata serve as heat recuperators, heating up the injected water as it flows through the cracks. This process is also known as *Hot-Dry-Rock-technology*. Compared to other geothermal systems that require specific geological conditions and are therefore tied to specific locations, EGS plants can be built almost anywhere.

5 Conclusion

This position paper presents different ways how a reliable power supply can be ensured in a future world featuring growing shares of fluctuating feed-ins from renewable energy sources. These observations are built upon analyses of the power system in 2050, which, in turn, are based on current energy scenarios and consider various flexibility options in different constellations, depending on the political and social setting.

Considering the national potential for power generation from renewable sources, the future power supply system will clearly be dominated by the fluctuating sources wind and photovoltaics. In addition, so-called flexibility technologies must ensure that power output and demand are balanced at all times. It is assumed that in 2050, predictable and flexible power generation units (natural gas- and coal-fired power plants, biomass power plants and solar thermal or geothermal power plants) and storage systems could be technically available, as well as methods to shift or altogether switch off loads (demand-side management). This could be complemented by technologies converting excess power into heat (power-to-heat) or chemically stored energy (e.g. power-to-gas/fuel). The key to a sustainable power supply system is clearly a cost-efficient technology portfolio consisting of fluctuating producers and flexibility technologies. There are, just as clearly, several different ways to obtain such a system.

The main conclusions of this position paper are as follows:

- In all of the energy scenarios, **wind and photovoltaics** will play a crucial role for the power supply in 2050. Amongst the renewable energy technologies, onshore wind and photovoltaics tie for the lowest generation costs. At the same time, it is their fluctuating feed-in that determines the flexibility requirements in the future power system. Consequently, the proportion of these technologies bears significantly upon the structure of the flexibility portfolio.
- Assuming that the price of emission allowances in 2050 will significantly surpass its current level, as the federal government's energy reference scenario suggests[52], a **power generation system boasting a high percentage of wind and photovoltaics** will, as a rule, come cheaper than a system dominated by fossil fuel power plants.
- **Simple as well as combined-cycle gas turbine power plants** will play a crucial role in the 2050 power system. Depending on the political and social framework conditions, they are operated with natural gas, biogas or – as part of gas storage systems – with hydrogen or methane. Under the assumption that carbon prices will reach a sufficient level to ensure that climate protection goals are met, the construction of new gas power plants can even now be declared a "no-regret-measure" – provided they are engineered for variable gas firing. Even though their full load rates

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will be very low and subject to strong weather-induced annual fluctuations, such plants will nevertheless constitute the backbone of a secure and reliable power supply. The market design will have to make sure that sufficient capacities are built and operated.

- It is possible to fully cover the power supply from renewable energy sources. The fluctuating renewables will then have to be supplemented by **flexibility technologies** such as storage systems, demand-side management and dispatchable energy technologies like biogas plants or solar thermal power plants with integrated heat storage. In the case of comparatively low percentages of fluctuating renewables, supply security could be cost-efficiently provided for by importing electricity from solar thermal plants in the Mediterranean via trans-European power grids. The ensuing implementation risks must, however, be considered. With a FRES proportion of over 90 per cent, relatively cheap bioenergy is a sufficient supplement. This would imply doubling the current amount of biogas. Whether biomass should be used to that extent for the power sector would have to be determined on the basis of a national biomass strategy and taking the regional and global consequences into account. The use of biomass could be reduced by resorting to an even higher share of wind and photovoltaics in combination with long-term storage units. The resulting cost increase would be minor.
- Large-scale power plant technologies for centralised generation require a powerful transmission grid. The same applies to renewable energy sources which are highly concentrated in one region (e.g. wind in northern Germany, imported electricity from renewables). For economic reasons, a high degree of **decentralization** should be combined with a significant expansion of wind and photovoltaics all over Germany, particularly in areas with high load rates. Whether the power system should indeed be organised at the local, decentralised level or whether a predominantly centralised supply structure is preferable should be determined on the basis of a comprehensive assessment of the cost differences. It also largely depends on the level of public acceptance for the different variants.
- The most cost-efficient means of meeting **short-term energy storage demand** are demand-side management measures. In 2050, the bulk of the potential will be provided by thermal storage units and battery storage in electric vehicles and photovoltaic systems in households. DSM will likewise play an important role for industrial purposes.
- Longer periods with little wind and solar radiation can be bridged either with **long-term energy storage devices** or with flexible producers. The more flexible the available options and the lower the climate protection requirements are, the less long-term energy storage systems are used. They do, however, play a major role should the import of natural gas be restricted or the usable potential of bioenergy be lower than expected. If carbon emissions in the power sector are not reduced by more than 80 per cent compared to 1990, the role of long-term storage systems will be negligible.
- An extensive use of wind and photovoltaics, long-term storage systems, lignite or geothermal energy can mitigate the dependence on **energy imports**. With a high percentage of FRES, power surpluses are used for long-term storage by means of hydrogen production or methanation. As a consequence, the demand for power from natural gas and biogas is reduced.
- With strict climate protection targets, the use of lignite in combination with the **CCS technology** is a further option. It only makes sense, however, if

