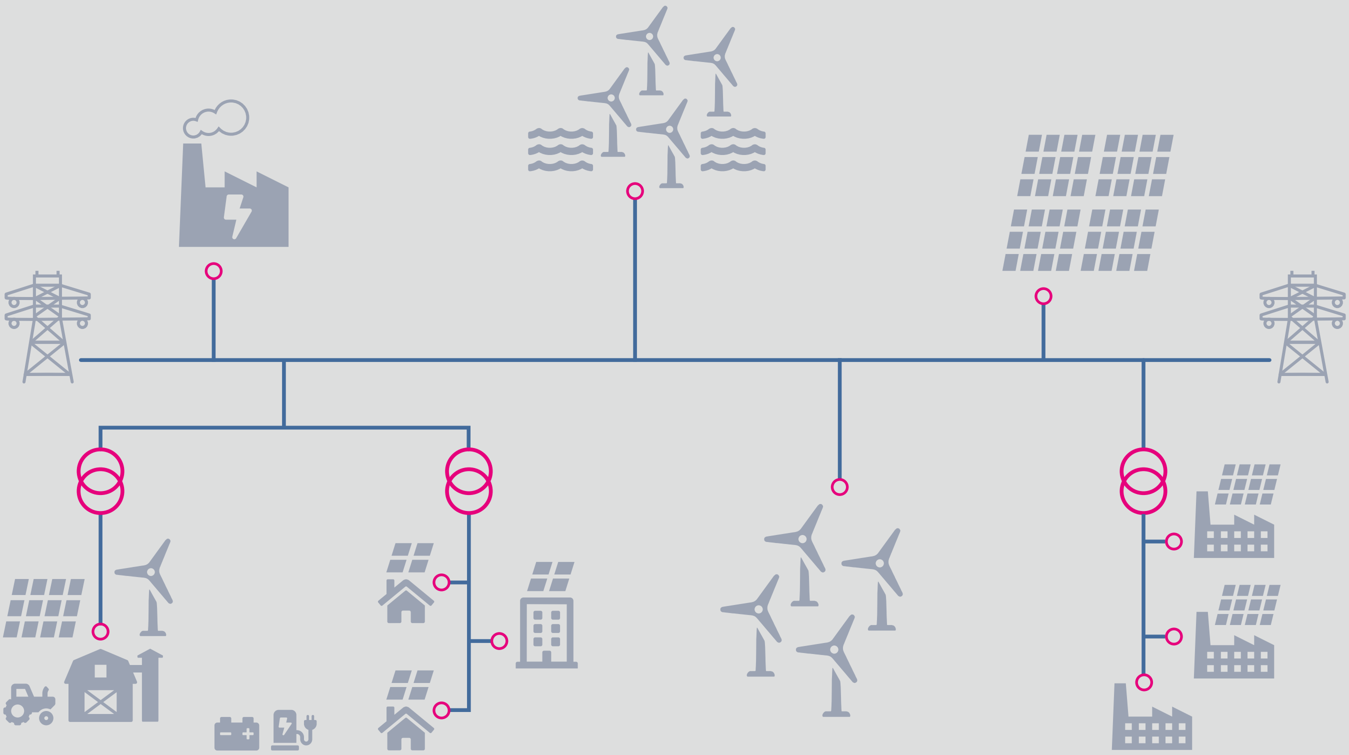
Position Paper
March 2020

Centralized and decentralized components in the energy system

The right mix for ensuring a stable and sustainable supply



"Energy Systems of the Future" is a project of:
German National Academy of Sciences Leopoldina | www.leopoldina.org
acatech – National Academy of Science and Engineering | www.acatech.de
Union of the German Academies of Sciences and Humanities | www.akademienunion.de

Impressum

Series publishers
acatech – National Academy of Science and Engineering (lead institution)
Munich Office: Karolinenplatz 4, 80333 Munich, Germany | www.acatech.de

German National Academy of Sciences Leopoldina
Jägerberg 1, 06108 Halle (Saale), Germany | www.leopoldina.org

Union of the German Academies of Sciences and Humanities e. V.
Geschwister-Scholl-Straße 2, 55131 Mainz, Germany | www.akademienunion.de

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Design and typesetting
aweberdesign.de . Büro für Gestaltung, Berlin

Printing
Laser Line GmbH, Berlin
Printed on acid-free paper, Printed in EC

ISBN: 978-3-8047-4061-7

Bibliographical information from the German National Library
The German National Library has listed this publication in the German National Bibliography; detailed bibliographic data are available online at http://dnb.d-nb.de.

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Preface

The energy supply is undergoing change. Increasing numbers of private individuals, energy cooperatives and municipalities are operating their own solar systems, biogas plants or wind farms and so complementing the major suppliers and power stations. Citizens are increasingly becoming prosumers who heat their houses in a climate-friendly and efficient way with heat pumps and connect the photovoltaic systems on their roofs to their electric cars with battery banks.

But will these decentralized systems alone be capable of meeting future energy needs? Since wind and solar power will increasingly also have to replace fossil energy carriers in the heat and transport sectors, power needs could double by 2050, as shown by the position paper "Coupling the different energy sectors – options for the next phase of the energy transition" which the Academies' Project "Energy Systems of the Future" (ESYS) published in 2017. Such a high level of demand can only be met by a four- to six-fold increase in wind power and solar system capacity. Achieving this will require not only decentralized plants but also large solar and wind farms capable of providing large volumes of power at low cost.

So how can centralized and decentralized technologies be combined to create a functional overall system and enable a secure, climate-friendly and competitive energy supply? This is the question the German Academies of Sciences have addressed in the present publication. They have concluded that the energy transition can only succeed if it is supported by the population. Energy transition planning must therefore focus more on conflicts with nature conservation and residents. Moreover, citizens should have much greater opportunities than they have so far enjoyed to be actively involved in the planning and decision-making processes. Opportunities for financial and political participation can increase acceptance of the energy transition. It is, however, also clear that power grid expansion, which is unpopular among some sections of the population, is unavoidable even if the energy transition is given a highly decentralized orientation.

Another finding is that digitalization will in future be indispensable for efficiently controlling a fragmented energy supply system. Another working group in the Academies' Project is addressing the question of how digitalization can be made secure. At the same time, practitioners are demanding a reliable regulatory framework for climate-friendly innovation and investment. We would like to express our sincere thanks to the scientists and reviewers for their commitment.

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Abbreviations and units

CO_2	carbon dioxide
DSM	demand-side management (flexible consumers)
RE	renewable energies
EEG	German Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz)
ICT	information and communication technology
KfW	German state-owned development bank (Kreditanstalt für Wiederaufbau)
AI	artificial intelligence
CHP	combined heat and power generation
PV	photovoltaics
GHG	greenhouse gas

kW	kilowatt
kWh	kilowatt-hour
MW	megawatt (one megawatt corresponds to 1,000 kilowatts)
MWh	megawatt-hour (one megawatt-hour corresponds to 1,000 kilowatt-hours)
GW	gigawatt (one gigawatt corresponds to one million kilowatts)
m^2	square metre
TWh	terawatt-hour (one terawatt-hour corresponds to one billion kilowatt-hours)

Glossary

Area grid	An area grid is a plant unit which belongs to an owner or co-owners (local unit). It may extend over several contiguous plots of land. Electrical energy is distributed within the area grid via lines and (as a rule) transformer stations belonging to the owner of the area grid (VSE 2018).
E-fuels	Synthetic fuels produced using electricity as the energy source. The electricity is firstly used to produce hydrogen by electrolysis. The hydrogen is then further processed using a synthesis method to yield carbon-containing fuels. CO_2 from the air or from production processes may serve as the carbon source. The manufacturing methods are known, among other things, as power-to-liquid (PtL) or power-to-fuel (PtF).
EEG plant	Renewable energy plant supported under the German Renewable Energy Sources Act (EEG).
Generating plant	Power generation plant. Such plants encompass wind energy and photovoltaic plants, and also dispatchable power stations using renewable fuels (e.g. biomass) or fossil fuels (e.g. natural gas).
Prosumer	A prosumer is a person who simultaneously consumes and produces the same product. A typical example in the energy field is a power consumer who generates their own power using a photovoltaic system.
Sector coupling	Sector coupling interconnects the power, heat and mobility energy sectors into an integrated energy system, so as to ensure supply of the required energy services to households, commerce and industry. Components of sector coupling such as combined heat and power generation, power-to-gas, heat pumps and heating elements (power-to-heat) and electromobility can con-tribute to the conversion of all areas of consumption to renewable energies, balance fluctuations in power grids and, through energy storage and transport, ensure security of supply as in-expensively as possible at all times and in all places.
System beneficiality:	Behaviour which is beneficial to the overall system means that both the market situation (price signals, balancing of supply and demand) and the grid situation (congestions, system services) are taken into account.

Summary

Achieving the Paris climate protection targets will mean changing our energy supply over from fossil energy carriers to renewable energies within a few decades. There are two competing paradigms in terms of the spatial arrangement of the energy transition: firstly, energy can be provided in as decentralized a manner as possible, i.e. **close to the point of consumption** in small installations, for instance using a rooftop photovoltaic system. Secondly, energy can primarily be obtained **in regions with good wind and solar resources** and then transported over potentially large distances to consumers, in which case it is also possible to use large-scale renewable energy plants with a capacity of several hundred megawatts. Which of these two approaches should be the primary focus is the subject of great controversy. In socio-political debate, a "decentralized" energy supply is often linked with public service provision, grassroots local decision-making and independence from major energy suppliers and thus has positive connotations. However, it is often unclear what precisely "decentralized" is taken to mean here, for example to what extent and how widely the decentralized units should be interconnected. The discussion also often concentrates very strongly on electricity generation, while less attention is paid to other important aspects such as providing flexibility, increasing integration across the power, heat and transport sectors and coordinating the overall system.

A systemic analysis, however, shows that only a **mix of more or less (de)centralized technologies and coordination mechanisms** can deliver an energy supply which is climate-friendly, secure and competitive. The individual components need to be integrated into a functioning overall system. This requires a reliable framework which encourages all the various stakeholders, from private households to major energy supply companies, to make the greatest possible contribution to the energy transition. **Incentives for investing** in renewable energy plants, storage systems and sector coupling technologies as well as for system-beneficial plant operation have a major role to play here.

Various pathways for transforming the energy system are conceivable. However, simply focusing on a simple "either centralized or decentralized" dichotomy, as sometimes happens in the socio-political debate, is inadequate. It makes more sense to distinguish between **different dimensions of (de)centralization**. These include above all plant size, voltage level of the feed-in, proximity of generation to the point of consumption, flexibility technologies such as storage and coordination of load balancing, which can be decentralized (e.g. in an individual household) or centralized (e.g. at an electricity exchange).

Wind and solar energy must be expanded both centrally *and* decentrally

What is certain is that the energy transition can only succeed if **renewable energies are substantially further expanded.** In the long term, the majority of available wind and solar potential will have to be used, with wind turbines in the north, south and offshore, and photovoltaic installations on buildings and on open land. As levels of sector coupling increase, electricity demand will continue to rise in future even given ambitious energy efficiency measures. If Germany's entire energy needs are to be met by renewables from Germany, there will have to be around a four- to six-fold increase in today's installed wind and solar capacity.[1] Existing **conflicts around land use** (nature conservation, perceived impairment of landscape and impacts on local residents) could intensify considerably depending on the future configuration of the energy supply. Energy saving measures can reduce renewable energy plant and power grid requirements. Efforts to cut energy consumption and increase conversion efficiency should therefore be intensified.

More stringent spatial planning can also assist with transparently weighing up concerns against one another. While citizen participation is already well established at local and regional level in Germany, greater weight should be attached to participative procedures at the federal state or national planning level. The interests of the public good could here be represented by "**lay planning assessors**" with the right of address being assigned by sortition.[2] A **higher-level debate about the energy transition spanning the whole of society** could elucidate the aims, systemic interrelationships and alternative solutions from various standpoints and so assist with developing socially accepted transformation pathways. Existing procedures for formal participation in local planning and approval procedures could be improved by better resourcing and skills development for those involved. In addition, informal events such as round table discussions or the like could also be established.

When it comes to expanding renewable energies, decentralized electricity generation by **PV systems in built-up areas**, in particular on roofs and other building surfaces, is the least socially controversial. Making the fullest possible use of this potential will help to alleviate land-use conflicts. Options for integrating PV systems in various kinds of residential development should thus be investigated. For example, refurbishment of existing housing stock could be combined with the installation of PV systems; residential and commercial developments with large areas of flat roof or car parking could be used for photovoltaic systems and energy plants could be combined with existing traffic and energy routes.

Large-scale solar PV farms, on the other hand, have the advantage of being capable of generating electricity at particularly low cost. Some energy providers are planning to build solar farms with an output of several hundred megawatts for instance on land which has previously been used for lignite or coal extraction and to market the generated electricity without EEG subsidies. "Agrophotovoltaic" systems, which are currently being trialled on a small scale, could alleviate competition for land use with the agricultural sector. These systems involve installing the PV systems higher above the ground so that agriculture can continue underneath. If, for example, the land under

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1 acatech/Leopoldina/Akademienunion 2017-1.

2 This concept is used in citizen assemblies.

the PV systems is managed as extensive grassland, this can contribute to maintaining biodiversity and so provide an additional environmental benefit.

Making increased use of **offshore wind energy** could reduce human impact in comparison with onshore wind energy because the installations are not located in the immediate vicinity of the population and so have hardly any effect on their everyday life. There is, however, a need for further research into environmental effects in this context.

Importing renewable energy could also alleviate land-use conflicts in Germany but care must be taken to ensure that any negative environmental and social effects of energy production are not simply relocated to another country. It may make economic sense to import energy from regions with more wind and sunshine. Europe's well developed integrated electricity grid is the most efficient and least costly way of transporting climate-friendly energy. Greater European integration with an increase in cross-border power trading makes good sense in order to make efficient use of the potential for flexibility across Europe. While grid extension will be necessary to achieve this, the need for additional storage systems in Germany will be reduced. Gaseous (PtG) and liquid (PtX) synthetic fuels (e-fuels) produced using electricity from renewable energy sources could be imported from non-European regions such as the Near and Far East or from African countries.

Grid expansion unavoidable even in more decentralized scenarios

Like onshore wind energy, the **expansion of transmission grids** is a cause of major social conflict when it comes to implementing the energy transition. One argument which is sometimes put forward in favour of a decentralized energy system is that it would make grid expansion unnecessary. Studies have, however, shown that **considerable expansion of both the transmission and the distribution grids by 2050 is essential** if the energy transition is to succeed. Various scientific investigations have made it clear that just as much additional grid expansion again as is now currently specified in the grid expansion plan to 2030 will be required by 2050. If grid expansion continues to progress only slowly due to acceptance problems, appropriately designed decentralized schemes and suitable incentives are one option for nevertheless being able to achieve short- and medium-term expansion targets for renewable energies. At the same time, however, it will in the long term be essential to work out how to achieve **social acceptance for grid expansion**.

While much of the debate around the energy transition is focusing on the transmission grid, **distribution grids** are attracting much less attention in society. However, the latter account for a much greater proportion of energy supply cost than transmission grids, and the demands placed on distribution grid operators have already increased significantly over the last decade and will continue to increase massively in future. This is because, the more decentralized is the energy system of the future, the greater the extent to which **load balancing** will have to be carried out **in the distribution grid**. Technical approaches to tackling the new challenges in the distribution grid include conventional grid expansion, innovative equipment for grip operation and possibly also control of new flexible consumers (e.g. electric vehicles and heat pumps). Smart distribution grids and a suitable **regulatory framework for the provision of system services in the distribution grid** will also be necessary.

Due to the fluctuating feed-in from wind and solar systems, future **flexibility technologies** will be required for balancing generation and consumption in the short and long term. Various technologies, including battery banks and power-to-gas, are **technically mature but for the most part still relatively costly**. More research and development, which will help to reduce **storage technology costs**, could substantially reduce anticipated future total system costs.

Digitalization for enabling coordination of decentralized, interconnected systems

Coordination of generating plants, storage systems and flexible consumers will in future become more complex, not least due to increasing levels of sector coupling. In both more centralized and more decentralized systems, coordinating the energy system will in future be one of the most significant technical challenges. This will probably be more pronounced for more decentralized systems due to the greater number of stakeholders involved. To coordinate them, increasing levels of automation and **digitalization** will be absolutely essential. As in other areas, artificial intelligence, autonomous and self-learning systems are offering previously inconceivable options for technically mastering even highly complex systems.

Digitalized energy systems do, however, also involve **risks**: the greater the level of interconnectedness, the greater is the potential scope for attack from cybercriminals, in particular if internet protocols are used for communication. Another risk is that autonomous systems may interact with one another in unforeseen ways and, in the worst case scenario, destabilize the energy system. **Resilience** and in particular also damage limitation in the case of an attack are therefore important criteria when it comes to developing a digitalized energy system. A multilayer structure with a central coordination level and decentralized cells, each capable of independently providing a basic supply and coupling/decoupling itself to/from the higher-level network, would appear to be advantageous in terms of resilience. However, in the past, the system has only been actively managed at high-voltage levels. There is still a lack of knowledge about operating energy systems in which decentralized installations provide stability. There is a significant need for research in this area.

What is vital is **to take a foresighted approach to shaping digitalization of the energy system**. This is because the demands placed on decentralized installations to contribute to system stability will grow in future. If plants are sufficiently well equipped with sensors and actuators from the outset, software updates will allow rapid adaptation to new, as yet unforeseeable, requirements. If, on the other hand, the appropriate hardware is not present, retrofitting numerous small installations is a highly complex, costly and protracted task.

Streamlining regulations, establishing CO_2 price as a key instrument

In addition to the stated basic technical requirements, coordinating generating plants, storage systems, grids and flexible consumers entails a **legislative and economic framework** which motivates stakeholders to make investment and operating decisions which benefit the overall system. Achieving climate protection targets will entail rapid and across-the-board transformation of the energy system which will in turn require extensive innovation. The **regulatory system should therefore encourage innovation** and enable energy transition stakeholders to develop and implement new technologies, products and services. However, today's largely impenetrable thicket of individual regulations gets in the way of achieving this. As a result, the **regulatory system must be streamlined as far as possible**.

A sufficiently high **CO_2 price** as a key instrument would assist in achieving climate protection targets as inexpensively as possible. This could be achieved by extending existing emissions trading to those sectors which have not previously been considered (possibly together with a minimum price) or by a CO_2 tax or duty. With a CO_2 price as leading instrument, those centralized and/or decentralized technologies which are most advantageous to the investing stakeholder would, in the absence of a prior political decision, win through on the market.

Techno-economic modelling would suggest that **more decentralized systems are probably somewhat costlier** than centralized ones, but the additional costs amount to only a few per cent in most studies. However, there has so far been almost no scientific investigation into long-term scenarios which cover the whole of Germany or Europe and use comprehensively decentralized energy systems, i.e. small generating plants and storage systems close to the point of consumption with decentralized load balancing. Further research is required to determine how much predominantly decentralized energy systems would actually cost in the light of system services and effects on distribution grid expansion. At the current state, it is uncertain to which extend decentralized generating plants and flexibility technologies can contribute to a cost-efficient climate protection. There is, however, a broad scientific consensus that transmission grid expansion is necessary and makes macroeconomic sense even in the case of highly decentralized expansion of generation and flexibility technologies, since it is an efficient and inexpensive flexibility option.

From an energy policy standpoint, however, there is a need for further instruments in addition to maximally cost-effective CO_2 avoidance. The resistance to the expansion of wind power and transmission grids has demonstrated that lack of acceptance is a major obstacle to the implementation of the energy transition. Instruments which **boost acceptance of the expansion of renewable energy plants and power grids** therefore increase the chance of achieving climate protection targets within the very narrow time window available. Using additional instruments to address negative effects on ecosystems and impacts on local residents also makes macroeconomic sense because these are external costs which are not included in a CO_2 price.

Enabling system-beneficial prosumption

In terms of acceptance and land-use conflicts, decentralized technologies which are constructed on areas which are already built up, i.e. in particular photovoltaic systems on roofs or other building surfaces, have advantages over other RE technologies. If **building owners can be persuaded to make their roof areas available for PV expansion**, this will open up potential renewable energy sources which provoke relatively little conflict. Germany could here make use of the regulatory options provided by the EU Clean Energy Package to facilitate **individual and collective**

self-consumption or even neighbourhood solutions. In the long term, however, the focus on self-consumption is insufficiently ambitious because the aim should be to **make the most comprehensive use possible of existing roofs and other building surfaces** for energy production, i.e. over and above own power requirements of the owners.

Issues of distribution and **infrastructure funding** must also always be borne in mind when it comes to encouraging self-consumption solutions.[3] It must accordingly be ensured that the costs of expanding renewable energy plants, of expanding and operating power grids and of maintaining security of supply are, like the benefits, fairly distributed among many energy system users. **Reform of the fees and surcharges** which fund these services may be of assistance here.

What is desirable is **a simple market structure which enables various models of prosumption but without resulting in ever more special arrangements.** Prosumers should have options for making system-beneficial[4] use of their self-generated electricity. In all probability, system-beneficial services will have to be provided by service providers on a competitive market. One requirement for this **is low-threshold access to secure ICT infrastructure even for relatively small prosumers** together with wattmeters for all consumers and generators. Grid operators might possibly be obliged to technically enable the connection of smart prosumer systems.

Overall, the aim should be to establish a legal and economic framework for prosumption which ensures on the one hand that potential roof area for photovoltaics is exploited to a major extent while on the other hand avoiding any harmful impacts of decentralized facilities on the overall system. The operational requirements on the system beneficiality of decentralized installations should therefore not be set unnecessarily high providing that impact on the overall system is low. At the same time, however, **technical and regulatory precautions** should be taken in order to be able to intervene quickly should **a rapid increase in prosumption** have problematic consequences on the overall system and **to change installations over to a more system-beneficial mode of operation.** Examples include equipping installations with the necessary metering and control technology and statutorily predefining the share of self-consumption systems in Germany's total power generation starting from which plant operating requirements become more stringent.

Grid-beneficial expansion and operation of renewable energy plants

In order to limit grid expansion, decentralized installations should in future increasingly be operated grid-beneficially, i.e. so as to assist with mitigating local grid congestion. Consumers should also be provided with incentives for **eliminating grid congestion**. Since under the current regulatory system, the market price signal takes no account of the grid situation, market-based use of renewable energy plants and flexibility, i.e. a response to electricity price signals, would not solve this problem. Conceivable

3 This also applies in principle to other measures, for example the introduction of comprehensive CO_2 pricing.

4 System beneficiality denotes behaviour which is advantageous for the overall system, taking account of both the market situation (price signals, balancing of supply and demand) and the grid situation (congestion, system services).

instruments might be **local markets for congestion management** and **widening the options for intervention by grid operators** in the event of problems. Three market stages could be differentiated using a traffic light system: green means that the power grid is operating without restriction for the market, red that system stability is jeopardized and the grid operator can intervene in the plant operators' schedules while amber means that there is a potential congestion in a defined grid segment. Distribution grid operators draw in decentralized manner on the flexibility offered by market participants in the grid segment in question in order to eliminate this congestion.

The introduction of **node-specific, time-variable prices** ("nodal pricing") would result in grid congestions being taken into account in the electricity price signal. This would provide incentives both for grid-beneficial operation and for grid-beneficial site selection for renewable energy plants and storage systems. This would, however, entail root-and-branch reform of the wholesale market. When it comes to implementing these instruments, it is important to ensure consistency between technical aspects and regulatory and market levels, to avoid excessively high transaction costs and to limit strategic behaviour in which individual stakeholders exploit inconsistencies in market design to the detriment of the community.

In addition to system-beneficial plant operation, efforts should also be made to ensure **system-beneficial expansion** of renewable energy plants and flexibility technologies. At present, the greatest expansion in renewable energy sources is in regions in northern and eastern Germany which are remote from the point of load, resulting in higher costs due to curtailment, higher levels of redispatch and grid expansion requirements. The current regulatory framework provides incentives for **site selection** which take insufficient account of **grid congestions**. One approach might be to introduce a **regional component into the remuneration model** in calls for tender under the EEG which, unlike the current reference yield model, would not primarily take the site-specific yield of the renewable energy plants into account but instead the grid situation. Further options might include raising **grid fees for generation plants** in regions with a need for grid expansion, and **limiting the compensation for lost revenues for curtailed volumes of energy**. In the medium to long term, incentives for system-beneficial site selection of storage systems and sector coupling technologies will help to reduce renewable energy plant curtailment.

Care must, however, be taken to ensure that such approaches are configured as simply as possible. In particular, they should be guided by their actual effectiveness in terms of grid relief. They should not put any additional hurdles in the way of small stakeholders and, if possible, be compensated by the discontinuation of other regulations. This is the easiest way of avoiding any potential conflict with the desired regulatory streamlining.

Similarly to self-consumption, **grid fees** have significant distribution effects, for instance between households with and without photovoltaic systems and between regions with higher and lower levels of feed-in from renewable energy sources. Moreover, no incentive is provided for grid-beneficial operation of storage systems. In addition to the introduction of **grid fees for generation plants**, so that they contribute to grid expansion costs, it would also make sense to **restructure grid fees for consumers.** For small, low-voltage customers, the consumption-dependent proportion of the grid fees could be reduced and be compensated by a higher standing charge or, if a smart meter with wattmeter is available, a demand charge (price per kilowatt). For consumers, in addition to their own maximum purchased power, account could also be taken of the power drawn and fed in at the time of maximum grid load, which would provide an incentive not to contribute to increasing total peak load. Tariffs which vary depending on time and/or location of use are conceivable for purposes of fine adjustment. Consumers who give the grid operator access to control of their systems, could be offered special tariffs.

Joint implementation of the energy transition: political and economic participation

Economic participation by local stakeholders in the value creation from renewable energy sources can boost acceptance of the energy transition. One possibility for strengthening local economic participation might be a national **Citizens' and Local Authority Investment Participation Act**. Uniform regulation across Germany has the advantage of offering identical competitive conditions, which is in particular of significance in relation to the national calls for tender for wind, PV and biomass generating plants. On the other hand, regulations specific to individual federal states provide greater latitude for taking account of specific concerns in individual states. Furthermore, various other models for economic participation on a statutory or voluntary basis, some of which are already established at federal state level, are also possible. These include investment participation for citizens and municipalities and an increase in business or property taxes and special levies payable by the operators to the affected local authorities.

The energy transition is a very wide-ranging and complex multigenerational project and successful implementation requires all the parties concerned to have a high level of **knowledge about the relevant systemic interrelationships.** If there is to be a constructive debate about the various options for shaping the energy transition, it will be helpful for the population to be as aware as possible of issues including climate protection, the energy system and the course of planning and approval procedures and various fields of law. Scientists, planners and science journalists should redouble their efforts to **communicate expert knowledge comprehensibly**. Informal participation processes can offer **platforms for dialogue**.

The increasing levels of complexity in the energy system are also increasing the demands on specialists. For example, sector coupling increasingly requires interdisciplinary knowledge about various energy consumption sectors such as heating, power and mobility and the corresponding energy supply systems. Knowledge about data management and IT security is also becoming more important. **Initial and in-service training** should reflect these various factors.

1 Introduction

Changing the energy system over from fossil energy carriers and nuclear energy to renewable energies[5] opens up a range of new options for providing energy in a decentralized manner in smaller plants, for example using a photovoltaic (PV) system on a domestic rooftop. However, renewable energy plants are not always small – large-scale solar PV or wind farms can reach entirely the same kind of level of power generation (several hundred megawatts) as conventional power stations. Whether energy will in future be provided on a centralized or decentralized basis is hotly disputed by society at large. Centralized versus decentralized power generation is seldom approached as a technical issue, but is instead discussed from a socio-political standpoint.[6] In socio-political terms, “decentralization” can be a highly emotionally charged concept, often with positive connotations, and is frequently symbolically associated with the concepts of localism, community, public service provision, and grassroots local decision-making.[7] Decentralization is also sometimes, incorrectly, equated with self-sufficiency.[8]

Public debate sometimes tends to pass over certain fundamental aspects, however, or to deal with them inadequately. Such aspects include how decentralized plants will be technically embedded in the overall energy system and the resultant positive or negative impacts for instance on security of supply, grid and standby power station requirements, IT security and, last but not least, overall system costs. The fact that there is no single definition of decentralization makes an objective debate even more difficult, with it tending to be discussed in vague terms and with the primary focus being placed on various different aspects.[9]

A decentralized energy supply offers individuals the possibility of playing an active part in shaping Germany’s energy transition.[10] Prosumers with a PV system and a battery bank may, for example, meet most of the electricity needs of their households themselves, and citizens’ energy alliances can use wind farms or biogas plants to supply electricity to villages or urban districts.

In 2016, around one third of installed capacity of renewable energy plants was in the hands of private individuals, the proportion thus being approximately twice that of energy supply companies.[11] **Farmers** who operate biogas plants or wind turbines, for

5 Power generation using wind power and photovoltaic plants is considered to have major potential for expansion. While bioenergy and hydroelectric power can indeed make significant contributions in terms of dispatchable energy provision, they will see at best very limited expansion in Germany due to a lack of sustainably developable potential. The following discussion will therefore primarily focus on the possible more centralized or more decentralized options for the expansion of wind power and photovoltaics.

6 Ried et al. 2017.

7 Schwan et al. 2016, p. 19.

8 Schwan/Treichel 2019, p. 6. For various definitions of self-sufficiency (also referred to as autarky) see box: “Decentralization is not self-sufficiency”.

9 Section 2 looks in detail at the various definitions of decentralization.

10 Schwan/Treichel 2019, p. 4.

11 AEE 2018, based on data from trendresearch 2017.

example, also play a major role in energy production. **Energy cooperatives** and other type of citizens' alliance which operate renewable energy plants have also grown considerably in significance in recent years. Indeed, their numbers grew more than ten-fold between 2000 (142 energy cooperatives) and 2016 (over 1,700 energy cooperatives).[12] This **new multiplicity of stakeholders** is regarded as an important condition for acceptance of Germany's energy transition.[13] The stated numbers should not, however, obscure the fact that large energy supply companies continue to generate a considerable proportion of power. Accordingly, in 2017, the top five energy suppliers, RWE, E.ON/Uniper, EnBW, Vattenfall and LEAG, alone held a share of the German primary electricity sales market (power generation without right to payment under the EEG, rail traction power and self-consumption) which amounted to 274 terawatt-hours, or 46 per cent of net power generation. This was more than the total volume of power generated from renewable energy sources of 205 terawatt-hours.[14]

Advocates for decentralization often regard prosumers and energy cooperatives as drivers of the energy transition, whilst the large energy companies are seen as obstructing it.[15] They equate the term "centralized" with "fossil/nuclear". Decentralization is therefore seen as a necessary precondition for defossilization[16] and thus for a climate-friendly energy supply.[17] Surveys show that respondents trust decentralized stakeholders such as local citizens, municipal utilities and authorities and local government more than they do central stakeholders such as energy companies, the German federal government or the European Commission to find practical solutions to the problems involved in transforming the energy system.[18] Decentralization can also be interpreted as a policy objective in terms of the subsidiarity principle, according to which problems should be solved at the lowest political level possible.

In addition to the desire for wider participation, it is often asserted in socio-political debate that a more decentralized energy supply reduces or indeed eliminates the need for **power grid expansion**.[19] Scientific studies do not, however, generally confirm this simple relationship. The effects of decentralized plants on the need for grid expansion depend on the specific configuration of the energy system and therefore have to be looked at in a more nuanced way.

Given the high consumer prices for electricity in Germany and in particular the EEG surcharge, the socio-political debate often focuses on the **costs of the energy transition**. Studies show that the transformation of the energy system, including power generation, the buildings sector and transport could cost a total of 1,000 to 3,400 billion euro to 2050, or an annual average of around three per cent of Germany's 2016

12 Kahla et al. 2017.

13 For example Agora 2017-1, p. 52; Jacobs et al. 2014; Hoffmann 2017.

14 Bundesnetzagentur/Bundeskartellamt 2018, p. 42. When looking at the numbers stated, it should be borne in mind that some of the power generated from renewable energy sources and other power not included in primary electricity sales is also generated by the larger energy suppliers.

15 Schmid et al. 2017; Schmid et al. 2015.

16 The widely used term "decarbonization" is misleading, since, taken literally, it means turning away from using carbon. However, carbon in closed circuits – for instance carbon from sustainably obtained biomass or removing CO_2 from the air and further processing it to yield carbon-containing compounds – is harmless from a climate protection standpoint. What does have to be avoided is the input of additional fossil carbon into material cycles, which is why the term "defossilization" is used here.

17 Lilliestam/Hanger 2016.

18 Fuchs et al. 2016; Sonnberger/Ruddat 2016, p. 28.

19 Schwan/Treichel 2019.

gross domestic product.[20] Germany's energy transition is therefore a major socio-political project, comparable with the German reunification. Implementation therefore has to be as cost-efficient as possible if the energy transition is to find acceptance.

From an economic standpoint, calls for a decentralized energy transition are viewed with scepticism, as it is feared that it will lead to unnecessarily high costs. This is because as a rule a kilowatt-hour of electricity can be generated more cost-effectively in a larger plant than in a smaller one. For example, the electricity generation costs for a small rooftop PV system are roughly twice those of a solar farm.[21] In addition, strong, wide-ranging interconnectedness (if possible right across Europe) allows the effects of different regional weather to be compensated and flexibility (e.g. storage systems) to be inexpensively provided.

In addition to the **overall costs** resulting from the energy transition, **questions of distribution** also occupy a significant position in socio-political debate. In this connection, prosumers are sometimes viewed negatively as they use infrastructure such as power grids and standby capacity but without making a sufficient financial contribution due to the way in which grid fees, duties and surcharges are currently calculated. This is criticized as being an "erosion of solidarity" and "bottom-up redistribution" from tenants to home owners with a roof and PV system.[22]

The subject of (de)centralization is also controversial amongst experts. Opinions and assessments range from "as decentralized as possible, as centralized as necessary"[23] to "a good case has to be made for decentralization"[24]. However, amongst energy experts the consensus is that t**he energy system of the future will include both centralized and decentralized components,** with this being even more the case if, in addition to power generation, there is a greater focus on systems integration and flexibility and sector coupling[25] grow in significance. As the use of renewable energy sources increases, the energy system will in any event become more decentralized and thus also more complex, but it is unclear what impact the trend towards a more decentralized energy supply will have on the overall system. Will it lead to the growth of a functional new systems architecture or will fragmentation of the energy system lead to increasing numbers of problems? Security of supply, the complexity of overall system control and IT security will in particular need to be evaluated with regard to centralized and decentralized systems.

In this context, the present position paper has two aims, the first being to contribute to an objective, constructive discussion of possible development pathways

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20 acatech/Leopoldina/Akademienunion 2017-1, p. 79; ESYS/dena/BDI 2019. These costs include industrial energy requirements, but not defossilization of material use of carbon.

21 See section 4.2.2.

22 The relevance of distribution questions to the social debate on energy transition is clear, for example, from headlines such as "Trades want an end to the 'unfair' energy transition" (Welt 2017) and "Woidke criticizes energy transition's billion euro redistribution" (Süddeutsche Zeitung 2018). In a survey, three quarters of respondents considered the energy transition to be "expensive" and over half as "unfair", although 90 per cent were generally in favour (IASS 2018).

23 RLI 2013.

24 Agora 2017-1.

25 Sector coupling interconnects the power, heat and mobility energy sectors to form an integrated energy system, so as to ensure supply of the required energy services to households, commerce and industry. Sector coupling components such as combined heat and power generation, power-to-gas, heat pumps and direct electrical heating (power-to-heat) and electromobility can contribute to the conversion of all areas of consumption to renewable energies, balance fluctuations in power grids and, through energy storage and transport, ensure security of supply as inexpensively as possible at all times and in all places.

for the energy system by analyzing (de)centralization in technical, economic, environmental and societal terms. (De)centralization is not regarded here as a normative principle, but rather as a possible tool for achieving the policy goals defined in the federal government's Energy Concept, namely climate protection, withdrawal from the nuclear energy programme, security of supply and competitiveness[26]. Secondly, the position paper indicates approaches to integrating centralized and decentralized components into a robust supply system which is in harmony with climate protection targets. Time horizons to 2030 and to 2050 will be considered.

The following questions are central to the discussion:

- How can decentralization be meaningfully defined?
- What are the pros and cons of more centralized and more decentralized energy systems?
- Under what circumstances does it make sense from an energy policy standpoint to steer the energy system in a more decentralized or centralized direction?
- How can the respective disadvantages and risks of centralized versus decentralized systems or system components be mitigated and the advantages exploited?
- What measures and tools are available to policymakers?

Discussion of these questions in the working group clearly revealed that they could not be answered independently of the higher-level challenges of the energy transition. For example, the question of whether the expansion of renewable energy sources should be more or less (de)centralized goes hand in hand with the general challenge of accelerating the expansion of renewable energy sources. Similarly, regulatory frameworks for decentralized installations can only be discussed meaningfully as part of the overall legal and economic picture regarding energy supply and climate protection. For this reason, the possible actions described in section 5 address the higher-level challenges of the energy transition, this section also providing an analysis of the extent to which more (de)centralized components are capable of contributing to the overall solution.

This position paper focuses on electricity supply. On the one hand, as a result of increasing sector coupling, electricity will increasingly become the basis of energy supply.[27] As a result, electricity demand will grow in future. In addition, discussion of the issue of decentralization versus centralization in this area has so far been particularly intense and fraught with controversy. As sector coupling progresses, the discussion about centralized and decentralized supply components could also widen to include other technologies, for example the provision of synthetic natural gas (power-to-gas) or hydrogen could be more or less centralized. It would be beyond the scope of this position paper to cover these aspects of heat and gas supply in full. However, possible issues relating to sector coupling will be alluded to at certain points.

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26 BMWi 2016.

27 Sector coupling issues are discussed in detail in acatech/Leopoldina/Akademienunion 2017-1. This publication looks for example at the question of the extent to which the heat and transport sector can in future be supplied with electricity directly and the extent to which it makes sense to produce hydrogen or synthetic fuels from RE electricity.

2 So what is actually meant by decentralized? Dimensions of (de)centralized energy systems

Despite the sometimes intense emotions in the socio-political debate around decentralized energy supply systems, the ideas held about what decentralization actually means are often somewhat ill-defined. For instance, a stakeholder debate held in the context of the "Energy Systems of the Future" (ESYS) project with participants from business, science, politics and civil society revealed that the phrase "decentralized energy transition" is used in an emotionally charged and poorly defined way. The debate could not find any clear answer to the question as to what specifically is meant by decentralization and could serve as a firm foundation for it.[28] In its analysis, the think-tank Agora Energiewende concluded that terminological uncertainties around "decentralization" underlie many controversies.[29] A common understanding of what is meant by decentralization is, however, essential for coming to an objective agreement about the issue. It is also important in this connection to communicate the meaning of the term self-sufficiency and in particular of the misleading concept of "balance sheet self-sufficiency" (see box: "Decentralization is not self-sufficiency").

Decentralization is not self-sufficiency

Self-sufficiency, or autarky, is a key term in the debate in society around decentralization. The concept of self-sufficiency is associated with economic independence, autonomy and control over one's own energy supply, all of which are factors that boost acceptance of decentralized energy systems.[30]

Self-sufficiency means that an organizational unit or cell (e.g. a household, neighbourhood, municipality, district or federal state) produces everything that it needs from its own resources. It is therefore independent of imports and exports. An electrically self-sufficient organizational unit would for example meet all its own electricity needs itself and, using storage systems and load management, independently bring consumption and generation into line with one another at all times, so there would be no need for any connection with other organizational units via power grids.

The concept of **"balance sheet" self-sufficiency** must be distinguished from such genuine physical self-sufficiency. Balance sheet self-sufficiency means that, over a defined observation period (usually one year), just as much energy is self-generated as is consumed. However, since generation and consumption are not in line with one another at all times, excess volumes of energy are fed into the general energy supply grids and any shortfalls are made up with energy purchased from the grid. A "balance sheet self-sufficient" cell thus makes use of the services of external grids, generating plants and storage systems. Using the term "self-sufficiency" is therefore misleading because the "balance sheet self-sufficient" cell is dependent and also has effects on external systems.

Achieving true physical self-sufficiency is extremely difficult in particular for small cells, as the following calculations for a single-family detached house compliant with the KfW 40 Plus efficiency standard illustrate.[31] The installed photovoltaic system with its power rating of 20 kilowatts is comfortably capable of meeting the annual energy needs of the four-person household, including electricity requirements

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28 Schwan/Treichel 2019, p. 5.

29 Agora 2017-1.

30 Ecker et al. 2017.

31 This efficiency standard defined by KfW, the German state-owned development bank, specifies the requirements for government support.

for the ground-source heat pump and electric car. In the mild winter and sunny summer of 2018, it produced almost twice as much electricity as the household consumed. Nevertheless, over half of the consumed electricity had to be purchased from the grid as the installed battery bank with its capacity of 18 kilowatt-hours is much too small to compensate for seasonal fluctuations in sunshine and heating demand. This is clearly apparent from the following graphs of monthly power consumption and generation in 2018.

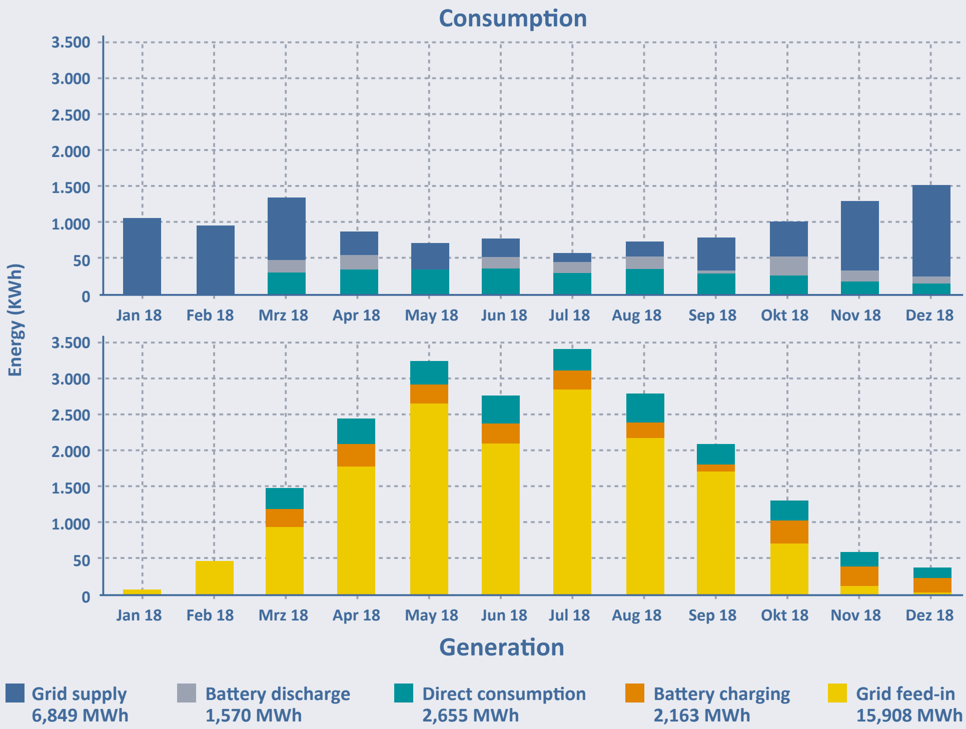

Figure 1: Monthly power consumption and generation of a detached house with PV-battery system, heat pump and electric car[32]

The household would need a battery bank with a capacity of over 5,000 kilowatt-hours and costing several million euro to achieve physical self-sufficiency.[33] This estimate clarifies the difference between balance sheet and physical self-sufficiency and shows that physical self-sufficiency for small energy cells with just one energy source (in this case a photovoltaic system) and one kind of storage system (in this case a battery bank) is incompatible with a maximally inexpensive energy transition.[34]

In areas with a dense residential population and in particular with energy-intensive industry, even balance sheet self-sufficiency is difficult to achieve, unlike for a detached house. In particular, if acceptance and environmental protection restrictions are taken into account, the renewable energy source potential for example in major cities is not typically sufficient to meet demand. If larger regions are considered as energy cells, rural areas with major generation potential can help to meet the high energy requirements in urban areas. However, estimates of potential have shown that even at federal state level, the federal states of North Rhine-Westphalia, Baden-Wuerttemberg, Hesse, Saxony and the Saarland are incapable of meeting their power demand with the wind and solar energy potential available within the federal state itself. They will therefore remain dependent on energy imports even in the long term.[35]

32 © Professor Bernd Engel, elenia, TU Braunschweig.

33 A battery bank in Schwerin with a capacity of 15,000 kilowatt-hours required investment of some twelve million euro (WEMAG 2017).

34 Physical self-sufficiency is possible for energy-efficient residential buildings if a number of flexibility technologies are used. This has been demonstrated by a multi-occupancy dwelling which has no connection to the power grid in Brütten, Switzerland, which is equipped, among other things, with a large battery, a large hot water storage tank, wastewater heat recovery, a hydrogen generator, a hydrogen tank and a fuel cell. The residents do, however, also accept limitations: for instance, the electric car belonging to the building could sometimes not be used in winter due to a shortage of electricity and the washing machine could also not run at certain times on foggy winter days. The residents can also consume only half the volume of energy of an average Swiss household, this being achieved by energy-saving technology (Schawalder 2017; Stiftung Umweltarena 2017).

35 Öko-Institut 2018-1, p. 27 ff.

According to Germany's Energy Industry Act, a decentralized generating plant is defined as "a generating plant which is located close to the point of consumption and load and is connected to the distribution network".[36] This definition is above all of relevance in a grid planning and grid fees context and in this respect is directed towards avoiding grid expansion costs and allocating grid costs on a causation basis.[37] However, when it comes to describing the options for the future energy system as a whole, the simplistic centralized/decentralized dichotomy falls short as it is incapable of adequately describing the full range of possible solutions.[38] For instance, small and large generating plants can coexist in an energy system and small, decentralized plants can be connected over a wide area via a power grid and be centrally controlled.

Various attempts have been made in the literature to get a handle on the complexity of the term decentralization by distinguishing a number of different dimensions of decentralization.[39] The think-tank Agora Energiewende concluded that it makes no sense to define decentralization strictly because important aspects of the debate around decentralization would otherwise be ruled out purely on the basis of definition. Instead, decentralization should be used as an umbrella term for various grid topology, economic, social and political aspects.[40]

This definition remains too vague for locating different energy scenarios on the decentralization axis. The Öko-Institut approach shown in Figure 2 would appear to be suitable. [41] On the basis of four dimensions of decentralization, this permits classification of the overall technical system including generators, storage systems and grids and, in part, also the regulatory aspects which serve to coordinate these components.

Figure 2 illustrates the significance of the different dimensions of decentralization on the basis of the relationship between need for power grid expansion and decentralization. The spatial dimension would initially appear to be crucial: a large proportion of power generation close to the point of consumption might indeed reduce the need for grid expansion. Depending on the level of local consumption, both small and large generating plants can be used here, for example a PV system for meeting a household's power needs or a multi-megawatt plant for meeting those of a large industrial plant. However, the need for grid expansion would only reduce if, in addition to generating plants, flexibility solutions, i.e. storage systems, flexible consumers and sector coupling solutions, were also available close to the point of consumption (integration dimension). This is because, in the absence of local flexibility options, all the power required for example during calm spells with low light would have to be purchased via the grid and the necessary connected load would be just about as high as without local generating plants. In addition, the need for grid expansion would only reduce if consumption and generation were balanced locally, i.e. within a defined cell covering a small area (coordination dimension). If, on the other hand, plant energy services are offered for sale outside the cell (e.g. on the electricity exchange or to balancing power markets), this can make variable demands on grid capacity.

36 § 3, paragraph 11, Energy Industry Act (EnWG).
37 See §§ 14, paragraph 2, 24, clause 2, no. 4, letter a) and clause 5, § 120 EnWG.
38 Funcke/Bauknecht 2016.
39 Agora 2017-1; Funcke/Bauknecht 2016; Öko-Institut 2018-1.
40 Agora Energiewende 2017-1.
41 Öko-Institut 2018-1, p. 17.

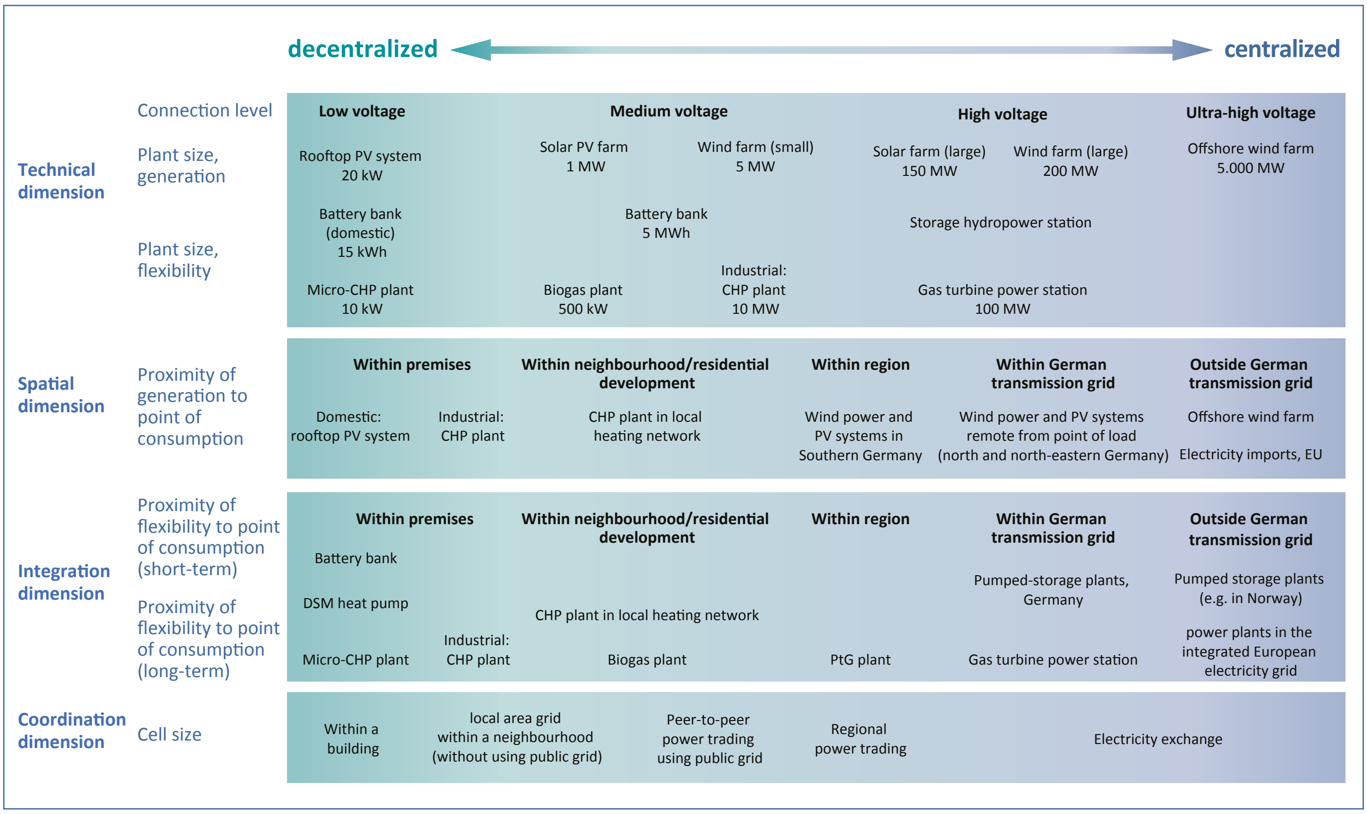

Figure 2: Dimensions of decentralization (based on Öko-Institut 2018) with examples of the implementation of different (de)centralized concepts for power generation

The necessary conditions for a reduced need for grid expansion are thus only met if a high degree of decentralization is achieved not only in the spatial dimension but also in the integration and coordination dimensions as well.

Various combinations of (de)centralization in the dimensions shown crucially determine which stakeholders are involved in energy supply and in what manner. The more components of the energy system which can be located in all four dimensions at the left-hand edge of Figure 2, the greater is the variety of options available to smaller prosumers such as households. The predominant stakeholders at the right-hand edge of Figure 2, in contrast, are larger energy supply companies. Energy cooperatives or municipalities, for example, may play a major role in the central zone. Combinations in which the technical dimension is decentralized (e.g. PV systems and battery banks) but coordination is provided centrally via major companies within the framework of a platform economy are, however, also conceivable. The role of the various stakeholders may *inter alia* have an impact on acceptance, economic distribution effects and the resilience of the energy system.

Figure 2 also makes it clear that **centralized versus decentralized** is not a binary either-or but that there are **many possible options between the two**. It therefore makes more sense to talk comparatively about ***more* centralized** and ***more* decentralized**. These gradations also occur within a single technology, as is most clearly apparent with photovoltaics, in which the various plant designs span the entire range from the left-hand, decentralized edge to the right-hand, centralized edge (see box: “Photovoltaics: centralized and decentralized”).

Photovoltaics: centralized and decentralized

Plant designs for photovoltaics range from highly decentralized to highly centralized, as illustrated by the following examples of a decentralized rooftop system and a centralized solar power station. A typical solar PV farm, remunerated under the EEG, is located between the two extremes of the decentralization scale.

Rooftop system with a nominal power of ten kilowatts for self-supply in a suburban area

Figure 3: Detached house with rooftop PV system[42]

These systems installed by private individuals are remunerated under the EEG, with new systems receiving a feed-in payment of approximately eleven eurocents per kilowatt-hour. Such systems are increasingly being equipped with storage systems and energy management and combined with sector coupling features (heat pump and electromobility) which means they can assist with maintaining voltage and frequency stability in the local low-voltage grid. Since the necessary capacity in the low-voltage grid is frequently determined by load (i.e. consumption), these systems can reduce or delay the need for expansion in the local grid arising from the increase in electromobility and use of heat pumps.

Large solar power station with a nominal power of 85 to over 1,000 megawatts

Figure 4: Solar PV farm[43]

Large-scale solar photovoltaic farms are primarily considered for sparsely populated areas such as former lignite mining regions. The electricity is fed into an ultra-high-voltage or high-voltage grid remote from the point of load and can therefore require additional grid expansion. Since the EEG only supports plants with a nominal power of up to ten megawatts, these plants have to generate revenue without support on the electricity market and consequently conclude Power Purchasing Agreements (PPA) with electricity purchasers. Solar farms are constructed with participation by major energy companies. They can assist with maintaining voltage and frequency stability and provide further system services such as balancing power and reactive power management[44]. Large-scale solar power stations with PPA are a relatively new development and the coming years will reveal whether they are a game changer for the energy transition.

Reactive power

Inductive and capacitive consumers (e.g. asynchronous motors) connected to an AC grid require energy to generate a magnetic or electrical field. This energy is, strictly speaking, not actually consumed but instead only briefly buffered and then fed back into the grid. It is known as reactive energy or reactive power. Grid equipment (overhead power lines, cables, transformers) also requires reactive power. In some cases, reactive power is not wanted as it is not usable and places a load on the grid. Reactive power is, however, sometimes required for maintaining voltage stability since reactive power only flows in the high-voltage grid where voltage differences prevail. Reactive power management may thus be used for maintaining voltage stability. A similar situation applies with regard to active power and frequency in the high-voltage grid: if active power generation and consumption are at equilibrium, a balanced or constant line frequency is obtained.

This clear decoupling of the interrelationships between voltage and reactive power on the one hand and active power and frequency on the other does not occur at lower voltage levels. Existing control algorithms from high-voltage technology therefore cannot be transferred unchanged to other voltage levels.

42 © Dissertation Marcus Bunk, elenia, TU Braunschweig.

43 © SMA Solar Technology AG.

44 See box: “Reactive power”.

3 Study overview: examples of centralized/decentralized scenarios

Possible future energy system developments are often investigated using energy scenarios. The model calculations used include physical models which, for example, allow calculation on the basis of weather data of how much electricity wind energy and PV systems generate each hour over the period of a year. It is then possible, on this basis, to calculate the extent to which storage systems and flexible power stations are needed to meet electricity demand. Further technical and economic interrelationships are also included in the models.

Different models differ depending on which parts of the energy system they deal with. Up to a few years ago, electricity supply was the focus of most models, but increasingly the energy system is being looked at as a whole, with interactions between electricity and heat supply and the transport sector being included in the analysis.[45] Older models were often based on a "copper plate", i.e. a power grid with unlimited capacity without congestions. Now, the transmission grid is increasingly modelled at line resolution. However, many studies still take no account of the distribution network nor do they investigate susceptibility to failure in any more detail.[46]

The configuration of the model calculations and the specified assumptions and parameters depend on the issue being investigated.[47] For many studies, the underlying question is "how can the 2050 climate protection targets be achieved as inexpensively as possible?" The results are therefore heavily dependent on the assumptions regarding the future cost trends of different technologies.