the percentage of wind and photovoltaics is relatively low: Power plants with the technological equipment for CCS are expensive and require a high utilisation rate to operate profitably. Moreover, this presupposes public acceptance of both the implementation of CCS and the continuation of surface lignite mining. At the moment, this is not the case, or is at least doubtful.
- **Geothermal power generation**, on the other hand, is an alternative only if a massive cost reduction can be achieved. However, its profitability would be significantly higher were it used for heat supply. Consequently, we face a clear usage competition, which might limit the availability of geothermal energy for the power sector.
- **Power-to-heat** and more flexible **CHP plants** (cogeneration) are highly cost-effective flexibility options. The coupling of the power system with the heat market is therefore of great importance and must be particularly considered in the design of an optimal energy system.
- For all technologies considered, research, development and the expansion of the installed capacity is crucial in order to realise further **cost-cutting potential**. In addition to technological evolutions, for instance by increasing efficiency and reducing material usage, the integration of such technologies into the energy system is also of major importance.

The calculations and analyses this position paper is based on indicate that there are a number of system configurations that feature a relatively similar level of electricity generation costs. These different possibilities reduce the risk of misallocations of technologies and also show that political decision-makers and the public can indeed choose from among a rather broad range of options. Apart from the expansion of wind and photovoltaic units and the provision of large numbers of gas turbines and combined-cycle power plants, there is virtually no technology that could not be replaced by other options.

Further flexibility potential that, for methodological reasons was not considered in this study (with the exception of the direct import of renewable energy), can be realised by a strong European grid expansion. The focus of this analysis was the modelling of a high number of potential variants of the power supply system. This required an algorithm simple enough for the calculations to be performed within a short time and could not include modelling the coupling of the German power system with other countries.

So far only a few attempts have been made to examine the impact of the European energy network on the flexibility requirements; further specifications are, however, necessary. Within the framework of the methodology used for this study, an assessment of the potential for the import and export of electricity would require detailed analyses of the possible developments in the energy system of each neighbouring country until 2050. Depending on the expansion level of renewables in neighbouring European countries, they may be able to provide flexibility for Germany, thereby reducing our need for storage systems. This would require a corresponding expansion of the grid exchange capacity, as well as a general willingness to rely on a foreign country to procure a service necessary for a secure power supply.

The integration of the heat sector involves the clarification of various issues with regard to the development of heat demand and its temporal characteristics. While doubtlessly presenting an easy and inexpensive option for taking in power surpluses, the heat sector cannot make a significant contribution to coping with dark and windless periods – at least with ambitious climate protection goals.

Including these further options significantly broadens the range of system variants to be examined. The question of how a Europe-wide grid expansion and the coupling of the electricity and heat sectors (and, in the long term, with the production of fuels and raw materials for the industry) would affect the demand we have examined for the different flexibility technologies, is an interesting starting point for further research.