In order comprehensively to model and compare the characteristics of centralized and decentralized energy systems, example scenarios should take account of all the dimensions of decentralization depicted in Figure 2. Table 1 also shows decentralized and centralized scenarios which take account of these dimensions.

45 For example: acatech/Leopoldina/Akademienunion 2017-1, BDI 2018, dena 2018.

46 Only the N-1 criterion is generally considered. This states that sufficient redundancy must be present to ensure operation even if one resource fails.

47 Energy scenarios as an instrument of scientific policy advice are discussed in acatech/Leopoldina/Akademienunion 2016.

	Decentralized scenario	Centralized scenario
Technical dimension	High proportion of solar PV farms and domestic rooftop systems, small onshore wind farms and relatively small distributed wind turbines	Predominantly large-scale solar PV farms and large-scale onshore and offshore wind farms, imported power
Spatial dimension	Major expansion of PV systems and wind turbines in or close to urban population centres and in the industrial regions in southern and western Germany	Expansion of onshore wind energy, primarily at sites in northern Germany with good wind conditions
Integration dimension	On-site load balancing by battery banks, flexible consumers (demand-side management), small flexible CHP plants (e.g. fuel cells, biogas combined heat and power plants), sector coupling, power-to-gas with grid feed-in	Also storage options remote from the point of load, for example use of pumped storage and storage hydropower stations outside Germany (in Norway among other places), central flexible power stations (e.g. relatively large gas turbine plants), sector coupling, power-to-gas (gas storage) or power-to-X (liquid products)
Coordination dimension	Major role for prosumers and self-consumption solutions. Power balancing takes place to a significant extent right on the consumer's premises and at distribution grid level (for instance, within a neighbourhood with local area grid[48])	Power balancing is coordinated predominantly at a central level (electricity exchange, balancing power markets)

Table 1: Qualitative description of centralized and decentralized scenarios

In recent years, a number of scenario studies have been published which discuss questions of (de)centralization and compare decentralized and more centralized scenarios.

Energy system models with the objective of **minimizing overall costs** tend generally to lead to a more **centralized scenario.** For example, in the model calculations new wind turbines tend to be built in the north and new solar systems in the south because the cost benefits of the better wind and solar energy resources outweigh the cost of additional grid expansion.[49] Larger facilities also benefit from economies of scale compared with smaller facilities, meaning for example that, if optimization is left to market forces, more solar PV farms tend to be built than rooftop PV systems. In many studies, the centralized scenario is therefore the basic scenario, while in decentralized scenarios specific aspects of decentralization (e.g. lower levels of grid expansion, alternative distribution of wind turbines, high proportion of rooftop PV systems) have to be specified by additional model restrictions.[50]

Table 2 provides an evaluation of current studies into (de)centralization in light of the time horizon to 2050. Also included is a metastudy which evaluates ten studies with the time horizon of 2030/2035.[51] It is clear that none of the scenarios models comprehensive decentralization in all four dimensions as listed in Table 1, but rather in each case only takes account of individual sub-aspects, with the type and regional distribution of renewable energy plants being most frequently investigated. In many studies, the focus is particularly on to the extent to which expansion of the transmission grid can be reduced by expanding renewable energy sources closer to load. One scenario

48 For a definition and discussion of local area grids see section 5.3.2.

49 Grid costs might be higher, however, if much of the grid expansion has to take the form of underground cables in order to gain public acceptance.

50 The models calculate the most cost-efficient way of achieving a defined climate protection target. The results therefore represent an economically ideal case. In reality, stakeholders behave differently if, for example, the legislative and economic framework results in a mismatch between the optimum from a business standpoint and that from a macroeconomic standpoint. Legislators can try changing the regulatory framework to bring the business incentives into line with the macroeconomic optimum, for example by pricing in external costs (in particular by using CO_2 pricing). Furthermore, other criteria beyond economic considerations may be important in particular to private individuals such as homeowners.

51 Öko-Institut 2018-1.

in which prosumers play an important role is analyzed in a study carried out on behalf of the environmental NGO WWF: in the scenario "Solar Focus" almost one fifth of total power demand is met by rooftop PV systems with battery banks designed to cover electricity demand of households (self-consumption).

Refer-ence	Commissioning body	Drawn up by	Title (translated)	Scenario (translated)	Aspects of (de)centraliza-tion investigated	Time horizon, CO_2 savings
WWF 2018-1	WWF	Öko-Institut Prognos	Germany's electric future II: Regionalization of renewable power generation	Energy transition reference (centralized)	High proportion of PV-battery systems for optimizing self-consumption	2050 93% CO2 in the power sector vs. 1990
				Solar focus (decentralized)		
BMWi 2017[52]	BMWi	Fraunhofer ISI Consentec ifeu	Long-term scenarios for transforming the energy system in Germany	Basic scenario (centralized)		2050 at least -80 % GHG in total vs. 1990
				Module 4: Less expansion of transmission grid (decentralized)	Can the climate targets be achieved even if grid expansion is delayed?	
				Module 5: Alternative regional RE distribution (decentralized)	More uniform regional distribution of onshore wind energy expansion	
RLI 2013	Haleakala-Stiftung, German Associa-tion for Small- and Medium-sized Businesses, 100 prozent erneu-erbar stiftung	Rainer-Lemoine-Institut	Comparison and optimization of centralized and decentralized expansion path-ways	Centralized scenario		2040 98 - 99 % RE in power sector
				Decentralized scenario	Expansion of onshore wind energy closer to load	
				Offshore scenario	Greater expansion of offshore wind energy	
Öko-Institut 2018-1	Renewables Grid Initiative	Öko-Institut	Decentralization, regionalization and power grids	Metastudy with evaluation of ten studies	Interrelationship between regionalization of renewables expansion and transmission grid expansion	2030/2035

Table 2: Studies analyzing decentralization in the energy system on the basis of scenarios

The differences between centralized and decentralized scenarios in terms of the installed capacity of the various technologies and the long-term need for grid expansion are relatively minor in most studies. In contrast, the differences between different studies owing to different basic assumptions (relating for example to power demand trends, underlying climate protection targets and energy imports) are very much greater (see Figure 5). Studies which assume that energy requirements in the heat and transport sectors will increasingly be met with electricity (for instance from heat pumps, electromobility or power-to-gas) while at the same time assuming low energy import levels, calculate a significantly higher electricity demand than the studies listed in Table 2.[53]

The cost differences between a centralized and a decentralized scenario are also low in most studies. In the three studies in Table 2 which consider the time horizon to 2040 or 2050, the additional costs for the decentralized scenario are at most two per cent.

52 Two further scenarios with decentralization aspects are planned in the context of the BMWi 2017 project: Module 7 (alternative RE mix) and Module 11 (decentralized system).

53 Some suggest over 1,000 terawatt-hours in 2050 (Ausfelder et al. 2017, p. 117).

The metastudy (Öko-Institut 2018) with the time horizon 2030/2035 suggests that the evaluated studies do not allow any unambiguous conclusions to be drawn as to whether and how regional expansion of renewable energy sources would influence total costs. The **small differences between centralized and decentralized scenarios** may, however, be down to the fact that the studies generally only investigate one aspect of decentralization. Since comprehensively decentralized scenarios have not been investigated, no statement in this respect can be made on the basis of the evaluated studies.

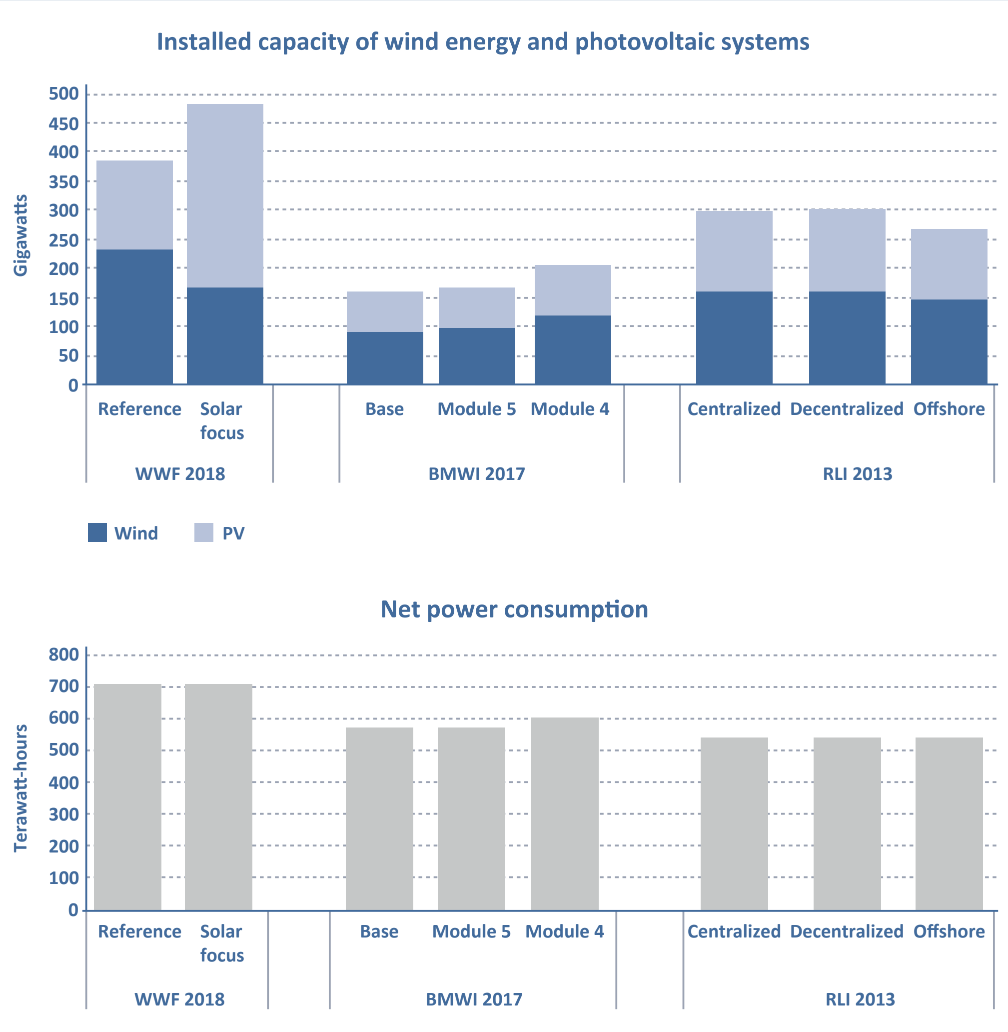

Figure 5: Installed wind energy and photovoltaic system capacity and net power consumption in 2050 in the scenarios analyzed

The coordination dimension is largely modelled on a heavily simplified basis in the evaluated studies, and the assumption in WWF 2018 that PV-battery systems will in future be operated to optimize self-consumption without taking any account of the overall system is very pessimistic. Even today, 50 per cent of domestic energy storage systems operate under higher system beneficiality requirements (limited feed-in), as this is a prerequisite of the KfW support programme. It is controversial whether the simplified model assumptions result in the possible cost benefits of decentralized systems with regard to grids and system services being underestimated.

The scenarios show how, under certain assumptions, the energy system can be most cost-effectively adapted to achieve climate protection targets, but they do **not allow any statement to be made as to how probable implementation of a specific scenario is.** Since, however, time is of the essence when it comes to climate protection, the chances of successful implementation constitute an important criterion when deciding on a transformation pathway and need to be taken into consideration alongside cost. Resistance to the expansion of power lines and wind turbines shows that **acceptance** is a substantial factor when it comes to successful transformation of the energy system. Different stakeholder groups show markedly different levels of acceptance of and support for the energy transition depending on the scenario presented, and decentralization aspects may also play a part in this. In addition to the technical transformation process, which can be modelled using energy scenarios, the **societal transformation process** has therefore also to be taken into account when deciding how to configure the energy system.

4 Major aspects of centralized and decentralized energy systems

More centralized and more decentralized forms of energy systems are elucidated below from various perspectives and their technical, economic, environmental and societal aspects evaluated.

4.1 Technical perspective

The debate in society around (de)centralization in the energy system usually focuses on renewable energy plants for power generation. A reliable overall system, however, needs further functions which can themselves likewise be provided in centralized or decentralized manner. These include short- and long-term flexibility (*inter alia* storage systems), energy transport (grids) and the coordination of all components. Increasing levels of sector coupling must also be taken into consideration when analyzing centralized and decentralized development pathways.

4.1.1 Wind and solar power systems

In wind power and photovoltaic systems, the volume of power generated annually is determined by the wind or sun conditions at the site. Accordingly, in Schleswig-Holstein over half of wind turbines provide over 90 per cent of the reference yield[54] whereas in Baden-Wuerttemberg just three per cent of turbines do so. Over two thirds of turbines in Baden-Wuerttemberg have a yield of below 70 per cent of the reference yield.[55] Accordingly, the land take, the impact on the landscape, the quantity of raw materials[56] required for producing the turbines and the power generation costs are higher when poorer wind locations are used.

Since power demand is particularly high in the industrial regions in the west of Germany and in Baden-Wuerttemberg,[57] but the best wind power potential is located in northern Germany, there is a conflict of interests between power generation close to the point of consumption and a high electricity yield per turbine.[58] This is illustrated by the

54 The reference yield is the volume of power which a wind turbine of a particular type would provide at a defined reference site with an average wind speed of five metres per second at a height of 30 metres above ground.

55 Data for the period from August 2014 to March 2016 (FA Wind 2016).

56 Constructing renewable energy plants entails a very much larger input of raw materials per generated kilowatt-hour of electricity than that required for conventional power stations. Among other things, numerous different metals are required. Demand for technology and special metals such as cobalt, platinum group elements and rare earths is also growing in other industrial sectors, such as the automotive industry, electronics and information and communication technologies. Energy technologies are rarely the most important area of application for a metal. Experts consider that, in geological terms, sufficient metals are available to meet demand. However, due to dependency on just a few supplier nations, raw materials markets can suffer supply congestions which need to be overcome by a strategic raw materials policy. Increasing recycling rates and maximizing the effectiveness of recycling can assist with meeting raw materials demand in an environmentally friendly manner and reducing dependency on imports (acatech/Leopoldina/Akademienunion 2017-2).

57 Öko-Institut 2018-1, p. 32.

58 For instance, according to a study commissioned by the Federal Ministry for Economic Affairs & Energy (BMWi), a decentralized scenario with a regionally more uniform distribution of wind power expansion would require eight per cent more wind turbines than a centralized scenario in order to generate the same volume of electricity (BMWi 2017, module 5: regional scenario).

estimate shown in Figure 6 of the extent to which, in balance sheet terms, annual power demand in 2030 could be met within a district by renewable energies. The left-hand figure shows the shortfall or excess for districts in the event of the entire theoretical potential being used, taking account of restrictions due to existing land use and nature conservation and of empirical values regarding the ratio of approvable areas to the areas available in principle. The right-hand figure is based on a more pessimistic estimate of potential which takes account of further acceptance and environmental restrictions. It is clear that in the metropolitan regions and in some of western Germany even the theoretical potential for electricity from renewable energy sources is insufficient to meet the high level of demand. In the long term, the situation will become more acute since power demand is likely to increase significantly after 2030 due to increasing levels of electrification.[59]

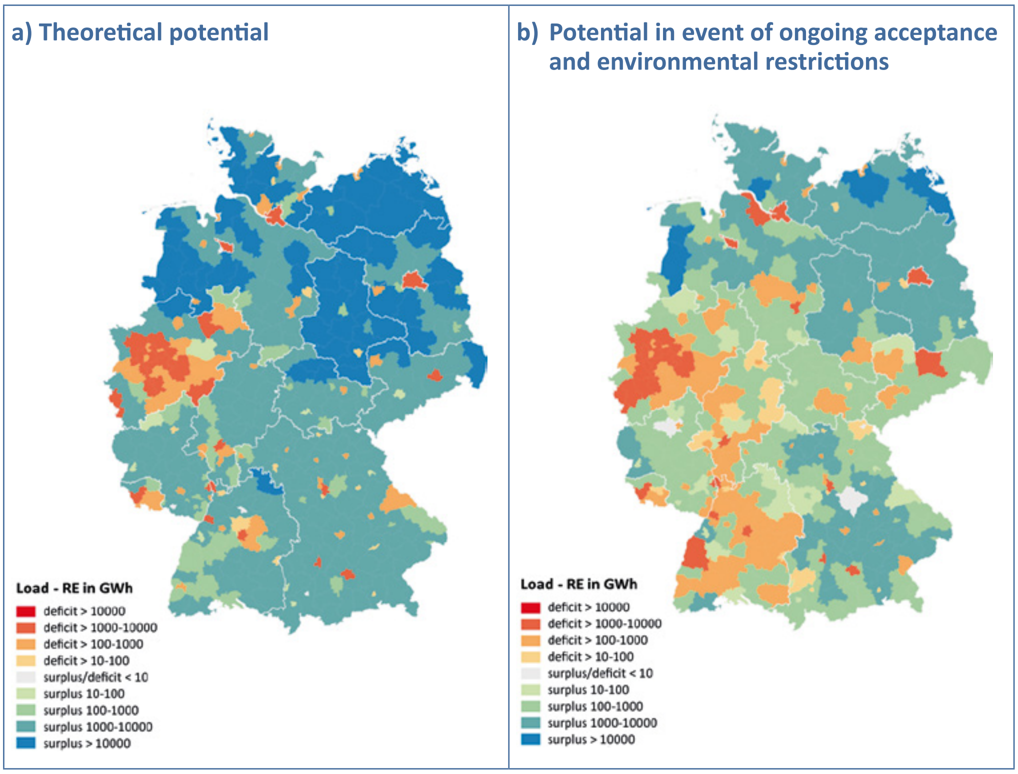

Figure 6: Possible extent to which renewable energies are capable of meeting demand in balance sheet terms at district level in 2030.[60] Underlying assumptions: electricity demand 431 TWh, onshore wind energy a) 1857 TWh, b) 253 TWh, photovoltaics 292 TWh, offshore wind energy 216 TWh, bioenergy 11 TWh, hydroelectric power 22 TWh.

The possible yields between different sites within Germany vary less severely for photovoltaic systems than they do for wind energy. Total annual insolation for sites with the least sunshine is, for instance, a quarter lower than for those with the most.[61] Many energy scenarios assume that photovoltaics will primarily be expanded in southern Germany. This might tend to reduce the need for grid expansion in a north-south direction[62]

59 How strongly power demand will increase depends on future trends in demand for energy services and on the efficiency of the technologies used. Energy scenarios include assumptions about advances in efficiency in conversion and consumption technologies. Most studies involve less detailed analysis of the consumption side than of the conversion technologies. Possibilities for energy savings due to sufficiency, i.e. doing without energy services (e.g. less car use, lower indoor temperatures, lower consumption in general) are not investigated in current energy scenarios.

60 Öko-Institut 2018-1, p. 28.

61 Based on German Meteorological Service data for averaged total horizontal insolation for 1981 to 2010 (Fraunhofer ISE 2019, p. 42).

62 Öko-Institut 2018-1, p. 5.

(see section 4.1.5). In fact, however, the expansion of solar PV farms has in recent years predominantly taken place in north-eastern Germany, since the advantages of readily available, lower price land more than offset the disadvantage of lower insolation.

Due to the anticipated increase in electricity usage for heating and transport (sector coupling), it is to be assumed that power demand will increase sharply over the coming decades, possibly doubling by 2050.[63] If wind and solar power systems on German territory are to virtually completely meet power demand, installed capacity will have to increase approximately six-fold over current levels.[64] Such huge expansion means that all potential, whether roof areas or open land, photovoltaics or wind energy, in the north or in the south, will in future have to be virtually fully utilized. The question as to whether for example additional wind turbines should be build in northern or in southern Germany is therefore one which will primarily arise in the next ten to twenty years. By around 2040, the potential will probably already have been so fully utilized that any further construction will have to use the majority of sites in all regions of Germany which have not yet been exploited.[65] Today's existing land-use conflicts around nature conservation, perceived impairment of landscape, impacts on local residents and competition with other land uses which have primarily arisen in response to the expansion of wind energy and transmission grids, will consequently probably intensify considerably (see section 4.3).

In the short term, one major goal is to bring about a considerable acceleration in the expansion of renewable energy sources because the current rate of expansion is insufficient for achieving climate protection targets.[66] This is a significant challenge in the light of land-use conflicts.

Although, at least in the case of an up to 85 per cent reduction in CO_2 emissions, it might well be technically possible to meet Germany's energy needs with domestic renewable energy sources,[67] the country will probably remain dependent on **energy imports** even in the long term. The reason for this is that, firstly, given increasing levels of land-use conflict, it would seem improbable that the expansion of renewable energy sources which is required for meeting the entirety of energy demand will be socially accepted. Secondly, regions with more wind and sunshine can generate energy at lower cost than Germany, so imports can also make economic sense.

Since in Europe there is a well developed integrated electrictiy grid, climate-friendly energy can be transported most efficiently and at relatively low cost in the form of electricity. Within the integrated European system, converting electricity into chemical energy carriers is above all of significance for long-term storage. For imports from non-European regions, however, gaseous (power-to-gas) and liquid (power-to-X) synthetic fuels (e-fuels) produced using electricity from renewable energies offer greater security and diversity in sources of supply because such fuels are easy to store, and transport is not dependent on a cable or pipeline network.

63 acatech/Leopoldina/Akademienunion 2017-1, p. 38.
64 acatech/Leopoldina/Akademienunion 2017-1, p. 8.
65 RLI 2013, p. 42.
66 acatech/Leopoldina/Akademienunion 2017-1.
67 acatech/Leopoldina/Akademienunion 2017-1.

Supplying industry with energy

The debate around decentralized approaches often focuses on supplying households with energy, in particular on self-supply using photovoltaic systems. So far, however, these account for only a very small share of power generation.[68] Self-supply is much more widespread in industry and commerce.[69] Industry above all makes use of natural gas-fired CHP plants. Since energy-intensive industrial plants have very high energy requirements in a small area, power generation close to the point of consumption, for instance by photovoltaic systems on the plants' own roofs, is more difficult to achieve than it is for households.

Accounting for approximately 30 per cent of final energy consumption, industry's energy needs are greater than those for households.[70] Approximately three quarters of consumption is accounted for by energy-intensive basic materials industries (chemistry, metal production, coking plants and oil refining, glass products, ceramics, rock and earth products and paper and paperboard).[71] Much of the energy required by industry is in the form of process heat at high temperatures of sometimes several hundred degrees Celsius (see figure).

Supplying industry and commerce with climate-friendly energy is a major challenge because energy-intensive industries are heavily dependent on a reliable energy supply and on electricity prices in order to remain competitive. Approaches to meeting energy requirements with renewable energy sources include conversion to electricity-based processes and the use of hydrogen or synthetic natural gas.[72] Bioenergy will also be able to assist with meeting industrial energy needs in future.[73]

The many different industrial processes involved mean that there is no universal solution but instead one has to be specifically tailored for each process. Energy-intensive businesses are currently trialling technical solutions in pilot projects.[74] However, commercial use is at present hindered by an unhelpful regulatory framework which makes climate-friendly technologies uneconomic in comparison with conventional processes.

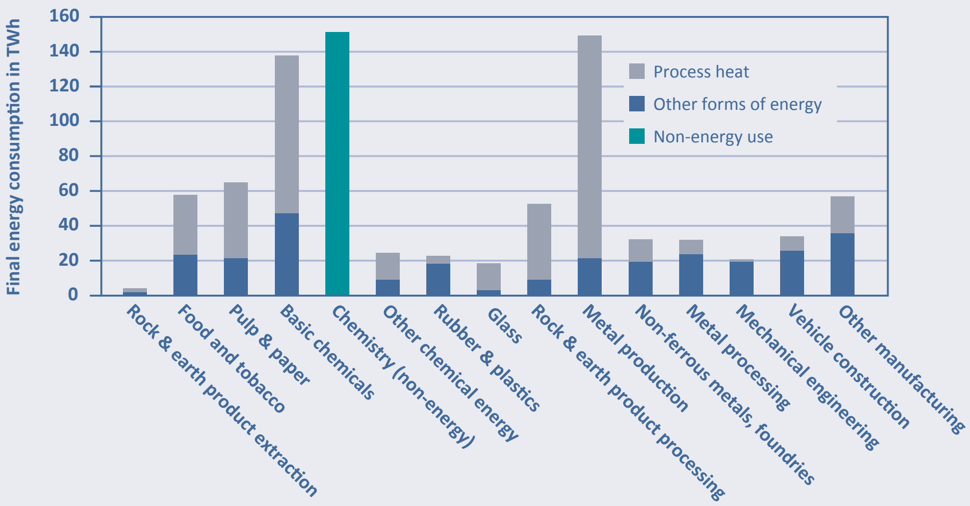

Figure 7: Industrial final energy consumption broken down by sector (source: Ausfelder et al. 2017, figure 11, based on data from Fraunhofer ISI 2016 and Statistisches Bundesamt 2016)

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68 No publicly accessible statistics are available which record power generation from photovoltaic systems for self-consumption, so this can only be estimated on the basis of total registered EEG plants (Aretz et al. 2017, p. 15). Based on data for 2016 (2015 for those federal states in which no data from 2016 was available), self-consumption from photovoltaic systems in Germany in this period was approximately 2.8 terawatt-hours (AEE 2017). This amounts to approximately 0.5 per cent of Germany's 2016 power consumption (BMWi 2019). According to an estimate from the German Association of Energy and Water Industries (BDEW), self-supply from Germany's single and double occupancy dwellings is at present approximately five terawatt-hours (DUH 2019).

69 Estimates suggest that in 2014 approximately 7.1 per cent (40 terawatt-hours) of Germany's electricity end-use consumption was met by industrial and 3.5 per cent (20 terawatt-hours) by commercial self-supply (BNetzA 2016, p. 7), overall around twenty times the self-supply from photovoltaic systems in 2016.

70 BMWi 2019.

71 acatech/Leopoldina/Akademienunion 2017-1, p. 33.

72 acatech/Leopoldina/Akademienunion 2017-1, p. 35.

73 acatech/Leopoldina/Akademienunion 2019.

74 Agora 2019, slide 4.

4.1.2 Short-term flexibility

Batteries will in future be the technology of choice for short-term storage of just a few hours. These can take the form both of **small-scale decentralized storage systems** in households and of **large-scale centralized storage systems** with a capacity of several hundred megawatts[75]. Suitable sites depend on a storage system's specific task. If its purpose is merely long-term (seasonal) energy balancing, siting can be flexible. In general, however, storage systems are mainly located close to generators or consumers. In this case, they can also be used to relieve grid congestions and provide instantaneous standby[76] and balancing power as well as reactive power. It may therefore be assumed that there will in future be a need for both site-related and site-independent storage solutions.

Installing both generating plants and storage or other flexibility systems (e.g. flexible consumers) close to the point of consumption makes it possible under certain circumstances to reduce levels of grid expansion above all in the distribution grid. Further detailed investigations are required to determine the number of regions or areas in which the requirements for simultaneous generation close to the point of consumption and flexibility are equally well met. Potential might in particular be available in medium-sized urban areas, and could to a certain extent also be increased by reconfiguring distribution grids. For example, if periurban integrated grids were connected to urban "sinks", it might be possible to ease the burden in terms of system services and grid expansion requirements.

Short-term flexibility can be provided not only by storage systems but also by **flexible consumers** (demand-side management; DSM). In relation to private households, attention is primarily focused on electric cars and heat pumps but the flexibility potential they offer is disputed. In the case of **electric cars,** the potential depends above all on the extent to which their owners will be willing to make the vehicle's batteries available to the energy system for charging/discharging operations. While **heat pumps** with thermal storeage do indeed offer considerable flexibility potential for a few hours to a few days, they only do so during the heating period and if the heating system is not in continuous operation due to extremely cold conditions. In the case of large industrial consumers, production processes can possibly be shifted in time to a limited extent or self-generation on the industrial site may be reduced.[77]

Overall, battery banks, electric cars and heat pumps have **great potential** to provide highly decentralized short-term flexibility in households and other consumers. There is, however, no guarantee that this flexibility is being used for the purposes of the overall system and contributes, for example, to reducing the need for centrally installed flexibility or grid expansion. There are simple and reliable methods, which have no appreciable impact on self-consumption capacity, of ensuring system-beneficial operation with regard to the avoidance of overvoltages.[78] However, this will not be sufficient for very high expansion targets and moreover assumes that it will be possible to motivate households to operate the installations in a system-beneficial manner.

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75 Spiegel Online 2019.