Whatever options we might have, implementing a low carbon power supply will not happen by itself. Market rules and regulations favouring a comprehensive systemic transformation toward the selected target system are required to pave the way. A further key challenge will be to design an economically efficient development path from today until 2050, factoring in the insecurities inherent in such long periods of time.

Glossary

Carbon Capture and Storage (CCS)

With carbon capture and storage technology, carbon dioxide (CO_2) from industrial processes or combustion power plants is captured from the exhaust gas and permanently stored to prevent its being released into the atmosphere, thus contributing to global warming. Deep layers of sediment are frequently used for storage purposes.

Demand-side management (DSM)

Demand-side management refers to the shifting of an electrical consumer's power demand to a later time. Thus, the power demand can be adapted to the fluctuating feed-in from wind and photovoltaic units.

Dark and windless periods

Long periods with little or no power generation from wind and photovoltaics are referred to as dark and windless periods. The longest dark and windless period is decisive for the structure of the respective power supply system.

Fluctuating renewable energy sources (FRES)

The two defining characteristics of fluctuating renewable energies are that while indeed being inexhaustible, they are not constantly available. Solar and wind power generation depend entirely on meteorological conditions and are consequently subject to fluctuations beyond our influence and control. In contrast, renewable energy from geothermal power plants, hydropower reservoirs or biomass is available on demand.

Gas turbine and combined-cycle gas turbine power plants

Gas turbine (GT) and combined-cycle gas turbine (CCGT) power plants have significantly lower investment costs and carbon emissions than coal or lignite power plants. The possible fuels, however – natural gas, methane, biogas, hydrogen – are considerably more expensive than various types of coal. Hence, GT and CCGT power plants are used wherever full load periods are infrequent, or when the use of coal-fired plants is partly or totally impossible for reasons of emissions reduction. Experts estimate that in 2050, GT and CCGT power plants can reach efficiency rates of 45 and 60 per cent, respectively. The higher efficiency in CCGT plants results from a combination of gas and steam turbines, which, however, also entails higher investments. Accordingly, GT power plants are used when very low full load rates are expected, whereas CCGT plants cover in case of a higher number of full load hours.

Geothermal power generation

Geothermal power generation uses steam turbines to convert heat from deeper strata of the earth into electricity.

Short-term storage systems

Short-term storage systems (storage time up to several hours) are highly efficient, meaning that only very little power is lost during storage. Their long life cycle allows for a high number of charging and discharging processes. Short-term storage devices include flywheels, coils, condensers and batteries of all kinds.

Long-term storage systems

The full potential of long-term storage systems (storage time from one to several weeks) is usually only used once or twice a year. Consequently, low investment costs are necessary to ensure profitability. As long-term storage devices are but rarely used, efficiency is of secondary importance. The present state of technical developments allows for only two variants: very large water or gas storage systems. There is no potential for corresponding water storage units in Germany.

Power-to-gas

With the power-to-gas technology, water is transformed into easily storable chemical energy sources (hydrogen or methane). The model calculations invariably assume the production of methane.

Power-to-X

All technologies allowing for the decoupling of power from the electricity sector for use in other sectors are referred to as power-to-X technologies. In this position paper, power-to-heat (electric heat generation) and power-to-gas (production of synthetic natural gas by means of electricity) were taken into account.

Residual load

The residual load is equivalent to the difference between the total power demand of all electricity consumers and the total amount of power generated from fluctuating renewable energies. It is imperative that electricity generation and consumption are kept in balance at all times. In the event of a positive residual load, additional power must be provided; if a negative residual load occurs, the excess power must either be used for storage, in power-to-X technologies, or curtailed.

Reference scenario

For the purposes of this position paper, a power system featuring the renewable share (67 per cent) and the net electricity demand (458 terawatt hours in 2050) from the German Federal Government's target scenario[53] is used as reference scenario. The respective flexibility portfolio was calculated by means of the method used for all variants. With a view to the risks their implementation would involve, the reference scenario excludes both the lignite CCS technologies and solar thermal power generation. It also sets a carbon reduction target of 90 per cent compared with the 1990-level.