76 Immediate balancing of grid frequency fluctuations which is achieved today physically by the inertia of the flywheel mass of rotating power station turbines and generators.

77 UBA 2015.

78 See for example Moshövel et al. 2015.

System beneficiality and grid beneficiality

This document draws a distinction between grid beneficiality and system beneficiality.

Grid beneficiality denotes behaviour which has a positive effect on the power grid and thus assists in inexpensively ensuring electricity supply, for example by contributing to grid congestion management or to maintaining frequency and voltage stability. For example, the site selected for a renewable energy plant is grid-beneficial if the plant is constructed close to consumers so that the electricity does not have to be transmitted via potentially congested lines in the grid. Operation of a plant is grid-beneficial if decisions such as whether the plant is running at full load or part load are made with consideration for grid congestions.

System beneficiality is defined more broadly and is taken to mean behaviour which is beneficial to the overall energy system and takes account of the situation both on the market (price signals, balancing of supply and demand) and the grid. In an integrated energy system, account must also be taken, in addition to the electricity supply, of the interfaces with the heat and transport sectors. In addition to the system services in the power grid which usually run over short timescales, the overall integrated system requires further functions such as long-term storage for handling calm spells with low light.

4.1.3 Long-term flexibility

A distinction should be drawn between short-term balancing of generation and consumption, which can be relatively well managed with batteries and DSM, and bridging **calm spells with low light** lasting several weeks or indeed **seasonal balancing**. Using current technology, the only way the volumes of energy required for this purpose can be stored is in the form of **chemical energy carriers**. If, due to increasingly stringent climate protection requirements, fossil fuels can no longer be used, all that remains, in addition to the limited potential offered by bioenergy, is the production of hydrogen (electrolysis) and optionally further processing of hydrogen to form synthetic liquid or gaseous energy carriers (power-to-gas, power-to-fuels). In addition to sector coupling technologies, (transmission) grids and electricity imports are also capable of providing long-term flexibility (see section 4.1.5).

Electricity can be generated in long calm spells with low light by using **hydrogen or synthetic methane** as fuel in flexible power stations and converting it back into electricity (power-to-X-to-power). Energy scenarios which consider Germany in isolation (without electricity imports) reveal that, despite massive expansion of renewable energy sources, there will in future still be a need for some 60 to 130 gigawatts of combustion power stations or CHP plants, a figure which is of the same order of magnitude as today's power station fleet (100 gigawatts).[79] These power stations will, however, be operated at a very low utilization rate[80] so it may be assumed that electricity imports will be a distinctly more economic flexibility option. However, this will only satisfy the aim of reducing CO_2 emissions if the imports originate from a neighbouring country which likewise has a CO_2-neutral electricity supply, and investigations will be needed into whether imported electricity is really the less costly alternative given this condition. In addition to the countries' having a coordinated climate protection policy and

79 acatech/Leopoldina/Akademienunion 2017-1; dena 2018; BDI 2018.

80 For example, in model calculations for 2050 carried out in the ESYS project, full-load hours were 2,000 to 4,000 for CHP plants, 1,000 to 2,000 for combined cycle power stations and several hundred for gas turbines (acatech/Leopoldina/Akademienunion 2017-1, p. 43). These calculations assumed that coupling capacity with foreign countries remained constant at approximately 15.5 GW.

coordinated electricity market and environmental protection rules, using this option also entails sufficient interconnector capacity.[81]

In principle, both more centralized (e.g. large gas turbine power stations) and more decentralized power generators (e.g. small combined heat and power plants or fuel cells) may be considered. Energy scenarios primarily make use of gas turbine power stations and combined cycle gas turbine (CCGT) power stations, while more decentralized CHP technologies play a significant role in some scenarios.[82] The advantages and drawbacks of more centralized and more decentralized solutions for long-term flexibility are not specifically investigated in the studies discussed in section 3.

In addition to being converted into electricity in calm spells with low light, hydrogen and gaseous and liquid synthetic fuels can also be used in the **heat and transport sectors** and in **industry in order to cut greenhouse gas emissions from these sectors.** In addition, the **power excesses** which increasingly occur when wind energy and photovoltaics account for a large share of the energy system can be put to meaningful use. One example of a site-related flexibility option which is capable of reducing the need for expansion in the transmission grid is to install electrolyzers in the physical vicinity of offshore wind farms to convert electrical energy into hydrogen. If the hydrogen is further processed on-site into methane in appropriate synthesizers (power-to-gas), the methane can be fed into the existing gas grid.

The future role of power-to-X technologies in the energy system depends on how the energy supply in the heat and transport sectors is structured in future. If end-use applications are mainly purely electrical (e.g. electric vehicles, electric aircraft, electric ships, heat pumps, direct electrical heating, industrial electrical heating applications, industrial electrochemical reduction processes), the function of power-to-X will essentially be limited to the long-term storage of electricity. If, however, many end-use applications are operated on the basis of synthetic combustion and motor fuels, the latter will function more strongly as end-energy carriers. In this case, there would also be a greater need for infrastructure for importing synthetic combustion and motor fuels.[83]

The need for long-term flexibility complicates self-sufficient energy supply for the smallest units (e.g. households or multi-occupancy dwellings). This is because while a system for example comprising a PV system and battery can indeed balance fluctuations for a short time, electricity would have to be purchased from outside to bridge extended calm spells with low light.[84] A fuel cell installation or micro-combined heat and power plant would additionally be necessary in order to be at least electrically autonomous. In this case, energy could be purchased from outside in the form of hydrogen, biomethane or synthetic methane. The plant would, however, then be dependent on centralized structures for fuel delivery, i.e. hydrogen or natural gas pipelines. Making this “energy cell” completely autonomous would furthermore require an electrolyzer and a hydrogen tank. While from today’s perspective, this would appear largely unachievable for

81 European Commission 2019 discusses the possibilities of power exchange between EU countries and non-EU neighbouring countries including the Balkans, north African countries and countries of the Middle East.

82 For example Ausfelder et al. 2017.

83 acatech/Leopoldina/Akademienunion 2017-1 offers a detailed discussion of the potential, advantages and drawbacks of a direct electrical supply, of using hydrogen as an energy carrier and of synthetic combustion and motor fuels.

84 See box: “Self-sufficiency”. Bridging calm spells with low light by means of battery banks would require immense capacities.

an individual household or multi-occupancy dwelling, power-to-gas and CHP sector coupling components of the correct size are available for larger units such as neighbourhoods or businesses. Long-term flexibility may thus also be provided here in decentralized manner.

Providing long-term flexibility involves considerable expenditure for the energy system since, apart from massive expansion of renewable energy plants, dispatchable power stations are additionally required. In order to limit the costs of the energy transition, it is important to keep the required capital costs as low as possible, something which can be more simply achieved with larger power stations (see section 4.2.4). In addition, a European power market with associated European integrated grid is an inexpensive alternative to relatively costly power-to-X-to-power technology.

4.1.4 Natural gas grid

The chemical energy carriers produced using power-to-X technologies may either be used directly in the heat and transport sectors or converted back into electricity. Their advantage is that they can store energy relatively simply and with little loss.

In comparison with hydrogen, **synthetic methane** has the advantage that the existing **natural gas grid** can be used for transport and storage so there is no need for new infrastructure. The gas grid is very well developed in Germany and Europe which means that gases can even be transported across national borders within Europe. Transport losses within Germany are approx. 0.35 per cent of the transported energy content. Flexibility technologies such as power-to-gas or CHP can be relatively simply connected to the existing gas grid with its huge power and storage capacity (Germany: approx. 235 billion kilowatt-hours; Europe: approx. 1,070 billion kilowatt-hours); for instance, Germany's existing underground natural gas storage system is capable of storing approximately one third of the country's annual natural gas consumption. The flexibility of the gas grid is further boosted by LNG terminals and therefore renewable gas from non-European countries can also be fed into the gas grid. **Thanks to its high energy transport and storage capacity, the natural gas grid can make a substantial contribution to the security of supply** of the energy system of the future.

In the case of more centralized power generation from renewable energy sources relatively remote from the point of consumption, the gas grid can also help to make up for a shortage of electricity grid capacity for transporting energy to the consumer. Studies have shown that, with its capacity of approx. 53 gigawatts, the gas transport grid is capable of transporting at least the power surpluses arising in northern Germany, which would otherwise have to be curtailed, to southern Germany in the form of synthetic methane.[85]

More decentralized power-to-gas plants are, however, also able to relieve the load on power grids. Studies have identified potential of approx. 100 terawatt-hours biomethane and an additional approx. 80 terawatt-hours of methane from renewable electricity which arise essentially in northern and southern Germany.[86] According to the scenarios on which this study is based, production of methane from renewable energy sources will total approx. 42 terawatt-hours as early as 2030. Energy-optimized energy

85 Fischedick et al. 2013.
86 Erler et al. 2019.

cells with CHP and power-to-gas for sector coupling will be able to have a stabilizing action on the surrounding region.[87]

4.1.5 Grid expansion

Both the transmission and distribution grids will have to be adapted to the future structure of energy generation. In the media and the debate in society, attention very largely focuses on the transmission grid due to the protests against line construction, while the distribution grid is hardly mentioned. Many energy scenarios also take no account of the distribution grid, for instance just one[88] of the studies listed in Table 2 which consider centralized and decentralized scenarios does so. Studies which do include the distribution grid[89], mainly take no account of sector coupling or European integration and do not investigate centralized and decentralized scenarios. They do show, however, that the costs for expanding distribution grids will be higher than for transmission grids.[90]

Energy scenarios make it clear that **transmission grid expansion** is an efficient and **inexpensive flexibility option**. As a general rule, the larger the region the grid covers, the better the use that can be made of "portfolio effects", which describe the fact that wind and solar radiation vary to a greater extent over a larger area. [91] Importing power from reservoir-storage hydroelectric power plants (for instance from Scandinavia or the Alps) is an important flexibility option during calm spells with low light. In the absence of grid expansion, more relatively costly local storage systems would have to be constructed and the associated energy losses would have to be made up by additional wind energy and PV systems.[92] However, long-term storage systems based on chemical energy carriers and standby power stations will remain necessary even in the case of a pan-European "copper plate", i.e. a grid with unlimited transmission capacity. This is because weather systems with low winds sometimes occur simultaneously across the whole of Europe which means that geographic smoothing effects are limited.[93]

A study for Europe has shown that sector coupling can mitigate the cost disadvantages of reduced grid expansion since, instead of costly local power storage systems, it is possible to use less expensive flexibility technologies such as thermal storage and the battery capacity of electric vehicles. Grid expansion, including across borders, nevertheless remains an important element in ensuring an inexpensive energy supply.[94] All the investigated scenarios which meet long-term climate protection targets[95] require **substantial transmission grid expansion**. While constructing larger numbers of wind turbines in southern Germany and building a large proportion of new photovoltaic systems close to the point of consumption could well delay transmission grid expansion by up to ten years, grid expansion is unavoidable in the long term.[96] Moreover, the need

87 Ruf et al. 2017.

88 BMWi 2018.

89 For example dena 2012, BMWi 2014.

90 Hanson 2020.

91 DWD 2018.

92 Öko-Institut 2018-2, p. 29.

93 Linnemann/Vallana 2018.

94 Brown et al. 2018.

95 Most of the scenarios are based on a reduction target for greenhouse gas emissions of 80 to 95 per cent by 2050 compared with 1990 levels, which was in line with the official political climate protection target at the time of writing the studies. Since the publication of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 degrees Celsius, achieving greenhouse gas neutrality by 2050 is increasingly being discussed as a target for Germany and the EU.

96 Öko-Institut 2018-1, p. 6; WWF 2018-1, p. 25.

for grid expansion may change from a north-south direction to an east-west direction.[97] For a 2030 or 2035 time horizon, some studies have concluded that expanding renewable energy closer to load, ensuring a high proportion of household PV-battery systems and allowing greater curtailment of electricity from renewable energy plants will together mean that the need for grid expansion can be substantially reduced, in some cases by up to 50 per cent.[98] By 2050, however, the total levels of grid expansion in more centralized and more decentralized scenarios could become more similar again.[99] The grid development plan provides for grid expansion up to 2035. Studies have, however, concluded that over 13,000 additional kilometres of electrical circuit will have to be built between 2030 and 2050, which is as much grid expansion again as is planned for the period to 2030.[100]

In urban areas, the necessary distribution grid expansion will be caused less by new renewable energy projects than by the increase in electromobility. However, in more sparsely populated rural areas with numerous wind energy and/or PV systems, these will crucially determine the dimensioning of the distribution grids. Overall, it may be assumed that decentralized systems will require major expansion of the distribution grid to integrate local generating plants. Nevertheless, they cannot dispense with expansion of the transmission grid which connects large-scale power stations which are remote from the point of load (offshore wind).

In both the transmission grid and the distribution grid, flexibility technologies such as storage systems, power-to-X and dispatchable power stations are capable of reducing grid expansion to a certain extent and offsetting peak loads, but only if they can be operated in a system-beneficial manner. PV-battery systems which are used for maximizing self-consumption, on the other hand, do not reduce the transmission grid expansion requirement.[101]

The studies evaluated come overwhelmingly to the conclusion that transmission grid expansion cannot in the long term be avoided by more generation and flexibility technologies. In the short to medium term, however, expansion closer to load might, to the extent that incentives can be provided for system-beneficial modes of operation, contribute to meeting climate protection targets despite delays to grid expansion.

4.1.6 Digitalization of the energy supply

As “digitalization” progresses, information and communication technologies (ICT) are coming to permeate virtually all areas of life. In particular, how humans interact with their technical and social environment is changing. A distinction is often drawn between “push factors” and “pull factors” in digitalization, the former being ICT industry innovations which change the energy world from the outside while the latter are ICT innovations which result from energy system requirements. It is therefore important to monitor both major trends in ICT and the energy system’s ICT needs.

97 WWF 2018-1, p. 115.
98 For example Prognos/FAU 2016, VDE 2015.
99 WWF 2018-1.
100 BMWi 2017, module 5, p. 32
101 WWF 2018-1, p. 130.

Trends in digitalization

Independently of individual technologies, technological penetration in the ICT industry is growing exponentially, for instance in terms of the available communications bandwidth, processor speed or the use of innovative software. This is because of generally very low marginal costs of production (approaching zero for software) and network effects. In many areas this results, on the one hand, in oligopolies or near-monopolies such as Facebook, Google, Microsoft, SAP or Amazon and, on the other, in companies which penetrate markets extremely rapidly ("WhatsApp"). Platforms, cloud services etc. are amplifying this development and meaning that almost no initial investment is needed to conquer a major market (e.g. Lyft, Uber). The desire for faster product introduction and innovation entails a risk of accepting reduced quality and so increases the likelihood of security vulnerabilities. While security is indeed playing an ever greater role in "operations technology" (OT), namely in controlling technical systems such as power grids and major power stations, ICT and OT are growing closer together. In particular in an energy system with numerous small, decentralized facilities, rapid innovation cycles and a link to the internet can result in quality shortfalls and thus security vulnerabilities.

Two widely discussed trends, which will probably have a particularly major impact on energy supply, illustrate this development:

The Internet of Things

Even today, sensors, a simple processor and the ability to connect to communication networks using internet protocols are almost ubiquitous features of just about every newly developed item of (electrical) equipment. Toothbrushes, domestic electrical storage systems, distribution transformers and inverters for PV systems will in future be able to enter into communication. While grid equipment has its own partitioned communication infrastructure, an Internet of Things infrastructure based on the internet is thus developing outside the grid operator and is largely outside the control of energy suppliers.

Artificial intelligence, autonomous and learning systems

Artificial intelligence (AI) is a field of information technology which is attempting to emulate cognitive abilities such as learning, planning or problem solving in computer systems. Machine learning is a key artificial intelligence technology. It requires a large volume of example data which specific algorithms (procedures for computers) use as a basis for developing models by pattern recognition. These models may subsequently be applied to new, unknown situations. "Deep learning", which recognizes complex patterns on the basis of big data sets, is becoming ever more important.

"Artificial intelligence" (AI) is capable of recognizing specific patterns even in very complex information and, for certain tasks, AI will sometimes far exceed human capabilities. Accordingly, AI is capable not only of "understanding" complex situations for instance in the power grid but also of forecasting future trends and determining the optimum operational measures. Combined with ever more powerful processors, this AI-based software will be capable of quickly analyzing complex situations and making decisions. This is dependent on the underlying data being valid. If an AI system is additionally capable of adapting its algorithms during ongoing operation and improving the previously trained models, it is known as a **learning system.** Depending on the field of application, AI systems can carry out their task very largely autonomously, for instance to navigate a car safely from A to B. It could consequently be possible to gain technical mastery over even highly complex systems like the energy supply of the future. Autonomous systems may, however, also interact with one another and so themselves generate new patterns and arrangements (emergence) which, in the worst case, can compromise the stability of the energy system. Appropriate precautions must thus be taken in good time.

Necessity of further digitalization in the energy supply

The increasing complexity of the energy system can only be managed with a high level of automation. Since the requirements on the control systems will change continuously over the course of the energy transition, the software used must be easy to maintain. If plants are provided with the electrical options for grid-beneficial operation, software updates will allow adaptation to new, as yet unforeseeable circumstances. If, on the other hand, today's grid codes[102] are hard implemented, changing them would entail replacing the sensors and actuators[103] which is a very complex, costly and troublesome task for small-scale systems. In the worst case, this will result in its not being possible to completely eliminate an identified vulnerability for a number of years.[104] Software updates, on the other hand, can generally be implemented within a short period but involve the risk of introducing malware.

System software solutions

The fundamental ICT technologies, sensors and metering technology which will be required for the energy system of the future are already available. In particular, very mature technology is available for centralized systems (high- and ultra-high-voltage grids, large-scale power stations). While transmission grids already exchange large volumes of data between themselves to secure the system, use of this technology is only just starting to increase at lower voltage levels.[105]

Examples in operations technology are grid operation with control desks, telecontrol for equipment control and measurement (switches, protective devices, measuring instruments), smart meters, the ICT systems embedded in power electronics (for instance inverters for PV systems), connection and control of transformers and the control of virtual power stations. The degree of autonomy is, however, mainly still very slight. In part, it is not yet clear how "smart" components will behave within the system. Initial investigations would indicate that, on the ground, control systems can potentiate one another and so might work against one another. The only way to avoid this is for controllers to be able to coordinate with one another, i.e. to have knowledge about the system which goes beyond simple local measurements of power parameters.

Genuine active system management with comprehensive possibilities for intervention has previously only existed at high-voltage levels. With decentralized

102 Grid codes specify the technical rules with which power generation or storage system facilities must comply in order to obtain grid access (including voltage quality to be maintained, behaviour of the facility in the event of frequency deviations, access options for the grid operator).

103 Actuators convert electrical signals (e.g. computer commands) into physical properties (e.g. mechanical movement for opening or closing a valve).

104 One example which may be mentioned is the 50.2 Hz problem. In order to contribute to maintaining frequency stability, the grid code specified in 2005/2006 that PV systems should immediately shut down in the event of frequency rising above 50.2 hertz. However, the tacit assumption was made at that point that PV systems would only slowly become established. By 2011, however, installed capacity had already reached 25 gigawatts. Rapidly shutting down such capacity could lead to a blackout (BDEW 2012).

105 For instance in "Cooperation of grid operators in the cascade" (application rule VDE-AR-N 4140).

installations, possible responses in the event of crisis are limited simply to shutdown. There is still a great need for research into how to operate a system in which decentralized installations are responsible for stability, as there is still a major lack of systemic knowledge and understanding in this regard. Since the complexity of this system renders control by human operators impossible, only (partially) autonomous control systems, probably with AI assistance, will be capable of reliably and efficiently operating such a system.

Coordination of the energy system of the future imposes stringent requirements on the availability and quality of data. Different data sources have to be brought together and merged. One challenge in this respect is the different temporal and spatial resolution of different data sets.[106]

Standardized functionalities for decentralized systems

Additional requirements apply to more highly decentralized systems, with there being a need for standardized communication interfaces, generally applicable protocol solutions and controller building blocks for controlling decentralized installations. The existing smart meter gateway standard offers too little functionality for many decentralized cases of use (see box: “Smart Meters”, section 4.1.6).

For reasons of resilience, energy generation installations should be capable of performing at least basic functions even in the event of communication breakdown. Decentralized data processing can reduce susceptibility to failure since operation can be maintained even in the event of a grid or communication structure breakdown (see following section).

There is thus a great need for research and development and for standardization for information and communication technologies. Major areas of development are for example the real-time simulation of increasingly complex systems, the development of a suitable IT infrastructure and smart grid management systems.

If households (prosumers) are also to be able to operate their own decentralized installations system-beneficially, there must a low threshold to using the necessary information and communication technology. Moreover, only if equipment and systems from different manufacturers are compatible (interoperability) will the technology be “ready for mass use” and contribute to automation.

User-friendliness

The more decentralized the system, the more stakeholders participate and the more important do the interfaces between the technology and users become. In particular for technologies for households and prosumers, care must thus be taken to ensure that ICT as far as possible reduces rather than increases complexity in use. This may be assisted, for example, by improved plug-&-play-capable equipment and fully automated configuration and integration into existing ICT ecosystems.

106 Ensuring congruence among such data is an unresolved scientific issue in multi-scale modelling. There is a need for research here.

Despite all efforts to make the technology user-friendly, however, sector coupling will itself make the energy system more complex and so require different groups of stakeholders to develop a good level of knowledge.

Data protection issues are another important aspect of future ICT systems but since these issues are independent of whether the energy system is more centralized or more decentralized they will not be discussed here.

Resilience and IT security

Technical solutions should be designed to increase system robustness and resilience (see section 4.1.8). In addition to data protection aspects, the (perceived) security of new technologies can be crucial to their acceptance. Sufficient attention should therefore be paid to these aspects both in designing and in communicating technology.

Ensuring IT security will be a major challenge in future. While legislation and regulations do indeed already specify comprehensive security measures for large grid operators and major power stations including virtual ones (starting from 420 megawatts), and these measures are constantly being further developed, there are still gaps in IT security concepts for the energy world in the age of the Internet of Things. Even if the primary task will be to defend the networked energy system from cyberattack, everyone concerned must realize that there will always be security vulnerabilities which attackers will be able to exploit successfully. The capability of autonomous operation, artificial intelligence and processing local knowledge about system states promise solutions at a technical level.

The trend towards ICT monopolies is creating a risk which should be taken particularly seriously. A uniformly structured system reduces resilience since it favours the occurrence of "Common Cause Failures"[107]. For example, if a large proportion of prosumers use an identical control unit for their installations, this makes it easier for potential cybercriminals to obtain information about and ultimately control over a large proportion of the system. Basic components which have an internet interface for which there are no security standards are a particular problem in this respect.

There is probably a greater risk of such "monocultures" arising in a more decentralized system than in a more centralized one. However, this does not necessarily mean in principle a lower level of security: for instance faults can be identified and remedied more rapidly in such a system, whereas highly heterogeneous ICT presupposes a large variety of stakeholders and higher levels of competition, in which speedy market introduction is important so correspondingly increasing the risk of insecure solutions.

The interaction between numerous individual installations, where each individual operator considers the influence of their installation on the overall system to be low, is virtually impossible to control and regulate. Not only at system level, but above all at device level, improved cybersecurity is thus an absolute prerequisite for ensuring energy system security.

107 These are failures of a number of components or systems which occur as a consequence of an individual failure cause or event resulting in mutually dependent failure behaviour.

In general, a centrally controlled overall system also benefits from a decentralized approach to ICT. Making decentralized installations capable of behaving partly autonomously may distinctly boost resilience for example in the case of communication failures.

In brief, digitalization on the one hand improves the resilience of the energy system, but on the other hand, among other things in the case of inadequate security precautions, also creates vulnerabilities and so makes the system more susceptible to hacking.[108]

Smart meters

In Germany, "smart meters" are taken to mean electronic metering systems combined with a communication device (also known in Germany by the acronym "iMSys"). In contrast with the old mechanical Ferraris meter, which is today still installed in most buildings and is generally read once a year, a smart metering system permits more frequent reading since the digital meter saves and is capable of transmitting quarter hourly values. Combined with a return communication channel, this would permit flexible power pricing for households which would, for example, take account of wind and solar power availability and grid congestions (see section 5.3.3: grid fees).

A smart metering system consists of an electronic metering system or "smart meter gateway" and a communication link which provides access to authorized users (e.g. the energy supplier). The smart meter gateway may include several measuring instruments and potentially replace not only the Ferraris electricity meter but also gas and water meters. Detailed technical regulations and certification by the Federal Office for Information Security (BSI) ensure that it is extremely difficult to hack the transmitted data. The infrastructure also allows other services which are in particular need of protection to be carried via this channel, so avoiding the household internet connection which tends to be less secure. This and many other issues are governed by Germany's 2016 Act on the Digitalization of the Energy Transition, which is also intended to ensure that consumers are not burdened with costs that they do not wish to bear. This Act is based under European law on the Electricity and Gas Directives (2009/72/EC and 2009/73/EC) of the Third Energy Package. The meter infrastructure is set to be rolled out over the coming decades. In the absence of customer consent, the smart metering system still sends a cumulative meter reading just once annually.

While high standards have indeed been set in terms of security, criticism has been raised with regard to some points:

Data protection: Even if the system is highly secure when it comes to data transfer, customers are ultimately compelled to have their data acquired electronically by a device or system and, ultimately, any device can be hacked. Moreover, much experience with the implementation of data protection standards on the internet has shown that value-added services ("apps", social networks etc.) are often associated with extremely non-transparent data protection provisions and moreover offer little possibility of personalizing settings. A consumer is thus often compelled to consent to all the supplier's data collection intentions. The power consumption data acquired and collected in this way reveal some often highly intimate items of information about the occupants of a household, in particular if these data are linked with data from other sources and subjected to artificial intelligence analysis. In the light of these reservations, which admittedly do not relate solely to smart meters, the question arises as to whether and how informational self-determination can be ensured under the present state of digitalization.

108 A dedicated ESYS working group is investigating the need for action in relation to "resilience of digitalized energy systems".

Security: Many experts question whether the security of smart metering systems actually leads to increased system security. This is not only because entirely different "security standards" prevail away from the data transfer links (small municipal utilities for instance sometimes still send power consumption data by unencrypted email), but also because the process of certification by the Federal Office for Information Security would seem too sluggish: not only has the Office taken a long time to draw up the technical guidelines, it also carries out the certification. This has led to the rollout required by the Act hardly having started due to an insufficient number of devices having been certified. It is to be feared that this will result in a narrow, unattractive market which is low on innovation and leads to (costly) national oligopolies and that it will not be possible to take quick enough account of new threats and security vulnerabilities in updated guidelines and certifications. A similar problem arises with value-added services: new functionalities relating to energy or other services which are likewise important for the energy transition are thwarted by rigid processes. There is also a risk that, in order to avoid protracted certification processes, these new functionalities will communicate over the open internet without any technical security requirements.

Security of supply: The existing certification procedure can also weaken security of supply for similar reasons. If in future an innovative digital economy energy service provider takes on the energy management of households, for instance including domestic storage systems, electric vehicle charging, heat pumps and PV systems, the provider will have the capability of influencing several gigawatts of electrical power. Security of supply can be jeopardized if cybercriminals gain control of this system. An infrastructure of smart metering systems could mitigate this risk. However, here too, there is a risk of the energy service provider switching over to the less secure open internet since there is such a premium on being first to market a product in the digital economy. If, on the other hand, this route via the internet were to be prohibited by regulation, i.e. if smart metering systems and their associated inertia were to be required here too, a part of the energy transition which is particularly well suited to engaging society would be prematurely stifled.

Moreover, the scenario of an attack via smart meters of the kind described in the novel "Blackout"[109] cannot be directly transferred to Germany because the planned smart meters are as standard only capable of metering not of switching.

4.1.7 Coordination level

As a result of the fluctuating feed-in of wind energy and solar power, balancing consumption and generation will become more demanding in the energy system of the future. System services which are currently provided by coal- or gas-fired power stations will increasingly in future have to be provided by renewable energy plants and storage systems. This includes immediate balancing of grid frequency fluctuations which is achieved today physically by the inertia of the flywheel mass of rotating power station turbines and generators (instantaneous standby) and the provision of primary balancing power which absorbs short-term changes in load within a few seconds. The increasing number of interfaces between power generation, the gas grid and the heat and transport sectors (sector coupling) are also increasing the complexity of the energy system of the future.