Solar thermal electricity (Concentrated Solar Power, CSP)

Solar thermal plants concentrate solar rays to generate high temperature heat. This heat energy is then converted into electrical energy by the means of steam turbines. If thermal storage units are added, the heat can be stored and used to generate power during times without solar radiation.

Full load hours

Full load hours are a benchmark for the utilisation rate of a facility. A full load hour is defined as the equivalent of one operation hour at nominal load. Consequently, 1,000 full load hours are achieved with 1,000 operating hours at nominal load, or 2,000 operating hours at 50 per cent of the nominal load. The nominal load refers to the maximum output a facility can permanently produce at normal intended operating conditions. The full load hours are usually indicated in reference to one year. Accordingly, 1,000 full load hours per year signify that the plant generates 11.4 per cent of the power it could generate were it operated at nominal load for the entire 8,760 hours of the year.

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References

AEE 2012
Agentur für Erneuerbare Energien (Renewable Energy Agency) (Ed.): *Akzeptanz Erneuerbarer Energien in der deutschen Bevölkerung. Bundesländergenaue Ergebnisse einer repräsentativen Umfrage von TNS Infratest im Auftrag der Agentur für Erneuerbare Energien* (Renews Spezial Ausgabe 56), 2012. URL: http://www.kommunal-erneuerbar.de/fileadmin/content/PDF/56_Renews_Spezial_Akzeptanzumfrage_2011_online.pdf [Accessed: 20.5. 2015].

AGEB 2014
Arbeitsgemeinschaft Energiebilanzen (Working Group on Energy Balances): *Auswertungstabelle zu Energiebilanzen. 1990 bis 2013*, 2014. URL: http://www.ag-energiebilanzen.de/index.php?article_id=29& fileName=ausw_10092014_05112014_ov.pdf [Accessed: 30.06.2015]

Balser 2015
Balser, M.: "Bayerns lange Leitung". In: *Süddeutsche Zeitung Online* 2015. URL: http://www.sueddeutsche.de/bayern/energiewende-bayerns-lange-leitung-1.2331870 [Accessed: 30.06.2015]

BEE 2014
Bundesverband Erneuerbare Energien e.V.(German Renewable Energy Federation): *Szenarien der deutschen Energieversorgung vor dem Hintergrund der Vereinbarungen der Großen Koalition*. Studie erstellt von Joachim Nitsch, 2014. URL: http://www.bee-ev.de/fileadmin/Publikationen/Studien/20140205_BEE-Szenarien_GROKO_ Nitsch.pdf [Accessed: 20.05.2015].

BMWi 2014-1
Bundesministerium für Wirtschaft und Technologie (Federal Ministry for Economic Affairs and Technology): *Entwicklung der Energiemärkte – Energiereferenzprognose*. Studie erstellt von Prognos AG/Energiewirtschaftliches Institut an der Universität zu Köln/Gesellschaft für wirtschaftliche Strukturforschung, 2014. URL: http://www.bmwi.de/BMWi/ Redaktion/PDF/Publikationen/entwicklung-der-energiemaerkte-energiereferenzprognose-endbericht,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf [Accessed: 20.05.2015].

BMWi 2014-2
Bundesministerium für Wirtschaft und Technologie (Federal Ministry for Economic Affairs and Technology): *Abschlussbericht Metastudie Energiespeicher*. Studie erstellt von Fraunhofer Institut für Umwelt, Sicherheits und Energietechnik UMSICHT und Fraunhofer-Institut für Windenergie und Energiesystemtechnik IWES. URL: http://www.umsicht.fraunhofer.de/content/dam/umsicht/de/dokumente/pressemitteilungen/2015/Abschlussbericht-Metastudie-Energiespeicher.pdf [Accessed: 04.08.2015].

BMUB 2014
Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety): *Klimaschutzszenario 2050*. Studie erstellt von Ökoinstitut e.V. und Fraunhofer-Institut für System- und Innovationsforschung ISI, 2014. URL: http://www.oeko.de/oekodoc/2019/2014-604-de.pdf [Accessed: 20.05.2015].