These challenges apply both to more centralized and to more decentralized systems. However, the **more decentralized** the system is, **the more demanding** will it be to coordinate the numerous decentralized renewable energy plants, storage systems and flexible consumers. If, for example, households have a PV system, a battery bank, a heat pump with thermal storage and an electric car, they are in principle capable of

109 Elsberg 2012.

relieving the load on the grid by local load management. This does, however, entail forecast-based, system-beneficial operation of the systems. If, on the other hand, as is currently conventional, the systems are primarily operated with the aim of ensuring that the highest possible proportion of the electricity generated is self-consumed, without taking any account of the requirements of the higher-level system, decentralized systems may increase the need for grid expansion.[110] It is therefore important to provide incentives for system-beneficial operation of decentralized systems (see section 5.1).

An interconnected system with decentralized generating plants and flexibility options requires a **control hierarchy** which both takes account of local and supra-regional balancing and integrates supra-regional constraints into local load management. Control of integrated units within given grid structures, for example virtual power stations, will also become more important here. The greater the number of decentralized installations, the more it will in future be necessary to balance power via the distribution grids (instead of, as previously, by the transmission grid). This will mean developing the appropriate information and communication technology and expertise among distribution grid operators.

4.1.8 Resilience

Ensuring a high level of security of supply entails energy system resilience. A **resilient system** is capable of maintaining its functionality even under stress or, after failure, of rapidly reestablishing an acceptable level of functionality and of learning from such events.[111] It is capable of handling the harmful effects of any possible influences without collapsing.[112] Possible influences include on the one hand "shocks" such as component failures, external influences such as earthquakes or extreme weather events, grid overloads or cyberattacks (see section 4.1.6) and, on the other hand, "gradual processes" such as material fatigue.

Current trends towards sector coupling and decentralization in the energy system demand a nuanced evaluation when it comes to resilience. While interfaces to the heat and transport sectors, storage systems and demand-side management do indeed increase complexity, they also increase the system's heterogeneity and modularity. While, on the one hand, this might be capable of reducing the possibility of abrupt collapses, the complex structure and operational management of heterogeneous grids might, on the other, increase susceptibility to failure in comparison with a centralized grid structure.[113]

On the assumption that smaller units can be more readily monitored and controlled and the emergency measures together with resources better planned, decentralization could increase system resilience. In order to ensure that the inherent susceptibility to failure of decentralized systems and the extent of damage in the event of breakdowns and failures are kept to an absolute minimum, it is advantageous for decentralized systems to be capable of decoupling themselves from the higher-level system ("stand-alone mode") and of recoupling themselves at the appropriate time

110 Some scenarios (e.g. WWF 2018-1) investigate non-system-beneficial self-consumption.

111 acatech/Leopoldina/Akademienunion 2017-3, p. 6.

112 Kröger 2017, p. 52.

113 It is known from systems theory that closely coupled systems are more susceptible to failure than loosely coupled systems. Appropriate buffers as decoupling options should be kept on hand with a view to resilience.

("grid-connected mode").[114] There is a need for research into the additional costs of such systems so that the gains in terms of additional security can be weighed up against the costs.

If a subgrid is isolated from the remainder of the grid in the course of a fault scenario, the smaller is the isolated network, the greater is the impact of internal faults. However, only a few consumers are affected. A higher annual rate of breakdowns is expected with decentralized structures, but the energy shortage arising from the breakdown is smaller. In other words, susceptibility to failure might indeed rise locally, but the risk of cascades with an impact on the overall system across Germany or even Europe remains low.

What is crucial is to ensure that decoupling and recoupling of different grid zones is well coordinated by **smart operational management**. If this is the case, the highest possible level of local freedom of action can increase the resilience of the overall system.

A system which acts in a purely decentralized manner without central coordination, in contrast, is significantly more difficult to make resilient. The challenge is to ensure that the subsystems which act in decentralized manner do not influence one another in such a way that they jeopardize the stability of the overall system. It must be borne in mind here that the interaction between different faults may give rise to very complex effects on the system ("emergence"). The stability of the overall system must be ensured by suitable distributed algorithms for status evaluation and control even under exceptional circumstances such as cyberattacks. Implementing such algorithms with the necessary reliability is a particular challenge for a completely decentralized approach.

In summary, the security, susceptibility to failure and resilience of, in particular decentralized, energy systems of the future can as yet only be inadequately evaluated. There is a **need for research** among other things into analytical methods for gaining an understanding of the complex behaviour arising from rare events and combinations of events including attacks and tampering. However, the general **assumption should be that digitalization distinctly increases energy system vulnerability**. The macroeconomic **costs** in the event of a long-lasting blackout over a large area might well also turn out to be very high.[115] It is for these reasons that great significance should be attached to the issue of resilience in the assessment of the system architecture of the energy system of the future.

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114 See box: "Microgrids".

115 Hirschl et al. 2018.

Microgrids

The concept of “Microgrids”[116] is frequently a subject of discussion in relation to decentralized energy systems. This term denotes self-contained regional (low-voltage) subgrids which, on a temporary basis, are capable of carrying out their own energy balancing autonomously and separately from the remainder of the grid. Microgrids achieve this by calling on local, decentralized generating plants, storage solutions and flexible loads and using them to provide the local energy supply. They can be operated either coupled to or decoupled from the grid, i.e. autonomously as a stand-alone grid. A uniform definition of this term is yet to be established, it remaining unclear, for example, whether microgrids are smart and what order of magnitude they have. Microgrids may in principle assist in avoiding peak loads, reducing grid losses and increasing the resilience of the overall system. Figure 8 shows how different authors define the range of functions and aims of microgrids in the literature. It is clear that there is a great variety of conceptions of what a microgrid is and the purpose it serves.

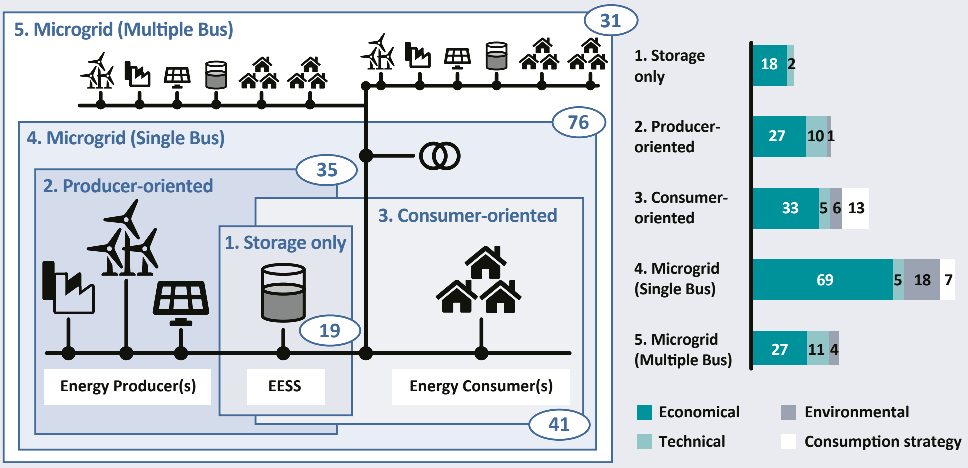

Figure 8: Range of functions and aims of microgrids in the literature [117]

4.2 Economic perspective

4.2.1 Classification of economic aspects

The energy policy triangle contains, as one of the main aims of the energy transition, not just environmental compatibility and security of supply but also economic viability. The economic aspect relates to how the energy transition can be configured most cost-efficiently or inexpensively. Minimizing total energy system costs is therefore also a leitmotif and objective when it comes to striking a balance between more centralized and more decentralized energy system configurations. It is also necessary to consider further aspects which cannot be simply quantified in terms of cost, such as changes to the landscape.

The **total system costs** are calculated in energy system studies as the sum of all the costs of the components involved in electricity supply (and sometimes also heat supply and the transport sector). They include fixed and variable costs for generation, transmission and distribution of energy and, if applicable, further system components, for example storage systems for providing the necessary flexibility. Macroeconomic and technical optimization calculations in energy system models tend to lead to the

116 For example Hirsch et al. 2018, VDE 2013, Siemens 2019, Industry of Things 2016, Handelsblatt 2019-1.

117 Weitzel/Glock 2018.

conclusion that **total system costs are lower in more centralized systems than in more decentralized systems,** although these differences are often small.[118] More centralized systems are distinguished by large generating units, a high degree of interconnectedness and an extensive grid infrastructure. Lower capital costs per installed power generation capacity and economies of scale make the generation of electricity in large power stations more cost-efficient than in small generating units. Furthermore, fluctuations in feed-in of wind and solar power due to weather conditions can be better balanced out over larger areas.

However, the underlying energy system models constitute an abstraction of reality and it is therefore necessary, when making comparisons and drawing conclusions, to take account of the simplifying assumptions made. First and foremost, the "decentralized scenarios" in the present studies do not model comprehensive decentralization (as described in table 1). In general, only distribution of wind turbines closer to load or an increased proportion of rooftop PV systems is investigated, for instance. In addition, the studies also generally assume strong interconnectedness in "decentralized scenarios". The impact of system-beneficial operation of decentralized plants is not generally taken into account. The present scenarios therefore do not permit any reliable cost estimates to be made about many aspects of decentralized energy systems.

Account also needs to be taken of the fact that the definition of the total costs used in the models does not include all macroeconomically relevant aspects. Effects such as environmental impact, impact on landscape and burdens on residents, which may be interpreted as external costs, are not initially taken into account in the models. By comparing different scenarios based on different assumptions (e.g. relating to the maximum stress allowed on the landscape), these aspects can be included in the evaluation. An investigation of a wider range of scenarios in energy system studies and greater inclusion of externalities when interpreting the results could provide a better basic principle for comparing more centralized and more decentralized energy systems. There is a need for research here.[119]

Overall, despite the gaps in knowledge in terms of the cost of comprehensive decentralized energy systems, the present energy system studies suggest that a more decentralized configuration of the energy system of the future leads to higher costs.

4.2.2 Electricity generation costs

Recent years have seen a marked drop in the cost of generating electricity using renewable energy sources. It does need to be remembered that electricity generation costs are heavily site-dependent and the positioning of a plant has a significant influence on overall generation costs. Horizontal global radiation at a site is critical to the energy output of PV systems, the equivalent for wind turbines being wind strength.

This **site effect** is more marked with wind turbines than with PV systems, since the full-load hours achievable also vary considerably with wind strength. For example, the electricity generation costs for a solar PV farm set up in southern Germany in 2018 are between 3.7 and 5.0 cents per kilowatt-hour, while for a new wind turbine

118 See section 3 and Hanson 2020.

119 Using models which take account of comprehensive decentralization would, however, require a very high level of detail and so lead to major challenges both in terms of data and computation.

at a coastal site with strong winds and 3,200 full-load hours the equivalent costs are between 4.0 and 4.9 cents per kilowatt-hour. However, at less favourable sites, electricity generation costs are distinctly higher; for instance, for a solar PV farm set up in northern Germany in 2018, these costs amount to between 5.1 and 6.8 cents per kilowatt-hour and for a wind turbine at a relatively low-wind site costs may run as high as 8.2 cents per kilowatt-hour.[120] A combined cycle power station has electricity generation costs of between 7.8 and 10.0 cents/kWh, but in contrast to wind and solar systems power generation is flexibly controllable.[121]

Within any technology group, however, **highly decentralized technology options** continue to suffer from considerable **cost disadvantages**. This is true of both renewables and conventional generation technologies. For instance, the electricity generation costs of a small rooftop PV system in southern Germany are between 7.2 and 8.4 cents per kilowatt-hour.[122] The costs of natural gas and biogas combined heat and power plants also fall, the larger are the plants,[123] since larger plants have lower capital costs per kilowatt of installed capacity and can be maintained and serviced more cost-effectively.

The **electricity generation costs of the most cost-effective renewable technologies are accordingly** already **lower than those of conventional plants**.[124] This is true both of larger PV systems at high-radiance sites and of wind turbines at high-wind onshore sites.[125] It is accordingly also already the case that, apart from CHP plants, virtually no further conventional thermal power stations are being planned for Germany.[126] The fundamental cost benefits of larger over smaller plants will continue to exist, however, in future systems. For example, it is anticipated that the electricity generation costs of solar PV farms will be between 2.2 and 3.9 cents per kilowatt-hour in 2035 and those of rooftop PV systems between 4.2 and 6.7 cents per kilowatt-hour.[127] As far as total system costs are concerned, **smaller plants** would thus only appear to make sense **if they are able to make a major contribution to cost savings in some other way**, e.g. by reducing the need for grid expansion.[128]

4.2.3 Stakeholder structure from an economic perspective

Expected returns, the proportion of borrowed and own capital and interest on borrowed capital vary between different groups of investors. Against this background, there needs to be careful scrutiny of capital costs which are assumed to be identical for

120 Fraunhofer ISE 2018.

121 Fraunhofer ISE 2018. (It is here assumed that CO_2 certificate prices and fuel prices for coal and gas will rise in future.)

122 Fraunhofer ISE 2018.

123 ASUE 2011.

124 The calculated electricity generation costs of fossil fuel-fired power stations are heavily dependent on the achievable full-load hours. An increase in full-load hours can reduce the electricity generation costs of fossil fuel-fired power stations provided the market situation allows this (Fraunhofer ISE 2018).

125 Fraunhofer ISE 2018.

126 On the other hand, it should be borne in mind that power generation in PV systems and wind turbines is dependent on external factors, while in conventional power stations and biomass plants it is controllable. This flexibility advantage of controllable plants is not modelled in the electricity generation costs. System context therefore needs to be taken into consideration in a more detailed assessment of the advantages of different plants.

127 Fraunhofer ISE 2018.

128 This is a macroeconomic, normative statement with regard to achieving the political/overall societal objective of cost-efficiency. It should be noted descriptively that smaller, more expensive plants will very probably be built (see also Karneyeva & Wüstenhagen 2017). This is due both to the wide range of stakeholders involved, their preferences and expectations regarding financial returns (see the following section) and to national regulations, which have an impact on the economic viability of investments made by different stakeholders, for example the regulations regarding self-consumption/prosumption (see section 4.2.5).

different technologies in overall system studies. For instance, small investors generally have lower expectations regarding returns than do institutional investors.[129] The cost benefits of the resultant lower capital costs are not sufficient, however, to make up for the additional costs of smaller plants.

Nevertheless, there are two economic aspects which need to be considered when looking at the role of decentralized facilities in the electricity supply of the future. On the one hand, investment decisions made by private investors are not only made on the basis of likely returns but also of non-monetary aspects[130] and therefore an active group of private investors is likely to demand lower returns from generating plants than institutional investors such as insurance groups and infrastructure funds. And these private investors will be contributing investment capital to the energy transition which otherwise probably would not be available.[131] On the other hand, there may well be a considerable **risk** that the potential areas identified for wind and solar PV farms in the energy scenarios will not actually be available due to **local resistance**. From an economic perspective, the negative external effects of large wind and solar power systems, for example adverse effects on landscapes, are not taken into account in technical and economic system models, or at best are only broadly taken into account. If these external effects are taken into account, the **decentralized expansion of renewables**, in particular of rooftop PV systems, could be **more advantageous,** not least because it reduces the risk of climate protection targets being missed due to local resistance to the expansion of renewable energy. Exploiting this potential could therefore be both a low-risk, financially worthwhile investment opportunity for ordinary citizens and strengthen acceptance of and participation in the energy transition, as well as having a positive regional economic impact.

4.2.4 Flexibility from an economic perspective

The energy system of the future will need new forms of short- and long-term flexibility rather than conventional power stations. **Provision of the necessary flexibility is generally less expensive in a more centralized system**, as synergies between sites which are remote from one another can be exploited. In a more centralized and spatially more extensive system, fluctuations in feed-in from wind and PV systems due to weather conditions can be partly evened out[132] whereas, in a more fragmented and thus more decentralized system with only limited supra-regional connections, local standby capacities have to be greater, so increasing total system costs. The cost of ensuring security of supply thus constitutes a higher proportion of total system costs in a more decentralized system. Battery banks, electric cars and heat pumps with thermal storage can provide very decentralized short-term flexibility, but at present there is no guarantee that this flexibility will be used for the benefit of the overall system. On the other hand, these short-term flexibility technologies are not sufficient to even out seasonal fluctuations (or indeed just fluctuations lasting several days) in feed-in from renewable energy sources (calm spells with low light). If the need for centralized installed flexibility such as gas turbines and grid capacity is not reduced or is reduced only

129 See for instance Helms et al. 2015.

130 These non-monetary aspects may include an interest in technology and a desire for energy supply independence, and also a personal readiness to drive the energy transition forward.

131 The assumption here is that such use of capital is more desirable in overall societal terms than alternative uses (e.g. investment in real estate or shares). Given the current global economic situation, in particular with persistently low interest rates, a shortage of capital does not seem to be a significant obstacle to investment.

132 DWD 2018.

slightly by the installation of decentralized flexibility, then in macroeconomic terms we have an **efficiency problem**, as sub-optimal use is being made of available resources.

4.2.5 Prosumption

For a prosumer system operator, self-consumption is economic if the remuneration for fed-in electricity is below the respective electricity purchase price (minus the duties payable on self-consumed electricity).[133] In recent years, the fall in EEG grid feed-in tariffs has made feed-in less economically attractive for rooftop PV systems in Germany.[134] In this segment, it is therefore primarily self-consumption which is the economic incentive for installing new generating plants.[135] However, economic viability is heavily dependent on the size of plants (PV system with or without storage system) and on the assumptions underlying the calculation of economic viability. Current studies suggest that with the regulatory framework as it currently stands, **larger rooftop PV systems** on detached houses are more **economic** than smaller ones, through the level of self-consumption is lower.[136] Self-consumption is also an important motive for installing power plants when it comes to other technologies such as micro-CHP, both at individual household level and in the commercial, trade and services sector and in industry.

From a societal and macroeconomic standpoint, **supporting prosumption**, in addition to involving the use of private capital, opens up the possibility of assisting in the energy transition by developing available rooftop potential, increasing acceptance and providing decentralized flexibility. The think-tank Agora Energiewende emphasizes, however, that optimizing a system for self-supply can lead to systems being relatively small compared with the available roof area and thus to the loss of significant potential roof area available for energy transition purposes.[137] According to the above studies, this does not currently appear to be case, but could arise if the privileges for the proportion consumed by the system owner become relatively more important.[138]

Given the way in which grid costs, surcharges and taxes are currently funded, an increasing proportion of self-consumption could unbalance matters, leading to an extra burden on the general public, because it would mean fewer people paying the fees and surcharges which are paid alongside the price of power itself and are used to fund the expansion of renewables and power grids and to ensure security of supply. At the moment, this problem has primarily arisen due to self-consumption in industry.[139] However, if the emphasis in the expansion of solar systems is on self-consumption systems, then they could also become problematic, especially since the grid and other costs per kilowatt-hour thereby avoided are generally markedly higher for small systems. It is, however, possible for excessively high incentives for self-consumption and

133 Schill et al. 2017.

134 In 2009, the remuneration rate was 43 cents/kWh for plants below 30 kilowatts, in 2012 it was 24 cents/kWh for plants below 10 kilowatts and in 2019 it was approximately 11 cents/kWh. Since around 2012 the EEG feed-in tariff has been below the end customer price.

135 Another incentive or funding option for private, grid-connected power plants is “net metering”, which is used for example in the USA and the Netherlands. The electricity meter for a domestic system runs backwards to provide a credit against the power fed in at the end of a billing period. This approach provides incentives for installing a PV system and for feeding in to the network, but not for grid-beneficial behaviour or the addition of storage capacity.

136 Dietrich/Weber 2018; Bergner et al. 2019; Bergner/Quaschning 2019.

137 Agora 2017-1.

138 This is the case, for example, if the current limit for photovoltaics of 52 gigawatts enshrined in the EEG is reached and self-consumption support funding continues to provide incentives only for the development of small systems.

139 Fossil power stations also self-consume electricity (e.g. to operate feedwater pumps or coal mills). This is comparable overall with industrial self-consumption. Since power station self-consumption is met at least in part by the grid and not by the plant itself, it is necessary at least to give some thought to including it in any reorganization.

the associated negative redistribution effects to be limited by reforming the fees and surcharges.

A further challenge is that the systems are currently designed to self-optimize and not to respond to system shortage signals and there has so far been little **incentive to adopt system-beneficial operating modes** and to provide flexibility. The first steps have been taken towards providing financial incentives for system-beneficial behaviour, but it is not yet known whether these steps which be sufficient if there is growth in the proportion of prosumer systems and consequently in their impact on the overall system. It is imperative to ensure, in future, that even if there is a high proportion of rooftop PV systems with and without storage systems, these do not have a negative impact on the overall system. Effective instruments must accordingly be developed in good time.

4.2.6 Grid costs and total costs

Grid expansion also constitutes a considerable cost factor when designing the energy system of the future. However, studies suggest that transmission grid-related costs are in the long term largely independent of whether the energy system is centralized or decentralized. The broad consensus is much more that **transmission grid expansion** cannot be avoided through decentralized expansion of generation and flexibility technologies, as it represents an efficient and inexpensive flexibility option. **The majority of grid expansion-related costs** will arise in the **distribution network** and, according to working group estimates, these costs will be **markedly higher in a more decentralized system**.[140]

Although more decentralized generation close to the point of consumption will potentially, in conjunction with corresponding storage systems, reduce grid expansion costs, these cost effects are limited for various reasons. Grid costs in particular are substantially capacity-driven, which means that it is not the average but rather the maximum power exchange across regions which acts as a costs driver.[141] The aggregation of numerous prosumers, whose systems feed in energy in a time- and weather-dependent manner, partially levels out these fluctuations.

In a large system, peaks in demand are markedly lower compared with average demand than in a small system. In addition to the tendency towards higher generation costs, smaller systems also make greater demands on grid control, which also raises costs. It is not only the long term which needs to considered in relation to grid expansion, but also the timeline. For the 2030/35 time horizon, some studies have concluded that expanding renewable energy plants closer to load, ensuring a high proportion of household PV-battery systems and allowing greater curtailment of electricity from renewable energy sources will together mean that the need for grid expansion can be substantially reduced, in some cases by up to 50 per cent. By 2050, however, the total levels of grid expansion in more centralized and more decentralized scenarios will become more similar again.[142] More decentralized expansion of renewables can therefore contribute to reaching climate protection targets even if transmission grid expansion

140 Hanson 2020.

141 Decentralized systems without wide-ranging interconnection and in which load balancing proceeds exclusively within small, self-sufficient cells would drive costs very high and are not evaluated here (see box entitled “Decentralization is not self-sufficiency”).

142 WWF 2018-1.

progresses more slowly than planned. In urban areas in particular, rooftop photovoltaic systems could be developed without additional load on distribution grids.[143]

It should thus be noted that, on the basis of current knowledge, **more decentralized energy systems** with a high proportion of small plants tend to be **more expensive** than more centralized systems and thus at first glance are **economically less attractive**. Given the risks of delayed grid expansion and local resistance to transmission grid expansion and new wind and solar farms, decentralized solutions, in particular rooftop PV systems, offer the **opportunity to increase acceptance of further renewable energy source expansion and to drive expansion forward,** in the process drawing on capital from private investors for the energy transition. However, if the energy transition is to be more decentralized, energy and flexibility must be provided in a way which is cost-efficient for the overall system, with account also being taken of the fact that **transmission grid expansion** is **essential** in the long term even for a decentralized system.

4.3 Environmental and spatial planning perspective

Climate change is placing a great stress on ecosystems around the world and is closely linked to the lifestyle of the western industrialized nations. It will only be possible to achieve climate policy targets if the consumption of fossil fuels is reduced enormously and the resultant savings do not result in higher energy consumption from other sources (rebound effect).

The provision of energy services always has environmental consequences. More efficient energy use can contribute to reducing the stress on ecosystems and therefore, irrespective of whether energy provision is centralized or decentralized, options for reducing energy consumption should always be investigated.

Due to the low power density of the primary energy used, land use is in principle high for renewable energy sources.[144] Impacts of relevance to protecting nature and the environment involve species and biotopes (e.g. the death of birds and bats caused by wind turbines), cultural landscapes (e.g. impairment of landscapes) and the land-use system (e.g. further industrialization of agriculture for energy crop cultivation and in the case of competition with other uses). Different regions have different competing land-use factors, and humans feel themselves affected to different degrees by the energy transition. Added to that, the limits to the capacity of the landscape to be used for energy infrastructure and use are seldom discussed. It is likely that these conflicts, which already constitute a substantial obstacle in particular to the expansion of wind energy and power grids, will only intensify as renewable energy sources are expanded. More attention should therefore be focused on careful handling of the scarce resource which is land than has hitherto been the case.[145]

143 Bergner et al. 2018.

144 To cover a power demand of 700 terawatt-hours in 2050, energy scenarios suggest that 1.5 to 2.3 per cent of Germany's land area will be needed for wind farms (total farm area, unsurfaced area) and 0.2 to 0.5 per cent will be needed for solar PV farms (WWF 2018-1, p. 88). For comparison, the proportion of Germany's land area used for traffic purposes (roads, pathways, car parks, railways, aircraft runways) amounts to five per cent (Statistisches Bundesamt 2017).

145 BfN 2018, p. 6 ff.

One problem is that there is no simple definition for the term "land consumption". This is because land may not actually be "consumed", just modified, for example improved or degraded. In addition, stress on a landscape is not limited to a two-dimensional portion of the earth's surface but rather covers a three-dimensional portion of the ecosystem, which also has societal functions. The term "land consumption" is nevertheless used as a rough construct for the purposes of argument to demonstrate the spatial impacts of various kinds of energy production.

Land demand per kilowatt-hour of electricity generated tend to be higher in Central Europe for wind energy than for photovoltaics, but these values may vary widely depending on location and type of system.[146] It should be borne in mind that with wind energy only a small proportion of the land used for a wind farm has to be surfaced for foundations, while the rest of the area of the wind farm can be used for agricultural purposes. The land beneath and between photovoltaic systems can also be used for other purposes. A combination of wind energy and photovoltaic systems on the same land is also conceivable, thereby contributing significantly to more efficient land use; however such dual use would have to be systematically researched. Incomparably more space is needed to generate one kilowatt-hour of biogas from energy crops: around six to twenty times as much as for one kilowatt-hour of electricity from photovoltaics.[147]

Apart from the land area needed, conflicts differ depending on the technology employed. Conflicts regarding species conservation and perceived landscape impairment have hitherto been more pronounced for onshore wind energy than for photovoltaics (see section 4.4.2). An investigation into conflicts regarding bird conservation has concluded that greater expansion of photovoltaics (in particular rooftop systems) can reduce the risk of conflict compared with wind energy. Nature-compatible wind energy expansion would nonetheless in principle be possible, but would require steering through better spatial planning instruments.[148]

Another study, which, in addition to bird and bat conservation, also examines quality of landscape with regard to human recreation, identifies just 0.05 to 0.1 per cent of Germany's land areas as suitable for wind turbines and 0.6 to 2 per cent suitable under certain conditions. The authors of this study consider photovoltaics to be the most nature-friendly of the renewables.[149] They also consider stringent spatial planning to be a prerequisite when it comes to allocating land for renewable energy plants optimally with regard to nature conservation.[150]

4.3.1 Circumstances in natural regions and existing situations

If an environmentally responsible energy system is to be developed, then the landscapes of natural regions have to be taken into account. Natural regions are both particularly suitable and particularly problematic when it comes to energy generation. They are

146 In scenarios for 2050 from WWF 2018-1, the average annual yield per unit area for wind farms is 45 kWh/m2 and for solar PV farms 62 kWh/m2 (WWF 2018-1, p. 151 f.). Yields can vary more than three-fold (BfN 2012) depending on location and therefore the average yield per unit area in scenarios depends on the assumed spatial distribution of the systems. The lack of a uniform assessment framework for land requirements is an obstacle when it comes to comparing the results of the various studies (Öko-Institut 2018-1, p. 6).

147 Nitsch et al. 2012, S. 80.

148 WWF 2018-2.

149 BfN 2018.

150 It should be borne in mind that these studies focus on selected aspects of species conservation, while other environmental impacts such as the raw material consumed in erecting installations are not considered. Comprehensive life cycle analyses would be needed for a full evaluation.

particularly suitable, for example, because of wind conditions, sunshine hours and the possibility of damming rivers for hydroelectric power or of energy recovery through fracking. Examples of obstacles are geological conditions, which may prevent particular uses or significantly increase the cost of planning measures.

Secondary problems are **conflicting space demands**, which are difficult to reconcile with energy production. Spatial planning not only defines priority areas for wind turbines, but also excluded or taboo areas. Nature and landscape conservation areas are therefore taboo areas for energy infrastructure. When it comes to residential areas, proximity regulations have to be complied with in relation to the long-distance effects of energy production and of storage and transport systems (noise, impact on landscape etc.). Under certain circumstances, higher expenditure can create compatibility between uses, enabling more and better planning options. This is the case, for example, with power lines, when overhead lines can be replaced by cable routes. Who bears these increased costs and who benefits from this investment is an economic and socio-political question.

Existing land use may offer potential ways of integrating new energy infrastructure, with the following being possible approaches:

1. **modernization** of existing energy infrastructure (e.g. repowering of wind farms),

2. **stacking** of uses (e.g. erection of PV systems on roofs),

3. **mixing** of uses (e.g. car park roofs with solar panels providing shade or PV systems over large areas of pasture land: agrophotovoltaics).

Such potential should be identified in the context of land use planning, with part of this process being to ensure that areas that are already environmentally burdened do not suffer yet more stress. Remediation of such areas could offer possible starting points for the integration of new energy plants in line with the above strategies.

4.3.2 More (de)centralized spatial planning strategies

Planning legislation at federal, state and local level ensures areas and corridors are set aside for different uses at different planning levels. Zoning plans, regional plans, state development plans and planning at federal level allow spatial needs to be coordinated, with environmental concerns being addressed and given expert consideration at municipal level (landscape plans), regional level (landscape structure plans) and state level (regional landscape plans). Such plans are frequently subject to legal challenge, meaning that the courts also bear responsibility for implementation of the energy transition. This spatial planning system also incorporates legally required assessments such as environmental impact assessments and planning determination procedures, so ensuring the implementation of further environmental protection. Under EU law, for example, certain species are strictly protected, which impacts on the likelihood of approval being granted for a route or project.

Plans are drawn up on the basis of policy decisions which place more or less weight on energy policy concerns as compared with other concerns (weighting). Public participation can be organized in parallel. During the planning process, the requirements of the various scenarios are translated into concrete land requirements, with those affected having the opportunity of clearly stating their interests. Those unaffected can play the part of "lay planning assessors" to formulate recommendations in the interests of the public good.[151] In principle, centralized concepts tend to impact more at higher level while more decentralized measures impact more at regional and local planning level. Participation is currently more practised at the lower levels than the higher levels.

Regional and local planning is of particular relevance when it comes to **more decentralized facilities**. The German regions differ in natural landscape and degree of development. They are battling with different problems (e.g. coal-producing regions) and will be faced with different challenges with regard to the energy system of the future.

Regional significance analyses of energy policy measures, including using geographical information systems (GIS), can improve the basis for decision-making, as they identify positive and negative impacts not just at a social but also a spatial level.

The Bundesnetzagentur, the Federal Network Agency, is responsible for overall approval of the German transmission grid, by planning the north-south and east-west routes, and for embedding it into the European grid using interconnectors to neighbouring countries. Distribution grids are planned on a smaller scale. Organizationally, it would be helpful for these to correlate with regional administrative authorities, so that political bodies can also bear responsibility for decisions on distribution grids. Technically, however, it would further simplify planning if the boundaries of planning areas were in line with the needs of energy transportation and other grid-related criteria. This would mean in practice that a conurbation with high power demand would be combined in a distribution network with the surrounding suburban and rural areas with a high concentration of renewable energy plants (regional grids).

4.4 Social perspective

When it comes to successfully transforming the energy system, one relevant question is how low-emission energy infrastructure can be embedded reasonably into society. Issues of social acceptance or future acceptability[152] are accordingly a major criterion. This also applies to the question as to whether the energy system should be structured in a more centralized or decentralized way. Other factors involved in this decision include not only the energy generation and transport infrastructure and its effects but also the relevant stakeholders and organizational structures of the overall system.

4.4.1 "Centralized" versus "decentralized" in the debate in society

In the current debate in society, the frequently expressed assumption or hope is that a decentralized system will enable a smaller-scale, more grassroots focused expansion of renewable energy sources and will reduce the need for grid expansion, in particular at the transmission grid level. As a consequence, decentralization has positive connotations and decentralized solutions are frequently communicated as the preferable

151 For the concept of "lay planning assessors" see Oppermann/Renn 2019, p. 57.

152 Acceptance is the empirically measured willingness of people to tolerate a technology or project in their surroundings. Acceptability is a value-based judgement as to how deserving a technology or project is of acceptance, the pros and cons having been weighed up. It is the result of an evaluation process based on criteria which are commonly agreed in the community making the judgement. See also acatech 2011 for difference.

expansion option. The evaluation carried out in this publication of the scenarios from various studies, in contrast, reveals that, in the long term, centralized and decentralized scenarios differ very little with regard to grid expansion.[153]

The discussion is frequently based on the narrative that "decentralized" means renewable and thus "clean" technologies, while "centralized" in contrast means fossil and nuclear energy carriers which need to be replaced. While this was correct for the first decades of the energy transition, today major energy supply companies are also planning large wind farms and PV systems and are so becoming stakeholders in the energy transition.[154]

Questions of acceptability are based on central norms and values which, by general opinion, are deemed to be standards for a constitutional state which permits free development for its citizens. In addition to the higher-level criterion of social justice, these include economic and political participation, transparency, maintenance of biodiversity and the creation of a sense of belonging for people in their respective cultural landscapes (see box: "Ethical criteria"). It is not least a matter of responding to the question for society as a whole as to how these central ethical values can be maintained or even strengthened as the energy system is transformed. If the stated criteria are applied to centralized and decentralized technologies and systems, it is apparent that neither centralized nor decentralized approaches are in themselves superior. Instead, as is shown below, the outcome of the evaluation is dependent on the specific technologies (wind energy, photovoltaics, power grids). There is therefore no reason on the basis of the social evaluation to have a general preference for a more centralized or more decentralized configuration of the energy system.

Ethical criteria

Justice	Fundamental to a diverse and plural society. Justice generally means **taking consistent and justifiable account of what is reasonable in each case**. From time immemorial[155], justice has encompassed justice in general (in Aristotle: complete righteousness, in later mediaeval times: focus on the common good), distributive justice ("to each their proportionate due"), commutative justice of a voluntary nature ("to each the same in exchange") and of an involuntary nature (corrective justice: "compensation for harm/reasonable penalty for an offence"). To these can be added modern concepts of procedural fairness including equality before the law and equity in participation in decision-making processes and in enabling the latter.[156]
Transparency and reversibility	Where transparency prevails, planning and decision-making processes are **disclosed** to all. The **procedural fairness** which is consequently enabled additionally includes the possibility of complaint and reversibility of decisions in line with the principle of equality (identical cases are identically treated).

153 See section 3.

154 For instance the energy supplier EnBW which is planning a 164 hectare solar farm in Brandenburg, or BayWA which has completed a 265 hectare solar farm in Spain. Areas in the Ruhr and in Lusatia in eastern Germany are of interest to large energy suppliers as sites for PV and wind farms. See Windmesse 2019; PV Magazine 2018; Handelsblatt 2019-2.

155 See Höffe 2015 for an overview of the various aspects of justice.

156 See Dabrock 2012 for the current debate around participation and in particular enabling.

Participation - **Political** - **Economic/ financial**	Participation is achieved a) politically when as far as possible **all social groups** can communicate their interests and so gain fair access to the political dialogue. Decision-making institutions have an obligation of careful consideration. b) Participation may, however, also have an **economic** or **financial** meaning. In this case, it must be clarified whether burdens and advantages are distributed socially, regionally and over time (equitable distribution across the generations).
Biodiversity and sustainability	Biodiversity means maintaining the biological diversity of **landscapes and ecosystems**, which are not least a resource vital to human life on earth (soil, clean water, clean air). Sustainability comprises environmental, economic and social components, which include the aim of biodiversity and thus the conditions for humanity's survival.
Possibility of responsible action[157]	Decisions should be taken in such a way that those affected can still act responsibly in the light of the consequences. This includes the requirement that these consequences must not create dilemmas in which the remaining options are ethically unacceptable or associated with unduly major disadvantages
Good life - **Sense of belonging** - **Social cohesion/ solidarity**	A good life involves taking account of fundamental cultural and social needs, including people's sense of belonging in their particular historical cultural landscapes and their emotional and cultural attachments. This category also includes the quest for the **common good, social cohesion** and **solidarity**, which are frequently embodied by, but not limited to, a **fair apportionment of the costs and benefits** of the risks and burdens of life.

Numerous conflicts, for instance the protests around the expansion of the Süd-Link power route or the formation of numerous citizens' action groups against the construction of wind turbines in their immediate locality, have shown in the past that citizens frequently consider that their central ethical values are challenged by the transformation of the energy system. The lines of conflict in matters of acceptance in relation to the technologies of wind energy and photovoltaics are addressed in a nuanced way below (see 4.4.2).

Research has shown that both the acceptability and the acceptance of energy infrastructure projects depend on a number of different influencing variables situated at the levels of technology (e.g. landscape impact), the individual (e.g. environmental or energy consciousness), context (e.g. location, planning procedures)[158] etc. and which are of relevance to both more centralized and more decentralized scenarios. Factors which influence both acceptability and acceptance include having an understanding of the necessity for the energy infrastructure and the associated aims and means, a positive cost/benefit or risk/benefit balance with a directly perceived personal benefit, experience of self-efficacy (possibility of exerting influence and maintenance of personal agency) and emotional identification with the measure or infrastructure. [159] Further important influencing factors are the qualitative characteristics of stakeholder relationships such as trust and the effect of the experience of justice during the planning procedure on acceptance. All the stated factors are closely linked to the form taken by the opportunities to participate (see following sections).

157 This corresponds to the principle of maintaining the conditions for responsible action (Kornwachs 2000).

158 Walter 2014; Zoellner et al. 2012.

159 Renn 2014.

4.4.2 Technology-related conflicts

Social conflicts around energy plants differ depending on the technology involved. Technology-related conflicts relating to wind energy and photovoltaics are discussed in detail below. In bioenergy, conflicts are heavily dependent on the nature of the plants and in particular on the nature of the raw materials used (e.g. wood, energy crops, waste materials).[160]

Spatial impact of wind turbines

Various acceptance factors arising from wind energy technology or its site-related effects are of relevance to the use of this technology.[161] In onshore wind energy, which will be significantly expanded in all the decentralized scenarios shown in Table 2, the greatest acceptance factor is landscape or spatial impact. There is a prospect of greater conflict arising from the need to build wind farms increasingly also in forest areas once all the free areas in northern Germany have been occupied. Already, there is a subjective feeling in many regions of a limit having been reached, with people complaining of being "visually hemmed in" by wind farms.[162]

Further major acceptance factors which may be mentioned include a fear of health impacts and effects on quality of life. The primary focus here is on the noise emissions and (infra)sound effects of the turbines, despite no harmful effects of infrasound having been demonstrated.[163] Individual federal states have addressed concerns at both of these levels by making their regulations governing distances from residential areas more stringent[164] and have so significantly reduced available land areas. This conflicts firstly with the aim of providing the greatest possible area for wind energy. Secondly, citizens might consider it unfair and thus unacceptable for distance regulations to differ greatly between the federal states and so feel themselves to be unequally and thus unfairly treated.

The fundamental principles of fairness and justice require that the burdens and advantages arising from the transformation of the energy system are distributed socially, regionally and over time (intergenerational justice). If, for example, energy infrastructure has been greatly expanded in one region but only other, far distant regions benefit from the energy which is produced and transmitted, this can result in great potential for conflict and a consequent lack or absence of local acceptance. Local concerns are thus an important factor when it comes to implementing energy projects and can often quickly result in projects not being implemented or having to be replanned, potentially leading to years of delay. One major example of this are the protests around the construction of the Süd-Link power route, which meant that underground rather than overhead lines had to be used, so delaying the project and increasing the costs of construction.

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160 A detailed examination of various bioenergy technologies, including with regard to social acceptance, can be found in acatech/Leopoldina/Akademienunion 2019.

161 Hildebrand et al. 2018, p. 198.

162 Taeger/Ulferts 2017; HMWEVL 2017.

163 Hildebrand et al. 2018, p. 198; UBA 2016.

164 In Bavaria, the "10-H regulation" has applied since November 2014 and specifies that wind turbines must be at a distance of ten times their height from a residential area. Some other federal states have recommended distances from inhabited areas (Brandenburg: 1,000 metres), rules for calculating the necessary distance on a case-by-case basis (North Rhine-Westphalia: 1,500 metres when installing five turbines of the four megawatt-class in the vicinity of purely residential areas) or various fixed distances (Schleswig-Holstein: 800 metres; Hesse: 1,000 metres). Berlin, Bremerhaven and Saxony have no distance regulations (FA Wind 2019).

Consideration should here be given on the one hand to suitable **financial participation and compensation schemes** which enable the affected citizens to benefit from the installations, for instance by enabling local wealth creation.[165] Opportunities for **financial participation** can counter the feeling that the only beneficiaries of the energy transition are major corporations and system operators while the tangible and intangible costs are borne by the population. Participation in the economic benefits of a plant can increase perceived distributive justice. It must, however, be borne in mind that financial instruments are just one aspect which combine with others in the process of nurturing acceptance. Whether and the extent to which they are effective is heavily dependent on context. In addition, overall little empirical evidence is available. Previous offers in relation to grid expansion (west coast route, "Rösler dividend scheme") met with little success, there being almost no demand for them. In relation to wind energy, the Participation Act in Mecklenburg-West Pomerania or the "Faire Windenergie" label in Thuringia have not yet been evaluated in terms of their effects on acceptance.[166] The **high level of context-dependence** is also apparent in cases in which, due to the absence of a relationship of trust, citizens have regarded the compensation offered by a system operator to be a "bribe", which has even intensified the conflict.[167] Financial participation is thus no guarantee of acceptability and acceptance, but instead one acceptance factor among many. The way in which the affected population evaluates offers of financial participation depends, among other things, on relationships of trust (see section 4.4.3).

On the other hand, the spatial distribution of infrastructure remains an important aspect of planning (see section 4.3). It is possible to measure the local concerns or burdens affecting residents in the form of a "level of burden", for instance by relating the density of existing installations in a region to its population density.[168] On this basis, an expansion pathway intended to ensure a level of burden which is as uniform as possible across Germany would intensify wind turbine expansion in southern Germany and Mecklenburg-West Pomerania while delaying expansion in the coastal regions and Lower Saxony. Including population density in the level of burden tends to lead to new RE construction in areas remote from the point of load.[169]

Important as it is to determine a "fair" distribution of the burdens of energy systems, the limitations of such a calculation are that local concerns are frequently of a "highly subjective nature"[170]. "Regional identities and attachments"[171] thus play a major role in the perception of concerns.[172] As a consequence, acceptance problems cannot be adequately predicted or resolved simply by calculations. It is apparent here that, when it comes to striking a balance between "centralized" and "decentralized", people's sense of belonging in their particular historical cultural landscapes and their emotional attachments play a decisive role. This has an impact on the ethical criterion of a "good life" which means taking account of the cultural and social needs an individual considers

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165 See Hildebrand et al. 2018, p. 198: commissioning local companies to carry out infrastructure measures during the planning, construction and operation of the installation, participation schemes (e.g. citizens' wind turbine) etc.

166 Hoffmann/Wegener 2018.

167 Cass et al. 2010; Walker et al. 2017.

168 Öko-Institut 2018-1 (p. 29) proposes calculating the level of burden by multiplying the proportion of a district's land area used for wind turbines by the population density.

169 Öko-Institut 2018-1, p. 30 ff.

170 Hildebrand et al. 2018, p. 199.

171 Hildebrand et al. 2018, p. 199.

172 Such an approach does not take account of environmental aspects either.

fundamental to their way of life. However, in terms of a sense of belonging, one concept of a “good life” may also involve a desire to actively shape and reshape this place where an individual belongs. This can be motivated, for example, by environmental grounds or reasons of solidarity, issues of the common good, social cohesion or an apportionment of costs and benefits which is perceived as fair. In a nutshell, a sense of belonging to a place is not synonymous with blind intransigence or a feeling of the place being sacrosanct, but may also include a willingness to change.

Offshore wind turbines have relatively few local impacts,[173] with stakeholders in shipping, the military, nature conservation associations and tourism primarily being affected. Existing approaches such as participation in defining layout patterns and further technological developments to mitigate environmental impacts (noise) should be continued.

Spatial impact of PV systems

PV systems have so far more rarely encountered acceptance problems in terms of changes to the landscape and land take. Consequently, a decentralized scenario with numerous PV systems and few onshore wind turbines theoretically offers advantages in terms of acceptance over a centralized scenario. The additional construction of photovoltaics which will in future be required may nevertheless lead to greater levels of criticism. PV systems may in particular be installed in areas which are already in use, such as residential and commercial areas with large areas of flat roof or car parking.

Support scheme for PV systems

In the debate in society around photovoltaics (installations on rooftops and on open land), there is less emphasis on technological effects than on the support scheme funded by the EEG surcharge. The main criticism here is a perceived redistribution from the bottom upwards: it is often higher income households which benefit from the systems or the feed-in tariff they earn because they have the financial means to invest and the necessary area in the form of buildings or land, while low-income households who cannot make such investments are co-funding the costs of the technology by paying the EEG surcharge.[174] Further development of existing approaches to roof exchanges[175] and tenant electricity models, which are already embodied in legislation, is currently under discussion to enable reasonable participation by broader sections of the population.

4.4.3 Trust in energy transition stakeholders

The inclusion of ethical criteria such as **trust and justice** is all the more significant when it is borne in mind that surveys have revealed that citizens tend to have greater trust in **smaller and local decision makers** when it comes to implementing the energy transition in Germany. Almost half the respondents from the 2016 Fraunhofer ISE acceptance survey stated that they had little or no trust in large energy suppliers in matters relating to the implementation of the energy transition in Germany (Figure 9).

173 Hübner/Pohl 2014.

174 Heindl et al. 2017; Agora 2017-1, p. 43; in Fuchs et al. 2016, p. 10 this aspect is described as a “real-life problem” with “a not […] inconsiderable potential for conflict”.

175 A roof exchange acts as an intermediary between roof owners who cannot or do not wish to invest in a PV system and potential investors. The owner then leases their roof for a defined period to the investor who shares a percentage of the income from the generated PV electricity with the owner (strom magazin 2019).

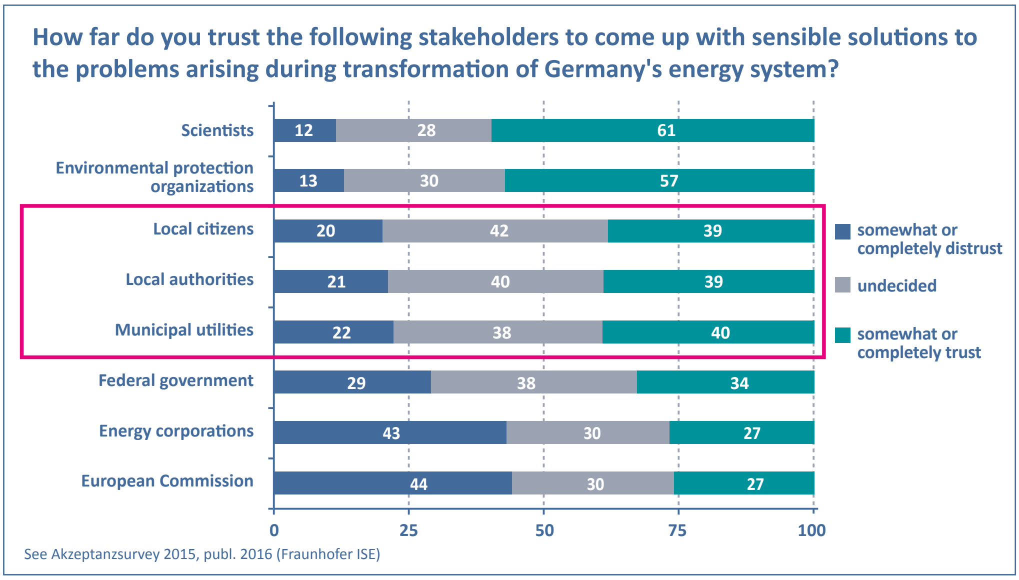

Figure 9: Survey results regarding trust in different energy transition stakeholders[176]

The survey also revealed that 42 per cent of the population considered large energy companies to lack good faith in the implementation of the energy transition. Only 23 per cent said that the companies were doing good work in the implementation of the energy transition (Figure 10).[177]

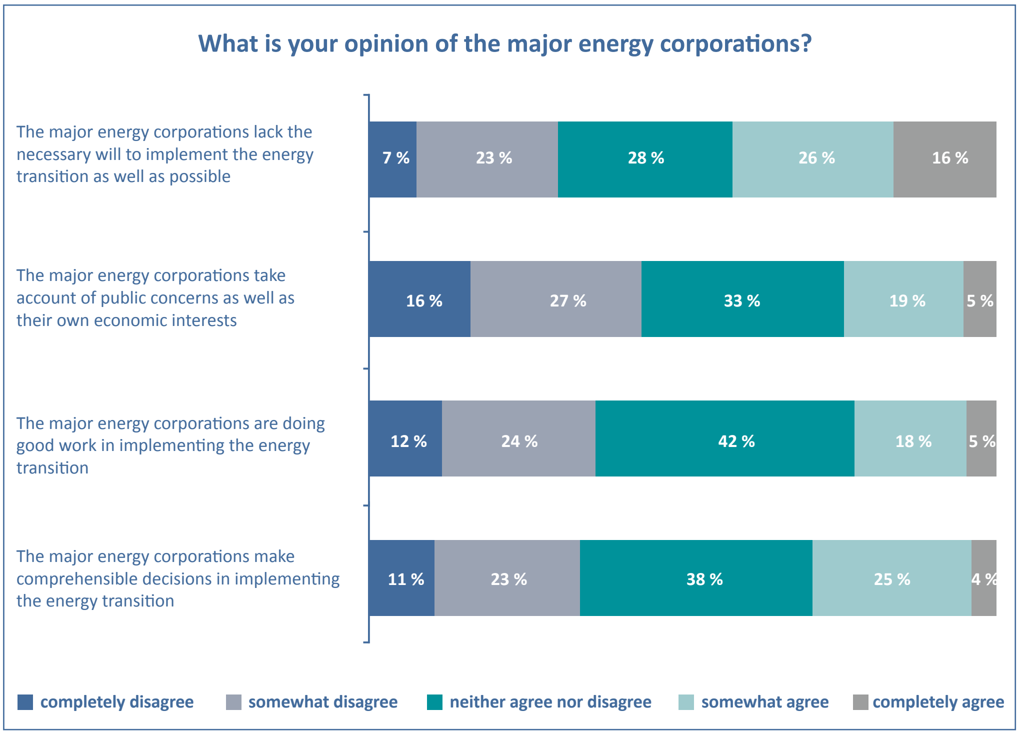

Figure 10: Survey results regarding the assessment of the large major energy companies[178]

176 Sonnberger/Ruddat 2016, p. 28.
177 Sonnberger/Ruddat 2016, p. 30.
178 Sonnberger/Ruddat 2016, p. 30.

In contrast, **environmental protection organizations** (57 per cent) and **scientists** (61 per cent) enjoyed high levels of trust among the population, presumably because they are perceived as being independent of power and economic interests (Figure 9).[179] Local stakeholders, who are closer to citizens' everyday lives, rank above the energy companies and the European Union in the surveys.

Research into social acceptance of the energy transition shows just how important it is for citizens to have trust in the various stakeholders involved in implementing energy projects. This is all the more the case where major project planners such as supra-regional energy suppliers are involved, who tend to be unknown to many citizens and appear to be anonymous. Precisely in the case of specific local participation processes, it is very important for there to be "positive feelings of trust between the stakeholders involved"[180] in order to bring about solutions which are satisfactory to all the parties concerned.

In the context of increasing digitalization of the energy supply, anxieties and fears among the population with regard to privacy, data protection and data security can lead to a loss of trust. [181] These scenarios also include anxiety about jeopardizing security of supply due to the vulnerability of digital infrastructure to cyberattack.[182]

In addition to specific measures for the efficient and effective design of public participation in line with requirements for transparency and fairness, there is also a need to inject **more facts and make the public debate more objective.** Simplified and frequently one-sided perceptions of the meaning of "centralized" on the one hand and "decentralized" on the other must be called out and carefully considered in the communication process. This need is all the more urgent in a time of media-induced "hypersensitivity".[183] It is precisely major projects and huge undertakings such as the energy transition which are the origin and aim of often highly emotional debates. While these should not be shut down where there are social challenges and stresses, they ought not to be the sole drivers. Dialogue and participation processes based on planning procedures are thus important windows of opportunity for discussing significant topics and for different stakeholders to encounter one another, sometimes for the first time. Ensuring a constructive configuration of this sensitive and course-setting stage is therefore vital.

4.4.4 Political participation by citizens in the energy transition

Over the last few decades, methods of participation which allow more comprehensive participation by citizens has in many cases become a central tool for greater acceptance of energy infrastructure. Possibilities for participation extend over the entire range from spatial and land-use planning to the planning and approval of specific facilities. It is important, in this context, to bear in mind that participation should not be understood merely as a tool for creating acceptance. If this attitude is adopted, then offers to participate may increase conflict (this is true in particular of financial participation). On the other hand, participation does not have a direct impact on acceptance of a particular

179 Sonnberger/Ruddat 2016.
180 Hildebrand et al. 2015, p. 54.
181 See Deutscher Ethikrat 2017.
182 acatech/Leopoldina/Akademienunion 2017-3.
183 Pörksen 2018.

measure or item of infrastructure, but rather addresses procedural fairness and thus acceptance of the approach.[184] In addition, a good participation process cannot outweigh shortcomings in a project or major infrastructure characteristics.

How exactly political participation by citizens in planning and approval procedures is designed is on the one hand specified by legal provisions for public participation and on the other hand influenced by the stakeholders involved. An example of the **increased importance of participation** and the cultural changes regarding participation on the part of project developers can be found in the field of grid expansion. For instance, the Grid Expansion Acceleration Act for the Transmission Grid (NABEG) provides significantly more opportunities to participate than the previous Energy Line Expansion Act (EnLAG). Transmission grid operators and the Bundesnetzagentur are also using consultations to involve the general public far more in the matter of grid expansion than was previously the case (e.g. scenario framework, grid development plan and Federal Requirement Plan Act).

Perceptions are in principle positive, even if the expansion of power routes is not automatically accepted by society as a result.[185] Opportunities to participate are obviously important both for more centralized and more decentralized energy systems. While at the level of centralized infrastructure the effort expended on participation procedures is on the whole greater and more financial and personnel resources are accordingly required, at a decentralized level aspects such as local or regional attitudes, sufficient representativeness (which can be endangered by particularly strident minorities) and the legitimacy of the overall system must be borne in mind.

As a general rule, conflicts arise above all if procedural **transparency** is perceived to be **inadequate**. It is precisely when citizens are not directly in a position to take a decision themselves, but rather are dependent on their elected representatives and the decisions of administrative authorities that disclosure of the planning and decision-making process is most helpful because citizens are then able to understand and evaluate the process and resist it where necessary. Participation and approval procedures which have been perceived as inadequate are a major reason why people become fanatical critics of wind turbines and are then no longer prepared to revise their opinion.

One problem is that existing legal provisions relating to planning procedures are so complex that they are incomprehensible to laypeople; consequently, the President of the Federal Constitutional Court, Andreas Voßkuhle, has called for the law to be made clearer and more comprehensible. He concludes: "[…] if only a handful of experts are capable of conducting a planning approval procedure with legal certainly, confidence in the functionality of the constitutional state will erode."[186] Journalists and science and planning communicators, as well as scientists and planners themselves therefore have the important task of enriching the debate around legal and planning policy aspects of the energy transition with clear, comprehensible messages. The limits to participation have also to be pointed out, in order to avoid that everything is discussed by everyone,

184 Roßnagel et al. 2014; Haug/Mono 2012; Knudsen et al. 2015.

185 Kamlage et al. 2018; Kamlage et al. 2014.

186 Andreas Voßkuhle in his presentation "Constitutional State and Democracy" on the occasion of the Leipzig legal conference (Voßkuhle 2018).

regardless of the actual possibilities to influence the outcome. Although not everyone will take the opportunity to actively participate in shaping the energy transition, participation does open up the possibility of giving citizens some expertise in planning policy, enabling them to spread knowledge and mediate in their own spheres.

Latterly, however, the febrile atmosphere in society caused in part, though not solely, by social media has led to a degree of disillusion regarding not only the effectiveness but also the legitimacy of many participation opportunities.[187] Informal formats, it would seem, do not automatically promote acceptance or reduce conflict, a further decisive factor being precisely how such formats are designed in practical terms. It is therefore necessary not only (where meaningful) to supplement the process with informal opportunities for participation but also to focus very heavily on improving formal procedures. One advantage of formal procedures is that they are more readily assessed in terms of predictability and procedural reliability. Being standardized, they can likewise in principle be more readily understood and compared. In any case, it should naturally be the aim of a functioning society to maintain confidence in the independence of the relevant authorities, which function to a degree as advocates of citizens' interests.