Bruns et al. 2012
Bruns, E./Futterlieb, M./Ohlhorst, D. /Wenzel, B.: *Netze als Rückgrat der Energiewende: Hemmnisse für die Integration erneuerbarer Energien in Strom-, Gas- und Wärmenetze*. Studie wurde erstellt unter Mitarbeit von Sailer, F./Müller, T., Berlin: Universitätsverlag der Technischen Universität Berlin 2012.

Demski et al. 2013
Demski, D./Spence, A. /Pidgeon, N.: *Transforming the UK Energy System: Public Values, Attitudes and Acceptability – Summary Findings of a Survey Conducted in August 2012*, London: UKERC 2014.

Dethloff 2004
Dethloff, C.: *Akzeptanz und Nicht-Akzeptanz von technischen Produktinnovationen*, Lengerich: Pabst Science Publishers 2004.

Elsner et al. 2015
Elsner, P./Fischedick, M./Sauer, D. U. (Hrsg.): *Flexibilitätskonzepte für eine nachhaltige Stromversorgung 2050* (Schriftenreihe Energiesysteme der Zukunft), München 2015.

Fh-ISE 2013
Fraunhofer-Institut für Solare Energiesysteme ISE (Fraunhofer Institute for Solar Energy Systems): *Energiesystem Deutschland 2050 – Sektor- und Energieträgerübergreifende, modellbasierte, ganzheitliche Untersuchung zur langfristigen Reduktion energiebedingter CO_2-Emissionen durch Energieeffizienz und den Einsatz Erneuerbarer Energien*, 2013. URL: http://www.ise.fraunhofer.de/de/veroeffentlichungen/veroeffentlichungen-pdf-dateien/studien-und-konzeptpapiere/studie-energiesystem-deutschland-2050.pdf [Accessed: 20.05.2015].

Heilek 2015
Heilek, C.: *Modellgestützte Optimierung des Neubaus und Einsatzes von Erzeugungsanlagen und Speichern für elektrische und thermische Energie im deutschen Energiesystem.* Dissertation. TU München, München. Lehrstuhl für Energiewirtschaft und Anwendungstechnik, 2015.

Hübner/Hahn 2013
Hübner, G./Hahn, C.: *Akzeptanz des Stromnetzausbaus in Schleswig-Holstein. Abschlussbericht zum Forschungsprojekt*, 2013. URL: http://www.forum-netzintegration.de/uploads/media/Akzeptanz_Stromnetz_SH_Mai2013_web.pdf [Accessed: 20.05.2015].

Hübner et al. 2012
Hübner, G./Müller, M./Wüstenhagen, R./Chassot, S./Roser, A./Gruber, E./Gehardt, T./Frahm, B.-J.: *Erneuerbare Energien und Ökostrom – zielgruppenspezifische Kommunikationsstrategien. Modul I – Analyse der Konsumentenentscheidungen für Erneuerbare Energien und Ökostrom*, 2012. URL: http://www.news.admin.ch/NSBSubscriber/message/attachments/32453.pdf [Accessed: 20.05.2014].

IEK-STE 2014
Institut für Energie- und Klimaforschung – Systemforschung und Technologische Entwicklung (Institute for Energy and Climate Research – System Analysis and Technology Evaluation): *Energiewende, Energiesicherheit, Energieeffizienz: Wahrnehmung und Einstellungen in der Bevölkerung* (STE Preprint Ausgabe 11), 2014. URL: http://www.fz-juelich.de/SharedDocs/Downloads/IEK/IEK-STE/EN/publications/preprints/2014/preprint_11_2014.pdf?__blob=publicationFile [Accessed: 20.05.2015].