Social media have led to new forms of public participation, which are on the one hand to be welcomed as they lower the threshold for people to make themselves heard even outside of filtered, mass-media communications. On the other hand, however, new forms of suggestive or manipulative communication (forums peddling unbalanced content, "filter bubbles") have grown up, which undermine the basic idea of transparency and participation, namely that of holding a dialogue in the public space in which particular interests are able to have their say but are subordinate to the objective of reaching a compromise. This threatens to erode the long held view of the general public as drawing on a basis of shared values and breaking down closed opinions, as current political developments pointing towards the rise of populism clearly show.

These current crises make it all the clearer just how important it is to the successful transformation of the energy system that all citizens are able to participate politically in the energy transition. As far as possible, all social groups need to to able to make their interests heard and to to have a fair access to the political dialogue. For this reason, ways need to be found of taking the recently identified threats to participation seriously and of continually seeking ways of improving the relevant institutional structure, including the opportunities for participation already provided by law, for example in the procedure for granting approval and of providing further informal opportunities for involvement.

187 See the systematic list of shortcomings in participation processes in Roßnagel et al. 2016.

5 Options for action

The aim of the energy transition is to ensure climate-friendly, secure, affordable and socially acceptable energy supply for all citizens and for industry. Whether energy should in future be provided in a more centralized or decentralized manner depends primarily on the extent to which centralized and decentralized technologies and coordination mechanisms are able to contribute to achieving this overall aim. The question as to what degree of (de)centralization is appropriate can therefore only be answered in the overall context of the transformation of the energy system. There are six fundamental challenges when it comes to a successful transformation:

Boosting renewable energy expansion: the expansion of wind energy and photovoltaics is currently too slow to achieve expansion and climate protection targets. This is all the more the case if the increasing power needs resulting from sector coupling are taken into account. Achieving long-term aims means that the majority of the available wind and solar potential must be utilized by means of wind turbines in the north as well as in the south and offshore, and photovoltaic systems on buildings as well as open land. To make Germany's energy supply climate-neutral in thirty years and not exceed the emissions budget compatible with the Paris Climate Agreement, a concerted effort must be made in the near future to exploit all possible routes.[188]

As renewable energy sources are comprehensively expanded, land use conflicts will intensify in future. These include conflicts around nature conservation, perceived damage to the landscape, impacts on residents and competition with other forms of land use. PV systems in already built-up areas, in particular on roofs, hold the lowest risk of conflict. Increased use of offshore wind energy, optionally with on-site hydrogen generation to limit power line construction, could reduce impact on people. There is, however, a need for further research into environmental effects here. Land-use conflicts in Germany could also be alleviated by greater energy imports, but it would need to be ensured that negative environmental and social impacts are not merely displaced to other countries.

The conclusion to be drawn is that both highly decentralized technologies such as rooftop PV systems and highly centralized approaches such as offshore wind farms or energy imports have their part to play in lessening land-use conflict. However, speeding up the expansion of renewables while at the same time keeping land-use conflict at the lowest possible level entails a suitable legislative and economic framework.

188 The federal government's climate protection targets are laid down for simplicity's sake in terms of individual years (2020, 2030, 2050). To limit global warming to below 2 or 1.5 degrees Celsius, however, it is not CO_2 emissions for a specific year which count, but rather the total quantity of emissions. If a short-term target is missed, the long-term targets have to be raised, so as not exceed the emissions budget overall. The fastest possible reduction in greenhouse gas (GHG) emissions is therefore essential.

A further lever for alleviating land-use conflict is more sparing use of energy, as the less energy is consumed, the fewer renewable energy plants and power grids are needed. A reduction in energy consumption, both by changing consumer behaviour and by increasing the efficiency of relevant technologies, should therefore be a policy priority.[189]

Implementing grid expansion: Both the transmission and distribution grids need to be expanded considerably by 2050 if the energy transition is to succeed. If renewable energy sources are expanded in a highly decentralized manner, expansion of the transmission grids may in part be reduced until around ten years later. Rapid expansion of more decentralized renewable energy plants could therefore contribute to achieving the short- and medium-term expansion targets for renewable energy sources, even if grid expansion is delayed due to problems of acceptance. A prerequisite, however, is that the decentralized plants are operated system-beneficially. At the same time, it needs to be clearly communicated that the long-term aims of the energy transition cannot be achieved without grid expansion. Ways must therefore in any event be found to achieve social acceptance of grid expansion.

Shaping digitalization: Given the fluctuating feed-in from wind and solar energy, bringing generation and consumption into line at all times will in future become more complex. Digitalization is indispensable if the growing coordination requirements are to be overcome. In more decentralized systems, the coordination challenges are probably even greater than with more centralized systems, since in the former there are more stakeholders (prosumers) to coordinate. Furthermore, a more decentralized system differs more from today's system than does a more centralized system, so there is less experience to draw on. The more plants are interconnected, the greater is the potential for attacks by cybercriminals. Resilience and in particular damage limitation in the case of an attack are therefore important criteria when it comes to developing a digitalized energy system. A multilevel structure with a central coordination level and decentralized cells, each capable of independently providing a basic supply and decoupling itself from the higher-level network, fosters a resilient energy system.

Strengthening the CO_2 price signal: An effective, uniform CO_2 price as a steering instrument would assist in achieving climate protection targets as inexpensively as possible. Whether more decentralized or more centralized technologies win through would then be decided by the market, so there would be no need for a political decision for or against specific technologies. Supplementary instruments are needed over and above the CO_2 price, for instance to create the necessary line networks or to cover external costs, for example resulting from land use-related conflicts.

Streamlining regulations: Today's largely impenetrable thicket of individual regulations makes it difficult for energy transition stakeholders to develop and implement climate-friendly solutions. For operators of decentralized facilities, for example, the very complex regulatory requirements are often a major hurdle. A new, simpler regulatory system would support the idea of the market as a "marketplace of ideas", i.e. it would be open to the integration of as yet unforeseen new products and services (see section 5.2.2).

189 See also acatech/Leopoldina/Akademienunion 2017-1, ESYS 2019.

Strengthening participation: The energy transition can only succeed if it is shared and actively supported by the population. Since the greater part of the journey towards a climate-neutral energy system still lies before us, it should be assumed that conflicts around the expansion of renewable energy plants and grids and around the distribution of the cost of the energy transition will continue to increase. In the short term, the existing high acceptance in particular of decentralized PV systems may well encourage citizens act as prosumers and drive the energy transition forward. This should be enabled and supported by a corresponding regulatory framework. At the same time, participation processes are needed for more centralized systems and for grid expansion, with the interests of different groups being taken into appropriate consideration and the processes being perceived as fair by all those involved. This means both economic participation, which contributes to a just and fair distribution of the benefits and burdens of the energy transition, and opportunities for political participation, which enable citizens actively to influence the energy transition and its impacts on their living environment.

The options for action discussed below indicate specific starting points for overcoming these six fundamental challenges by utilizing more centralized and more decentralized technologies.

5.1 Technical prerequisites for a secure and climate-friendly energy supply

Energy policy instruments are intended to ensure that the technical prerequisites for a secure and climate-friendly energy supply can be achieved as inexpensively as possible. The fundamental technical challenges facing energy systems of the future which make use of the wind and sun as the main energy sources apply irrespective of issues of (de) centralization. For instance, as levels of volatile feed-in into the power grid are increasing and power generation by dispatchable power stations is decreasing, it is becoming more difficult to keep energy supply and demand at equilibrium at all times. Flexibility options such as storage systems but also digital information and control systems are therefore becoming more significant.

Many of the technologies required for transforming the energy system (including renewable energy generating plants, flexibility and sector coupling technologies and underlying ICT such as smart meters or control algorithms) are already ready for service.[190] Action is therefore required to create options for using these technologies together with a corresponding **regulatory framework and incentives**. At the same time, there is still a need for research into improving the efficiency of technologies, reducing costs and increasing environmental compatibility, for example by selecting recyclable materials. In the absence of these further developments and cost reductions, extensive rollout of these technologies will not be possible. There will also be a need for long-term technology research in order to discover new ways, above and beyond simply further developing existing technologies, for meeting the various requirements of the energy system more efficiently and inexpensively and in a more environmentally friendly way.[191] Projects such as **real-world laboratories** can investigate the practical

190 Mazur et al. 2019.

191 For instance, solar films have been developed which redirect sunlight onto solar cells and so achieve distinctly better levels of efficiency than conventional silicon PV modules (Pieper et al. 2018).

implementation of technologies and provide insights as to how far technologies are ready for service in interplay with one another. They can therefore make a quick contribution to accelerating the energy transition. This trialling of existing technologies is, however, not a replacement for long-term research into innovative solutions.

Novel solutions also include reconsideration of existing paradigms in the light of technological progress. The **improvements in data exchange** brought about by digitalization could, for example, accordingly accelerate responses to events in the power grid and in future partly replace the conventional (N-1) criterion[192], which requires to hold resources in reserve. For example, in the event of an incident, power flows could be purposefully displaced, so making it unnecessary to hold redundant line capacity in reserve.

If climate protection is to be effective, there must be distinct acceleration in the expansion and secure and reliable large-area integration of renewable energy sources. It should be assumed that this can only succeed if more (de)centralized approaches are combined at both the technical and regulatory levels. In the long term, every kind of potential, whether centralized or decentralized, must be exploited.

5.1.1 Grids

Even in the case of a more decentralized configuration of the energy system, **transmission grids** will have to be expanded in order to balance regional fluctuations (see section 4.1.5). In addition, an integrated system is a prerequisite for the European power market. Even in the analyzed decentralized scenarios[193], Germany participates in the transnational power market which means that appropriate infrastructure for long-distance energy transmission will be required.

Transmission grids should be expanded in a manner which is as **socially compatible** as possible. Improving the economic viability and increasing the transmission capacity of **technologies involving underground cables** is also desirable in this context. In addition, laying empty piping in the course of grid expansion work is one option for ensuring that transmission capacity can be increased more straightforwardly at a later point in time.

Today, up to 90 per cent of renewable energy capacity is connected to the **distribution grid**.[194] However, the electrical grid as it has developed over time is not designed for feed-in into the distribution grid and a possible reversal of power flow from lower to higher voltage levels.[195] Challenges arise, among other things, in maintaining voltage stability: high feed-in by renewables at off-peak periods can increase line voltage by more than the permissible 10 per cent of the nominal value. Various measures can counteract this effect, including grid reinforcement, curtailment of feed-in and the use of storage systems or voltage regulators such as variable distribution transformers. **The more small, decentralized generation units there are, the more the distribution network will have to be expanded.** In addition, new power consumers,

192 The N-1 criterion states that sufficient redundancy must be present to ensure operation even if one resource fails.

193 WWF 2018-1.

194 BMWi 2014.

195 This situation is already occurring for example in windy regions of Schleswig-Holstein.

in particular electric vehicles and heat pumps, may make considerable distribution grid expansion necessary.

The need for grid expansion can be reduced by **capping power peaks** in (more centralized and) decentralized scenarios. The Energy Industry Act already allows for power peaks to be curtailed by up to three per cent.

Since in future a large proportion of plants will be connected to the distribution grids, **system services** such as congestion management and maintenance of voltage and frequency stability will in future have to be provided by plant operators or distribution grid operators at distribution level. Concepts must be developed for the future integration of decentralized resources into system operation. The interplay between transmission and distribution levels and the responsibilities of plant operators, distribution grid operators and transmission grid operators defined.[196]

In particular in more decentralized structures, numerous smaller-scale plants have to be coordinated to ensure system-beneficial operation. This will require appropriate **IT integration**. Future requirements for data exchange will depend on how tasks are to be apportioned between stakeholders, but this has not yet been defined so the requirements cannot yet be precisely quantified. The necessary **sensors and actuators** are already available and can be installed in the systems, which means that subsequent **software upgrades** will be quick and easy to roll out. One challenge here is that the system operators (including households) would have to permit a certain degree of external control of their systems.

There is also a need to develop **expanded simulation techniques** which model the new grid structures and take account of technologies such as sector coupling and storage systems. Moreover, **data exchange** and control of the various system components are playing an increasingly important role (see section 4.1.6). Responsiveness to rapid power fluctuations, the provision of instantaneous standby and system services will also have to be supported by appropriate technologies and ICT concepts.

When it comes to the **resilience** of grid operation, there is a lack of experience in locating faults and of concepts for reestablishing supply with decentralized facilities. It must in general be borne in mind that a more robust design is associated with higher costs which means that resilience and costs must to some extent be balanced against one another.[197]

It is desirable for **energy scenarios** to take greater account in future of distribution grids since it is otherwise almost impossible to compare costs meaningfully between centralized and decentralized scenarios.

5.1.2 Flexibility

Various flexibility technologies, such as battery banks and power-to-gas, are technically fit for service but for the most part still relatively costly. In the light of the great future

196 Discussions about collaboration between transmission and distribution grid operators are currently under way at the German and European level. Proposals regarding the future nature of collaboration are discussed, for example, in VDE 2015, Electra 2013, and VKU 2017. Some research projects are addressing the issue, including the SINTEG enera project and the TDX-ASSIST project (http://www.tdx-assist.eu/).

197 These questions are considered in more detail by the ESYS working group “Resilience of digitalized energy systems”.

need for flexibility, a **reduction in storage technology costs** would considerably cut overall system costs.

In order to reduce grid expansion and the overall requirement for flexibility technologies, storage systems should be operated in a **forecast-based and system-beneficial** manner. Achieving this will require not only adjustments to the regulatory framework to provide incentives but also smart ICT solutions. System-beneficial operation will probably be more difficult to achieve for decentralized storage systems in households than for more centralized storage systems operated by grid operators or energy suppliers.

There is a need for new concepts for providing **instantaneous standby** and primary balancing power because there will in future be an increasing lack of power station turbines for immediately compensating power imbalances. In future, directly coupled plants such as thermal power stations and grid-synchronized phase shifters will also be able to perform this task. Since renewable energy plants are normally operated on the grid via power-electronic converters, they can only provide instantaneous standby in conjunction with integrated storage systems and appropriate control strategies.

In order to minimize overall system costs, options for **importing** flexibility (and thus greater use of flexibility options remote from the point of load) should also be taken into consideration. While greater **European integration** with an increase in transboundary power trading does indeed increase the need for grid expansion, it does reduce the need to construct additional storage systems in Germany.

Non-European countries such as Russia or African countries can offer additional potential for flexibility imports since, being subject to other weather systems, they can offer good supplies of wind and solar energy at different times from Germany. Direct **power imports** would, however, entail the **expansion of power routes** across a number of national borders. This would appear difficult in light of the differing regulatory hurdles in the countries and possible acceptance problems. Account must also be taken of the possibly serious consequences of an interruption to power supplies. Importing **synthetic fuels (e-fuels)** from non-European countries would therefore seem to be more advantageous in terms of feasibility and energy security.

Both when importing power from countries which are not covered by the European emissions trading scheme, and when importing e-fuels, it should be ensured that they are generated from renewable energy sources and make the intended **contribution to global CO_2 savings**. Minimum standards and calculation methods would have to be defined here, for example in the context of **certification mechanisms**. It will have to be clarified in this connection how imported energy carriers derived from nuclear power or from fossil fuel-fired power stations with CCS should be evaluated. In Germany, this could be of relevance with regard to social acceptance.

In brief, the **technical challenges** of the energy transition above all involve further development of the necessary technologies for a wide-ranging rollout and reduction in the corresponding supply costs. **Technology agnosticism** is a key factor in ensuring a successful energy transition. This applies both to the wide-ranging implementation of existing technologies and to research into new technologies.

5.2 (De)centralization in its overall legal and economic framework

The energy systems of the future which are very largely based on renewable energy sources require a legal and economic framework which is as consistent as possible, irrespective of (de)centralization aspects. Providing a stronger CO_2 price signal as a key instrument would assist with achieving climate protection targets as inexpensively as possible. In addition, a new, simpler regulatory system would break down existing hurdles to the integration of innovative products and services.

5.2.1 Strengthening the CO_2 price

From an economic standpoint, a CO_2 price leads to (cost-)efficient avoidance of CO_2 emissions and is therefore a **first-best solution**. A **cross-sectoral CO_2 price** would include external effects in all areas of the energy system. However, setting a CO_2 price at the level of the damage costs of climate change to the environment[198], for example in the form of a tax, would appear to be politically virtually unachievable in the short term.[199] If it is not possible to set a CO_2 price which reasonably reflects external costs or is sufficiently high to achieve climate protection targets, additional support policy or regulatory measures will be required.[200]

At present in Germany, direct CO_2 pricing only applies in the context of the European Emissions Trading System (EU ETS) which covers the energy sector and energy-intensive industrial plants.[201] At least in the past, the steering effect of the EU ETS has been questionable in light of the low level of the price.[202] In addition, no account is taken of other sectors of the energy system, resulting in unequal marginal costs for CO_2 emissions in different sectors.[203] Another disadvantageous factor is that differing levels of taxes, duties and surcharges apply to different energy carriers.[204] In an international context, differing CO_2 prices in Germany and abroad may give rise to a further problem, "**carbon leakage**", i.e. the displacement of CO_2-intensive processes to regions with no or low CO_2 prices.[205]

The **CO_2 price should be enshrined as a key instrument** for climate protection in order to ensure effective pricing of CO_2 emissions across all sectors.[206] The two basic possibilities here are either to **extend emissions trading to sectors which**

198 The German Environment Agency accordingly recommends setting damage costs at 180 euro per tonne for one tonne of CO_2 emitted in 2016 and at 205 euro for one tonne of CO_2 emitted in 2030 (UBA 2019).

199 This is also reflected in the resolutions adopted by the federal government in autumn 2019.

200 These instruments must logically have the same steering effect in the context of climate targets as that considered to be unachievable by means of a CO_2 price signal. This will probably occur at the cost of reduced economic efficiency, i.e. still higher macroeconomic costs, but possibly with fewer redistribution effects than in the case of comprehensive CO_2 pricing. One example of such considerations are the political reservations about burdening commuters and low-income households.

201 An indirect CO_2 price component is already today implicitly present in other regulations and taxes, for example in energy or vehicle tax. The resolutions adopted by the federal government in autumn 2019 mean that there will in future also be an explicit price component.

202 Some shifts in the power generation mix have been observed since the price rise from under 10 euro per tonne to around 25 euro per tonne in the first half of 2018. However, at the current price level, gas-fired power stations will not displace power generation from lignite, since the (short-term) variable costs of lignite extraction and power generation remain lower. Even with hard coal, displacement only occurs if, as at present (mid-2019), the gas price is simultaneously low.

203 See acatech/Leopoldina/Akademienunion 2017-1, Ausfelder et al. 2017.

204 Agora 2017-2. This still applies after the adoption of the resolutions by the federal government in autumn 2019.

205 Studies have shown that, due to the compensation mechanisms and low certificate prices, the EU ETS has not so far caused any carbon leakage (based on Moore et al. 2019, Koch/Basse 2019, Martin et al. 2014). In the event of higher certificate prices in the future, however, the risk of carbon leakage could be higher.

206 See also acatech/Leopoldina/Akademienunion 2017-1, acatech/Leopoldina/Akademienunion 2019.

have not previously been considered or to introduce a **CO_2 tax or duty** in these sectors.[207] When designing such measures, in addition to obstacles to implementation, distribution effects play a major role in avoiding overburdening low-income households. If Germany were to go it alone and introduce a high CO_2 price, depending on the precise arrangements negative effects could be expected on the competitiveness of (energy-intensive) businesses and thus on Germany as an industrial nation. Implementing a CO_2 price in an alliance with other countries would therefore seem to be more promising.[208]

Border tax adjustments may be a cost-effective way of attenuating the negative consequences on industry. Exemptions, as already apply in the EU ETS and in the context of the EEG surcharge, could, however, also be extended to CO_2 pricing. In order to relieve some of the burden on all power consumers, previous regulatory arrangements such as the electricity tax or EEG surcharge should be abolished or adjusted.

In itself, CO_2 pricing does not steer the system in either a more centralized or a more decentralized direction. Energy scenarios show that a highly interconnected, more centralized system will probably be less costly. If this proves to be the case, CO_2 pricing will tend to push the system in this direction unless obstacles such as lack of acceptance prevent it. Ultimately, it is the market stakeholders who decide whether it will be more decentralized or more centralized technologies which prevail.

In addition, different technologies have different impacts which a CO_2 price does not reflect. For example, the landscape impact and impairment perceived by the local population are lower in the case of photovoltaics (in particular rooftop systems) than for onshore wind turbines. The regulatory framework should therefore be designed in such a way that those technologies which are predominantly accepted are treated preferentially because this will increase the likelihood of achieving climate protection targets within the very short time frame available.

5.2.2 Reducing complexity

The regulatory system should be greatly simplified in order to ensure a successful energy transition. This includes regulation of areas such as grid operation, expansion of renewable energies as well as duties and surcharges. The barely manageable profusion of individual regulations makes it difficult for energy transition stakeholders to develop and implement climate-friendly solutions. Ever more special arrangements and exemptions are frequently added to the existing system in order to offset the undesirable effects of previous measures.[209]

But how can the system of taxes, duties and surcharges be efficiently streamlined? The aim is to create a **level playing field**[210] for diverse innovation by means of technology-agnostic solutions. A new, simpler regulatory system should support the market as a "marketplace of ideas", i.e. provide **flexibility for integrating products**

207 See also acatech/Leopoldina/Akademienunion 2020.

208 If, as at present, further instruments are used in addition to CO_2 pricing, the challenge arises of making these various instruments consistent with one another. This is clear, for example, from the EEG surcharge, which is a substantial obstacle to sector coupling because it makes electricity more costly than other energy carriers.

209 For example, the first version of EEG dating from 2000 has just 13 paragraphs, while the 2017 version has over 100 paragraphs.

210 A level playing field is taken to mean identical conditions for all participants in a market, so enabling fair competition.

and services which are as yet unknown.[211] Highly complex regulatory requirements tend to be more of an obstacle for decentralized systems than for centralized ones since the transaction costs per installed unit are of greater significance. Accordingly, **cutting red tape and streamlining regulations could assist with a more decentralized configuration of the energy system**.[212]

With regard to long-term climate protection targets, one challenge is to avoid providing incentives for technical solutions which, while functional at present, make no sense in the medium to long term. It may make sense to proceed at two speeds, improving the existing system in the short term while in the medium to long term working towards a new, simpler regulatory system. This applies in particular to promoting individual power generation or sector coupling technologies. A transition to uniform and adequate CO_2 pricing could distinctly simplify matters here. Nevertheless, in the case of new technologies such as power-to-gas, it may be appropriate in the short to medium term to provide a certain degree of technology-specific support. When designing instruments, particular care should be taken to ensure that they are effective both under the current EEG regulatory framework and in the absence of the EEG or once EEG support has come to an end. This is because the statutory period of EEG support will end for ever more plants, and increasing numbers of new plants will be built which are economic without the EEG.

5.3 Setting appropriate economic incentives for decentralized generating facilities

As stated in sections 4.2 to 4.4, decentralized solutions, in particular **rooftop PV systems,** can **increase acceptance** of further renewable energy expansion. Building genration plants close to the point of consumption and providing flexibility can also assist in delaying the need for grid expansion. This enables renewable energies to be expanded more rapidly despite a delay in grid expansion. It may thus make **political** sense, despite the probably somewhat higher costs of decentralized systems, **to work towards decentralization** and so increase the likelihood of achieving climate protection targets.

An important prerequisite when it comes to achieving a reliable energy supply as inexpensively as possible is **system beneficiality**. With the energy system as it is at present, generating plants are not necessarily built and operated, nor flexibility provided, in a manner which is beneficial to the overall system. If the energy system is to become more decentralized, energy policy measures need therefore to ensure system beneficiality. Suitable instruments have the potential for increasing the system beneficiality of generators and consumers and flexibility in terms of both site selection and plant operation. In principle, over-regulation in general and regulating for specific cases should be avoided (see section 5.2.2).

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211 For example, unbundling means that distribution grid operators are not allowed to operate storage systems although they might have great need for and draw major benefit from such systems. At present, there is a lack of incentives for other stakeholders to set up storage systems and operate them for the purpose of the distribution grid. Section 5.3. sets out options in this respect.

212 The working group also makes some proposals below which will lead to additional or amended, and possibly more complicated, regulations. The basic idea, however, is to make the regulations as simple as possible but as complicated as technically and/or economically necessary. For example, the introduction of node-specific wholesale prices discussed in section 5.3.4 improves the coordination of economic market activity with physical and technical grid loads.

5.3.1 Options for local economic participation

At present, there are no uniform countrywide arrangements which allow local stakeholders to share in the wealth creation opportunities offered by renewable energy sources. In principle, a distinction is drawn between participation by citizens and participation by municipalities. Local economic participation is aimed above all at the technical and spatial dimensions of (de)centralization, since it is primarily a matter of financial participation in renewable energy plants. How participation is organized and its success have a significant influence on the size of the plant and where it is sited.

In some Federal States there are already provisions for voluntary or compulsory participation in renewable energy projects.[213] In Mecklenburg-West Pomerania project promoters are obliged to offer local investment participation[214], or alternatively pay a compensatory levy.

Moreover, local participation in financial yields is compulsory only to a limited degree, taking the form of rental payments to landowners and proportional business tax contributions where appropriate.

In the competition between Federal States for suitable sites, however, state-specific conditions such as participation clauses can result in a competitive disadvantage, because they increase operator costs. Countrywide calls for proposals can also run into problems if different regulations apply in different federal states, with legal action having been launched in Mecklenburg-West Pomerania, for example, on the basis that the legislative provisions constitute an attack on property rights and worsen the state's chances in such calls for proposals. It is also argued, from public finance law, that the alternative compensatory levy (which is expected to become the norm) is not justified by the special financial responsibilities of project promoters.[215]

Such **regulation of local economic participation** also throws up the **issue of fairness** compared with regulations relating to other infrastructure such as railway routes. Why should energy plants be treated differently from other infrastructure and industrial plants which local residents may likewise consider a nuisance.

Case studies show that **participation projects lead** locally to **high levels of acceptance**, while **outside investor models** tend to have **negative effects**.[216] Allowing affected citizens and communities to participate financially may increase acceptance.[217] There may also be good economic reasons for this: in the absence of economic participation, local stakeholders are affected by negative external effects such as overshadowing, impairment of landscapes or lights on wind turbines without receiving appropriate compensation. This results in dwindling acceptance, and indeed triggers resistance to expansion, with local residents lodging complaints about the construction

213 For example Mecklenburg-West Pomerania's Citizens' and Local Authority Participation Act, May 2016; Schleswig-Holstein's citizens' energy fund; Thuringia's "Faire Windenergie" label, early 2016; Hesse's wind energy dividend, 2016.

214 The basic idea behind Mecklenburg-West Pomerania's Act is to oblige project promoters to set up a limited liability company for new wind farms and to offer direct neighbours shares of at least 20 per cent in this company.

215 Wegner 2018.

216 See Schweizer-Ries et al. 2010, AEE 2012.

217 Social science investigations suggest that there is a connection between positive attitudes towards wind energy and financial participation (e.g. Schweizer-Ries et al. 2008, p. 46 ff.; Warren/McFadyen 2010; Pedersen et al. 2009; Devine-Wright 2005; Hyland/Bertsch 2017; Fachagentur Windenergie an Land 2016; Sonnberger/Ruddat 2016; Ott/Keil 2017; Hübner et al. 2019).

of new plants, for example. In recent years, this has contributed to a fall in the number of new projects. **Economic participation** could therefore be an important building block in the further expansion of renewable energy sources.

A **countrywide Citizens' and Local Authority Participation Act**, like that enacted in Mecklenburg-West Pomerania, could strengthen economic participation in new-build projects (centralized and decentralized; generators and flexibility). This would also create uniform rules for participation by affected citizens and/or communities providing sites. National regulations could **level the playing field for competition** throughout Germany, something which would appear important in light of countrywide calls for proposals for generating plants for wind and solar energy and biomass. On the other hand, regulations specific to individual federal states provide greater latitude to take account of specific concerns in individual states; it should for example be borne in mind that the state parliaments often reflect different distributions of power than the Bundestag and consequently also have different political objectives.