NEP 2014
Netzentwicklungsplan Strom (Grid Development Plan): *Zweiter Entwurf der Übertragungsnetzbetreiber*, 2014. URL: http://www.netzentwicklungsplan.de/_NEP_file_transfer/NEP_2014_2_Entwurf_Teil1.pdf [Accessed: 01.04.2015]

Ohlhorst 2009
Ohlhorst, D.: *Windenergie in Deutschland. Konstellationen, Dynamiken und Regulierungspotenziale im Innovationsprozess* (Reihe Energiepolitik und Klimaschutz), Wiesbaden: VS-Verlag 2009.

Pietzner/Schumann 2012
Pietzner, K./ Schumann, D. (Ed.): *Akzeptanzforschung zu CCS in Deutschland. Aktuelle Ergebnisse, Praxisrelevanz, Perspektiven*, München: Oekom-Verlag 2012, S. 47 ff.

SRU 2011
Sachverständigenrat für Umweltfragen (German Advisory Council on the Environment): *Wege zur 100 % erneuerbaren. Stromversorgung*. Sondergutachten, Berlin: Erich Schmidt Verlag, 2011. URL: http://www.umweltrat.de/SharedDocs/ Downloads/DE/02_Sondergutachten/2011_07_SG_Wege_zur_100_Prozent_erneuerbaren_Stromversorgung.pdf?__blob=publicationFile [Accessed: 20.05.2015].

TNS 2012
TNS-Infratest: *Umfrage zur Akzeptanz der Erneuerbaren Energien im Auftrag der Agentur für Erneuerbare Energien*, August-Oktober 2012. URL: http://www.unendlich-viel-energie.de/mediathek/hintergrundpapiere/akzeptanz-erneuerbarer-energien-in-der-deutschen-bevoelkerung2 [Accessed: 27.05.2015]

TNS 2013
TNS Emnid: *Ergebnisse einer repräsentativen Umfrage zur Akzeptanz Erneuerbarer Energien, durchgeführt von TNS Emnid im September 2013*, zitiert in: Agentur für Erneuerbare Energien: Akzeptanz Erneuerbarer Energien in der Bevölkerung Deutschlands 2013. URL: http://www.unendlich-viel-energie.de/mediathek/grafiken/akzeptanz-erneuerbarer-energien-in-der-bevoelkerung-deutschlands-2013 [Accessed: 27.05.2015].

UBA 2010
Umweltbundsamt (Federal Environment Agency): *Energieziel 2050: 100% Strom aus erneuerbaren Quellen*. Studie erstellt von Klaus, T./Vollmer, C/Werner, K/Lehmann, H./Müschen, K., Dessau-Roßlau 2010. URL: http://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3997.pdf [Accessed: 20.05.2015].

WI 2014
Wuppertal Institut (Wuppertal Institute for Climate, Environment and Energy): *Klimaschutzplan NRW: Zusammenfassung der Szenarienberechnungen des Beteiligungsprozesses*, 16.01.2014. URL: http://www.klimaschutz.nrw.de/fileadmin/Dateien/ Download-Dokumente/Ueberblick/Koordinierungskreis/Klima_NRW_Szenariendokumentation_ Klimaschutzplan_final.pdf [Accessed: 03.06.2015].

Wüste 2012
Wüste, A.: *Gesellschaftliche Akzeptanz unterschiedlicher Biomassenutzungsformen und Erfolgsfaktoren dezentraler Bioenergieprojekte*, Interdisziplinäres Zentrum für Nachhaltige Entwicklung der Universität Göttingen 24.01.2012. URL: http://www.bioenergie.uni-goettingen.de/fileadmin/ user_upload/admin/Konferenz/Vortraege_24-01-12/Wueste_BIS_Tagung_Goe12-01-24.pdf [Accessed: 20.05.2015].

The Academies’ Project

With the initiative ‘Energy Systems of the Future’ acatech – National Academy of Science and Engineering, the National Academy of Sciences Leopoldina and the Union of the German Academies of Sciences and Humanities provide input for an evidence-based discussion of the challenges and opportunities inherent to the German energy transition. Eight working groups (WGs) pool expert knowledge and identify relevant issues. Interdisciplinary ad hoc groups develop policy options for the implementation of a secure, affordable and sustainable energy transition.

The Academies’ Project seeks to provide systematic expertise and a set of reference points for decisions concerning the common goal “energy transition” on the basis of the following principles:

The energy supply of our country is a complex system

Raw materials and resources, technology, economy, society and law: In the energy system, we find multiple, cross-sectoral interactions. If not sufficiently taken into account, selective interventions can have paradoxical, unintended consequences. A prudent conversion of the energy supply system therefore requires a comprehensive understanding and assessment of the system as a whole. This must be developed in a common effort and in accordance with the highest scientific standards. However, there can be no master plan for the transformation because energy transition implies the continuous transformation of the energy system with all its inherent dynamics.

The aim of the energy transition is sustainability

Therefore, we have to agree on the criteria to apply to a sustainable energy supply and on how progress toward more sustainability can be benchmarked. In the energy concept of the German Federal government, supply security, economic efficiency and environmental sustainability form the basic conditions for a sustainable energy supply. Equally, social acceptability and social justice must be adequately taken into account. To determine whether or not these aims must be accorded equal significance, a discussion on values and suitable mechanisms for dealing with conflicts of values is required.

Science and research develop alternative approaches

Based on academically sound alternative options, players from politics, business and civil society can make well founded, ethically responsible and politically feasible decisions. In contrast to recommendations promoting one specific proposal, such options sketch out the consequences to be expected from one or the other approach. Thus, science can specify the advantages and disadvantages each solution would entail according to the current state of knowledge. The task of dealing with conflicting goals and the uncertainty invariably inherent to any such decision-making process is then a political one and requires a constant dialogue with the social groups involved.

Project participants

Eight working groups (WGs) pool expert knowledge and identify relevant issues. Interdisciplinary ad hoc-groups then develop policy options to address these problems.

WG Current Situation	WG Legislation	WG Technologies
WG Society	WG Resources	WG Options for Implementation
WG Economics	WG Scenarios	

The ad hoc group "Flexibility Concepts"

The ad hoc group "Flexibility Concepts" focused on the question how a secure power supply can be ensured in view of an increasing share of volatile feed-in from renewable energy sources. This included investigating potential ways of viably complementing the fluctuating power generation from wind and photovoltaics by flexible generation, demand-side management, storage mechanisms and grid expansion. The year 2050 was determined as time horizon. The different design options were considered in terms of their technological and financial requirements as well as with view to their social implications and the resources they would demand.

Procedure
All information available for the relevant technologies was pooled, evaluated and quantified according to standardised criteria by technology-specific expert groups. The expert group "Energy Scenarios" examined the flexibility requirements for potential energy systems in 2050 on the basis of currently available scenarios. By means of a computation algorithm developed for the working group, model calculations were carried out, yielding different options of how the identified flexibility requirements could be met.

During a workshop from 2nd to 4th December 2014, the chairmen of the respective expert groups agreed on the methodology, determined the framework conditions for the model calculations and discussed interim results. A further workshop on 30th January 2015 served to identify key points for the fulfilment of future flexibility requirements along with other impacts on the power system.

The **position paper** "Flexibility concepts for the German power supply in 2050. Ensuring stability in the age of renewable energies" provides a succinct synthesis of the results and points out options for the design of our future power supply.

Other formats:

- The **Analysis** "Flexibilitätskonzepte für die Stromversorgung 2050. Technologien – Szenarien – Systemzusammenhänge" (in German) provides a comprehensive documentation of the ad hoc group's methods and results and considers them in the context of energy policy issues.
- The **Technology Profiles** ("Technologiesteckbriefe", in German) document the data base as well as further details about individual technologies. They will be available online by the end of 2015 at www.acatech.de/flexibilitaetskonzepte-2050.

Members of the ad hoc group

The ad hoc group consisted of eleven specialist groups assembling around 100 experts from science and industry. Scientists and engineers worked alongside economists, psychologists and political and social scientists. A complete list of participants can be found in the analysis "Flexibilitätskonzepte für die Stromversorgung 2050. Technologien – Szenarien – Systemzusammenhänge".

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