Many other models of economic participation are however conceivable, and could be applied on a legislative or voluntary basis. For example, participatory investment in the form of equity contributions to renewable energy plants could be introduced, ensuring citizens or municipal companies have a direct share in profits. In Denmark, for example, investor participation is stipulated for all renewable energy projects. First of all, the project planner draws up plans for the plant and goes through the approval process and only then makes a statutory minimum of 20 percent of shares available for purchase by local residents.[218] A potential objection to such a system in Germany is that responsibility for regional planning policy lies with the individual states. However, if establishing uniform living conditions across Germany or safeguarding the legal or economic unit that is the German nation requires Federal legislation, then recourse could be made to the legislative powers of the German state. This needs more careful examination.

Another approach to greater financial participation of affected communities is to **levy or increase taxes and duties**, using such instruments as a special levy or the adjustment of business or land tax. In Brandenburg, communities where wind turbines are being built will in future receive money from the operators, the plan being a yield-dependent special levy of between 5,000 and 10,000 euro for each new plant.[219]

Soft instruments such as Thuringia's "Faire Wind Energy" **label** which encourage citizens and local companies to participate in renewable energy projects along the value chain[220], are a lower threshold approach to increasing levels of acceptance and leveraging potential.

Other conceivable participation options are the provision of outside capital, special reduced electricity tariffs for local residents or bilateral contracts.

218 Papke 2018.

219 MWE Brandenburg 2018; MAZ 2018.

220 This includes tradesmen, consulting engineers, farmers, households, financiers, manufacturers, municipal utilities, municipal companies, energy cooperatives etc.

Economic participation models could lead to more centralized or more decentralized configurations of the energy system, depending on what type of plant achieves local acceptance. In southern Germany, for example, if acceptance of the expansion close to the point of consumption of small to medium-sized wind or solar farms were to be achieved, this would lead primarily to a more decentralized system. On the other hand, participation models could also lead to a greater concentration of (wind energy) plants at high-yield sites if participation were to lead to greater acceptance of these.

5.3.2 Regulatory framework for prosumption

To achieve the energy transition, all wind and solar energy potential has in future to be leveraged: on- and offshore wind energy plants, and photovoltaic systems ranging from small rooftop systems on detached houses through medium-sized commercial and tenant power plants to large solar parks. **Prosumption incentives** can contribute to the better exploitation of available potential in terms of buildings and corporate property. Prosumption is not only conceivable at a domestic level but also in industry, and in the commercial, trade and services sector, with sector coupling in particular also assuming an important role in future.

It is especially important to create **regulatory frameworks which result in system-beneficial prosumption**. Regulations relating solely to self-consumption are insufficiently ambitious, with current self-consumption regulations resulting merely in domestic or consumer-related optimization. The objective of prosumption incentives should not, however, primarily be to cover self-consumption, but rather to incentivize prosumers to act as drivers of the energy transition and in so doing to exploit renewable energy and storage potential, to an extent through private capital which would not otherwise be available. For example, rooftop PV systems should be designed to ensure that rooftop potential is utilized as comprehensively as possible.

The regulatory framework for prosumption to a certain degree addresses all the dimensions of (de)centralization, as it affects plant size, consumption, flexibility options and the overall interplay of these factors. Better prosumption options would tend to steer the energy system in a more **decentralized direction**, since it is easier to exploit flexibility to balance generation and consumption at a decentralized level, i.e. within a building, neighbourhood or area grid[221]. However, the lack of technical infrastructure (digital connectivity) and obstacles in the form of regulatory framework details at present constitute considerable barriers, especially for small prosumers.

At present, self-consumption is heavily regulated, as power generation, even for private use, is treated in principle as a commercial activity. Accordingly, special arrangements have hitherto only applied to "property-related self-consumption" for individual operators, while there is no legal framework for communal self-consumption. **Tenant electricity models** are only admissible if the tenant electricity is consumed by end consumers such as tenants or flat owners in the residential building on which the solar plant is mounted or in an adjacent building.[222] Neighbourhood systems consequently cannot be planned although this could be advantageous with regard to exploiting prosumer potential and indeed for the overall system. Metrology-related regulations

221 An area grid is a plant unit which belongs to an owner or co-owners (local unit). It may extend over several contiguous plots of land. Electrical energy is distributed within the area grid via lines and (as a rule) transformer stations belonging to the owner of the area grid (VSE 2018).

222 "Direct spatial relationship" in legal terms (BNetzA 2017).

also constitute hurdles, as does the considerable legal and organizational effort flat owners have to undertake if they actually want to benefit from tenant electricity offers.

The Directive on the promotion of the use of energy from renewable sources in the current EU Clean Energy Package[223] does contain provisions for encouraging individual and collective self-consumption and accordingly gives rise to new opportunities and obligations for Germany. On the one hand, the EU Directive proposes raising the minimum level from **the current ten kilowatts to 30 kilowatts**, meaning **complete relief from the EEG surcharge on kilowatt-hours consumed on-site**, even in multi-occupancy dwellings.[224] According to the EU Directive, the minimum level of 30 kilowatts is also applicable to collective prosumption, for instance in the form of peer-to-peer models.[225]

However, the resultant shortfall in income due to the cessation of surchargeable kilowatt-hours may have to be made up for with public funding,[226] for example from tax revenues. "Emergency brakes" also need to be fitted to surcharge exemption systems, i.e. statutory requirements which allow for emergency countermeasures if prosumption is not carried out in a system-beneficial way and reaches orders of magnitude which are damaging to the overall system. According to the EU's Clean Energy Package, duties, surcharges and fees for self-consumption could be imposed or raised with effect from 01.12.2026 if the total proportion of the self-supply plants reaches over 8 per cent of the total installed electricity generating capacity.[227]

Further options for action relate to system-beneficial operation of prosumer plants, i.e. incentives should be designed to support the overall system in the best possible way while providing prosumers with the greatest possible number of different options from which to choose (freedom of action). One option would be a **reliable capacity cap**, as introduced by the KfW support programme, which limits the amount a PV system can feed in to 50 or 70 per cent of installed capacity. Another would involve **grid operators curtailing or switching off** the **prosumer plants** via a **control box**. A distinction could be drawn here between (voluntary) curtailment in return for payment, for example for system services, and compulsory curtailment due to problem situations. Smarter approaches could involve **grid-beneficial battery management** or other **flexible control options.**

It must be borne in mind that a prosumer response to market price signals is not necessarily grid-beneficial, as market price signals generally result in prosumers drawing power from the grid at times of high electricity availability and simultaneously low prices and feeding in to the grid at times of low electricity availability and high prices. Given that within the current regulatory framework market prices do not mirror grid

223 EU 2018.

224 For plants from a nominal power of 10 kilowatts (kWp) a reduced surcharge of 40 per cent of the EEG surcharge is currently levied.

225 Peer-to-peer trade in the context of energy systems is a concept which provides co-acting stakeholders with direct access to one another, meaning that central intermediaries such as exchanges, brokers or energy suppliers are no longer needed for electricity transactions and supply.

226 This would be necessary in particular if the income shortfall turns out to be higher than other reductions in EEG payments, resulting from the termination of subsidies to heavily subsidised old plants or from price increases on the electricity market leading to a reduced need for subsidies.

227 § 21, paragraph 3 of the Directive on the promotion of the use of energy from renewable sources (EU 2018).

load, this does not necessarily lead to lower grid load, but may on the contrary even increase it.[228]

More research into these alternative approaches is needed, possibly with real-world laboratory testing, if the advantages and drawbacks are to be better evaluated, and especially if large numbers of prosumer plants are likely to come online in the long term.

More far-reaching options for collective prosumption or **communal self-consumption** could contribute to achieving climate protection targets, as collective prosumption in principle offers serious, hitherto unexploited potential for expanding renewables and for sector coupling. Likewise, communal self-consumption could offer a feasible way of continuing to operate **EEG plants beyond the twenty years for which they are eligible for the feed-in tariff**.

Various models of communal self-consumption are conceivable, including **area grids** with a common connection point in which just the one grid exchange point is taken into consideration by the outside world. These have proven very successful in Switzerland, where end consumers are not free to choose their electricity supplier. With the possibility of supply via the area grid, freedom of choice is therefore increased, even if the choice consists only in whether or not to connect to an area grid as an end customer. An area grid does not as a rule provide free choice of electricity supplier and therefore is not a model which can be directly transferred to Germany and the EU, as it does not permit a free choice of electricity supplier and the resultant end customer competition provided within the EU. Germany has so far been restrictive in its treatment of area grids in order to protect the right of the consumer to a free choice of electricity supplier.

The higher-level grid could also be used for **peer-to-peer trading**, providing the trading partners involved are located within a distribution grid. **Aggregators**[229] could bundle prosumers and keep administrative costs low, or yet another approach could be to support and promote the development of **renewable energy communities**.[230] Such approaches need examining against the EU's legal framework, and questions of distribution and infrastructure funding have always to be borne in mind, with a careful examination being given to whether such regulations are advantageous not just for individual stakeholders, but also in terms of the overall system.

While prosumers remain relatively small in number, they cause no harm to the overall system, even if individual plants are not operated in a system-beneficial manner. There is therefore some latitude for developing technologies and operator models which could contribute to reaching climate protection targets initially as niche concepts. The possibility must, however, be built in from the outset of ramping up system beneficiality

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228 In terms of the reform proposals analyzed in Thomsen/Weber 2019 for grid fees, EEG surcharges and electricity prices, it is clear that these proposals may lead to an impairment of the system beneficiality of battery use in PV battery systems. This would probably only change if grid-beneficial behaviour were directly required of the operator or if corresponding monetary incentives were offered.

229 Aggregators pool and market generating plants, flexible consumers and storage systems, so as to scale up small plants to a commercial size.

230 Renewable energy communities would, for example, jointly consume, store and sell the renewable energy generated using production units belonging to the renewable energy community. They could obtain non-discriminatory access to all suitable energy markets either directly or by using aggregators (EU 2018, Article 22).

requirements as soon as growing prosumption starts to have tangible negative impacts on the overall system.

Low-threshold for access to robust ICT is crucial to the options for action in the prosumer context (see section 5.1). Sufficient ICT functionalities should be provided from the outset, which can subsequently be used in different ways depending on the legal framework. In this respect, grid operators might be obliged to technically enable the connection of smart prosumer systems. A lack of smartness or a lack of secure ICT infrastructure on the part of the grid operator should not impede system-beneficial use of self-generated and stored electricity. An additional prerequisite is **demand metering for all consumers and generators**, for which a rapid rollout of smart meters is essential.

5.3.3 Grid fees

Grid fees are paid for the construction, operation and maintenance of electricity and gas grids. At present, the payment of grid fees is asymmetric: **only consumers pay fees, with generators not participating**. The regulations for storage systems have been repeatedly adapted over the last few years in order to prevent anticompetitive double charging. The grid fees are made up either of the standing charge and unit price or the demand charge and unit price.[231] For most grid customers, small customers with an annual consumption of up to 100,000 kilowatt-hours, no demand charge is levied as power demand can only be metered with smart meters, which have not yet been installed for all domestic customers throughout Germany.

With the regulatory framework as it stands at present, grid fees lead to problematic distribution effects. On the one hand, households (and other consumers) with PV systems bear lower grid costs than households without PV systems but with the same consumption if they are thereby able to avoid drawing power from the grid, which is not in accordance with the costs-by-cause principle, most especially when, for instance, households with PV systems make just as much use of the grid infrastructure on dark winter days as do households without PV systems. On the other hand, consumers in regions with high feed-in from renewable energy sources, such as Mecklenburg-West Pomerania, often pay higher grid fees than consumers in regions with low feed-in, for instance in the Ruhr.[232] This uneven and potentially **unfair distribution of grid costs** is increasingly leading to **acceptance problems** and impeding the expansion of renewable energy sources.

A further problem with grid fees as currently configured is that they make it advantageous for prosumers to operate flexible battery banks, these being primarily designed to maximize self-consumption. Even combining them with market price signals does not lead to the same results as purely system-beneficial optimization, in particular as they do not incentivize grid-beneficial modes of operation.[233]

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231 The unit price relates to the amount of energy purchased in total over a given period (euro per kilowatt-hour), the demand charge to the peak demand (euro per kilowatt) metered over a given period (month or year) and the standing charge is a fixed rate (euro per month).

232 Households in Brandenburg paid the highest grid fees for 2018 with an average of 8.6 eurocents per kilowatt-hour. In comparison, households in North Rhine-Westphalia pay on average 6.3 eurocents per kilowatt-hour. In addition to the costs of integrating renewable energy sources, grid costs are influenced by utilization rate (dimensioning), population density, grid age and quality and the fee policy of the grid operator (Bundesnetzagentur/Bundeskartellamt 2018).

233 See Thomsen/Weber 2019.

Grid fees could be restructured in the following ways: for small customers (low-voltage customers) a **smaller, consumption-dependent amount** could be levied as grid fees and the difference could be made up either by a **higher standing charge** or, where smart meters with demand metering are used, by a **demand charge** (for the maximum metered demand and/or connected load). This would reduce the advantage for customers with self-generation over customers without it. It also makes sense from the standpoint of rewarding grid-beneficial behaviour to calculate fees not only on the basis of individual peak demand but also of **the power drawn or fed in at times of peak grid load.**[234] This could create major incentives for flexibility, in particular for larger loads, as power peaks which might occur would not be punished if they did not contribute to an increase in total grid load. Conversely, clear incentives are created for customers not to add to the increase in total peak load by drawing power.[235]

Another option is the introduction of **grid fees for feed-in suppliers as well (G component)**[236], in order to make such suppliers contribute to grid expansion costs and thus indirectly to control site selection. This G component could be adapted to regional needs, so that in areas close to the point of consumption with high demand, i.e. in southern and western Germany, the G component would be lower and in areas with high supply and low demand a higher amount would be due.[237] At the same time, such a configuration of grid fees reduces the likelihood of regional differences for consumers. **Tariffs which vary depending on time and/or location of use** are here conceivable for purposes of fine adjustment. Grid operators could control consumers using **special tariffs**, as in the past with night storage heaters and heat pumps and where applicable by provisions on a case by case basis for particular consumers or for consumers at trouble spots in the grid.

If grid fees are to be restructured, distribution effects must be taken into account and revenue neutrality ensured.

In addition to the grid fees to be paid by grid users, a critical eye needs to be cast over the fees to be paid by grid operators for "system services". While balancing power for maintaining frequency stability is currently procured and paid for on a market basis, other system services, for instance provision of reactive power and black start capability, have hitherto not been paid for or payment has only been on the basis of bilateral contracts.[238] Further research is required to identify reasonable market and remuneration models.

5.3.4 Generator-side incentives for system-beneficial site selection

The current situation with regard to renewable energy source expansion demonstrates that new capacity is not always added in a system-beneficial manner, with system-beneficial here primarily being used to address the "spatial dimension" (see section 2) of (de)

234 For example the British "Triads" model. The Triad refers to the three half-hour periods with highest system demand between November and February. National Grid, the power transmission network operator serving Great Britain, uses these Triads to determine grid fees for consumers with load-profile metering.

235 Utilization-dependent grid fees will be discussed in detail in acatech/Leopoldina/Akademienunion 2020.

236 In some countries, the grid fee is broken down into an L component (Load) and a G component (Generation), with the L component allocated to consumers and the G component to generators. The G component, which in Germany is zero, is already in use in other European countries such as Austria, Sweden and Great Britain.

237 Haucap/Pagel 2014.

238 A black start capability power station is capable of starting up independently of the power grid in the event of a power outage and so contributing to reestablishing the electricity supply.

centralization. At present, the greatest expansion is in regions remote from the point of load, resulting in higher costs due to curtailment, higher levels of redispatch and grid expansion requirements. Not even the new calls for proposals under the EEG lead to expansion close to the point of load, resulting instead in a concentration in northern and eastern Germany.[239]

The reference yield model[240] as an incentive instrument for spatial management of wind energy expansion and the defined grid expansion area[241] as a regulatory instrument designed to establish a minimum level of site diversification fail to offer sufficient incentives for system-compatible expansion of renewable energy sources. The main reason for this is that insufficient account is taken of grid congestions.

Furthermore, the compensation stipulated under paragraph 15 of the EEG of 95 per cent of lost revenues for curtailed volumes of energy creates false incentives. The fact of paying money for electricity that is not produced carries potential risks when it comes to acceptance of statutory funding and surcharge provisions. Curtailment also involves consequential costs for the overall system.[242] On the other hand, the curtailment of electricity from renewable energy sources requires a reasonable distribution of risk, as feed-in suppliers are dependent on a grid operator (monopoly) and have no lever to use against the grid operator if it does not drive grid expansion forward. **Compensation for lost revenues for curtailed volumes of energy** could therefore **be abolished**, though only up to a limit of for instance 3 per cent of annual energy production (as set out during the grid planning procedure). Curtailment without compensation would also create additional incentives for the feed-in supplier to use electricity locally, without recourse to the grid (storage system, sector coupling).[243]

A further possibility involves taking account of regional distribution **in calls for proposals** via **a regional component in the remuneration model** which, unlike the current reference yield model, would primarily take account not of the yield of the renewable energy plants but instead of the grid situation. Alternatively, **grid fees for feed-in suppliers** could be raised in areas where grid expansion is required (G component) (see section 5.3.3).

In the context of comprehensive reform of the wholesale market, **node-specific, time-variable prices ("nodal pricing")** could also be introduced which, when associated with a flexible, location-independent market premium, could lead to market-based incentives for system-beneficial site selection.[244] Another way of controlling

239 Haucap/Pagel 2014.

240 The reference yield model first of all defines a "reference site" with a specific wind power, to which the value of 100 per cent is assigned. All other sites at which wind power systems are planned can then be compared to the reference site: at an 80 per cent site, wind levels are on average 20 per cent lower than at the reference site, and at a 120 per cent site 20 per cent higher. The price paid is then corrected by a correction factor, which is higher at low-wind sites and lower at high-wind sites.

241 Within the grid expansion area, the Bundesnetzagentur only authorizes a limited number of projects in the context of calls for proposals for onshore wind energy until a fixed total installed capacity is reached. The grid expansion area currently includes the northern part of Lower Saxony, Bremen, Schleswig-Holstein, Hamburg and Mecklenburg-West Pomerania.

242 BMWI 2014, for example, sets a value of 100 euro/MWh on replacement purchase of the curtailed volume of energy.

243 Amending compensation regulations to this effect would undoubtedly reduce the profitability of renewables investments but the distribution effects would appear acceptable if a maximum limit of 3 per cent is adopted. These regulations could conceivably also be applied only to new plants.

244 See acatech/Leopoldina/Akademienunion 2020 for a detailed discussion of a nodal pricing system.

site selection is to use spatial planning control instruments, but their primary emphasis is not the situation in the electricity transmission and distribution grids.

As the regulatory framework stands at present, grid planning and grid expansion take their cue from the expansion of renewable energy sources, whether anticipated or already in place. Consequently, decisions by project developers on sites for example for wind turbines are made largely independently of the grid situation, these decisions then being taken as basis for the determination of grid expansion requirements and planning of the grid. The above-described options may assist in better coordination of the expansion of renewables and of the grid, as they create incentives for grid-beneficial positioning of renewable energy plants.

Incentives also need to be put in place for system-beneficial site selection for **storage systems**, as well as for generating plants, given that, in the longer term, storage systems offer the possibility of avoiding curtailment. If the construction of storage systems were incentivized, more renewable energy plants could be built in northern Germany. In principle, similar instruments can be used to control the building of additional storage systems as for the building of additional renewable energy plants. However, **node-specific prices** in this case have the particular advantage of signalling to the storage system in time-variable manner which mode of operation is system- and grid-beneficial at any given moment.

As a whole, it is necessary to ensure that generator- and storage-side incentives have a sufficient steering effect, while also ensuring sufficient transparency, comprehensibility and calculability for investors.

5.3.5 Coordination of decentralized components in the distribution network

The integration of decentralized renewable energy plants and flexibility already presents some major challenges to the distribution network. Since expansion of the distribution grid is associated with high costs (see section 4.2.5), decentralized components have to be operated system-beneficially so as to reduce grid expansion. Grid-beneficial operation is of relevance if grid congestions impede unfettered trading. In normal operation, a distribution grid operator does not have to intervene in the schedules of decentralized plants.

At present, coordination tends towards the rigid: feed-in from non-curtailable PV systems is limited to 70 per cent of nominal power, and feed-in from PV storage systems to 50 per cent. There is also legislation in place covering reactive power injection, to prevent voltage band violations and, increasingly, proposals for e-vehicle charging stations come with the right for the grid operator to limit charging operations.

The interplay between large numbers of small plants can lead to problems. For example, the simultaneous response to market price signals by a large number of storage systems (e-vehicles, PV battery banks) in one region can lead to grid congestions (“high simultaneity”). If nodal pricing were used (see section 5.3.4), the problem would not arise, as the grid situation is already taken into account in the market processes and possible congestions are already contained in the price signal.

Flexibility among larger and smaller consumers could also in future be used to deal with local grid congestions, but the current zonal pricing system does not make use of this option, resulting in higher grid expansion costs.

The **introduction of an amber light stage** might make coordination smarter.[245] As with traffic lights, a distinction would be drawn between a green market stage, a red grid phase and a transitional amber stage between the two. In the green stage the power grid operates without restriction for the market, while in the red stage system stability is jeopardized. The amber stage comes in as soon as there is a potential grid congestion in a defined grid segment, with the distribution grid operators then drawing on the flexibility offered by market participants in this grid segment in decentralized manner to prevent the red stage, i.e. intervention in schedules, from kicking in. A prerequisite for this is identifying and issuing calls for proposals for the necessary capacity, with **local markets** such as Enera being possible options for congestion management. Regionalization of energy trading provides distribution grid operators with the possibility of efficiently accessing decentralized generators, loads and flexibility.[246] Configuration is an important factor here, however.[247] Once again, **node-specific pricing** is a fundamental option, **with widening of the options for intervention**[248] **by grid operators in the event of problems** also being something to consider.[249] **Regulatory approaches for reactive power injection** (voltage-based characteristic curve) may also lead to more grid-beneficial operation.

System-beneficial coordination of decentralized components is a prerequisite for a well-functioning, cost-efficient, decentralized energy system. When it comes to introducing these instruments, it is important to ensure consistency between technical aspects (e.g. ICT) and the regulatory and market levels. Account also needs to be taken of the specifics of the various grid voltage levels and, at the same time, efficient coordination between voltage levels must be ensured.[250] High transaction costs also need to be avoided and options limited for strategic behaviour (where individual stakeholders exploit inconsistencies in the market design to the detriment of the community).[251]

5.4 Options for action in society

Spatial planning instruments and greater participation by citizens in planning procedures can help to alleviate land-use conflicts and boost acceptance of the energy transition. One challenge is the complexity both of the energy system and of the relevant legislative and policy areas which demands a high level of knowledge and understanding of the system from everyone involved.

245 BDEW 2015.

246 A prerequisite is smart metering systems or modern measurement devices (with a linked smart read-out and communications module).

247 See in particular Hirth/Schlecht 2018 for criticism of (local) market-based redispatch. These objections are taken up by Voswinkel 2019 in the context of local markets and countermeasures are proposed.

248 To be able to intervene purposefully in problem situations in the distribution grid, distribution grid operators have not only to have the appropriate right to intervene but also the necessary technology (e.g. means of accessing electric vehicle charging devices). The latter is not yet the case everywhere.

249 § 14a EnWG already provides for low-voltage consumer devices with a separate meter point administration number (e.g. night storage heaters, heat pumps and electric cars) to be controlled by the grid operator and for a reduced grid fee then to be levied as a quid pro quo.

250 See also ESYS "Electricity market design" working group.

251 Various options for achieving flexibility for overcoming grid congestions are also discussed in acatech/Leopoldina/Akademienunion 2020.

5.4.1 Spatial planning options for action

It is precisely as onshore wind energy is expanded that there will also be an increase in potential nuisances caused by the energy transition for humans and the natural world. The spatial planning system must ensure that the nuisances are kept as minor as possible by weighing up different concerns against one another and designing an appropriate land-use concept. **Spatial planning should be strengthened to ensure transparency in the consideration of differing landscape concerns**. Particular weight must be attached to citizen participation processes at the federal state or national planning level. Participative processes are, however, more difficult to design at a higher level than those at a regional and local level. This is because at these levels of scale there is a polarization of citizens into those who are affected and those who are not, with the former feeling cheated and organizing themselves against the projects and the latter feeling that the issue is utterly irrelevant to them. Selecting citizens by lot as "lay planning assessors" in the interests of the public good can alleviate this problem.

Areas which are already in use can also offer potential sites for (renewable) energy plants. For instance, **residential and commercial areas with large areas of flat roof or car parking could be used for installing photovoltaic systems.** All land-use categories should be checked to establish their suitability for integration of renewable energy plants. Since areas which are already in use are exposed to a certain degree of environmental impact, it makes sense to locate further infrastructure there or to combine a number of routes. This is particularly attractive if, by modernizing the infrastructure, impact can be reduced. Combining systems in this way may, on the other hand, be problematic if additional infrastructure with an impact is introduced into an already heavily industrialized area, so further increasing the already high levels of impact on the environment and population. Issues of justice must be taken into consideration here.

Photovoltaics above all offer various possible options for combining **energy production** with other **land uses:**

- The possibility of integrating **PV systems in residential areas** should be investigated and trialled in various kinds of residential development.
- Possibilities for using **building-integrated photovoltaics** should be investigated and further developed. This involves integrating PV modules with multiple functions in the building envelope where, in addition to producing energy, they for example provide thermal insulation, weather protection, acoustic insulation or light control.
- Combining the **refurbishment of existing building stock** with new PV systems should be researched.
- The upgrading of conventional residential developments with single occupancy housing to **energy-efficient residential developments** could be tested and demonstrated in pilot schemes.
- Careful consideration should be given to the role of **industrial areas as energy production locations,** so for example offering the possibility of recharging vehicles during working hours.
- **Renewable energy plants could be combined** with existing traffic and energy routes.

- The feasibility of solar noise control walls should be investigated.
- The plans of some energy suppliers to make use of former **lignite and hard coal mining** areas for large **solar and wind farms** are very promising. These areas have already been available for energy production for decades and continued use could have positive effects on local wealth creation, for instance thanks to new job creation. In this way, a positive link could be created between structural change and the areas recovered for renewable energy plants.
- Additional environmental benefits in the case of large solar PV farms could increase acceptance of the plants. For example, the **agrophotovoltaics** model could be an option for at least some of the area in order to counter land take. This model involves installing the PV systems higher off the ground so that the land below can be put to agricultural use. Extensive grassland use under PV systems could contribute to maintaining biodiversity.

Making greater use of offshore wind energy can alleviate land-use conflicts. Gaps do, however, remain in our knowledge about the environmental impacts involved and there is a need for further research in this area.

5.4.2 Design of public participation in planning procedures

If citizens are involved in planning procedures at an early stage and are provided with a right of action, decisions can be revised while ensuring procedural fairness. This can create the level of institutional trust required for future, similar projects. Greater use should accordingly be made of current theoretical and practical insights into participation. This can apply irrespective of whether the energy system is to develop in a more centralized or more decentralized direction.

If actual or at least perceived shortfalls in legitimacy in decision-making are to be eliminated, existing or perceived deficiencies with regard to both procedural fairness and distributive justice must be overcome. New and expanded forms of participation should be directed towards carefully identifying and involving all relevant partners in the debate and their interests, including necessary expert opinions and ensuring efficiency and transparency of the processes. The fairest possible distribution of benefits and burdens is also crucial to acceptance.

There are various options for designing participation processes[252]:

- **Existing formal forms of participation in local planning and approval procedures could be improved**, for example by skills development and better resourcing for those carrying out the procedures.
- In addition, **informal formats** should be facilitated and structurally embedded.[253]
- A higher-level **debate about the energy transition spanning the whole of society** for systemically elucidating aims, background issues and alternatives and establishing an ongoing communicative framework would still appear to necessary and meaningful.

252 A more detailed discussion of various options for citizen participation in the energy transition can be found in Oppermann/Renn 2019.

253 For example the “Faire Windenergie” label in Thuringia.

It should be borne in mind that informal formats do not automatically promote acceptance or reduce conflict, a further decisive factor being precisely how such formats are designed in practical terms. It is therefore necessary not only (where meaningful) to supplement the process with informal opportunities for participation but also to focus very heavily on improving formal procedures. One advantage of formal procedures is that they are more readily assessed in terms of predictability and procedural reliability. Being standardized, they can likewise in principle potentially be more readily understood and compared. In any case, it should naturally be the aim of a functioning society to maintain confidence in the independence of the relevant authorities, which function to a degree as advocates of citizens' interests.[254]

5.4.3 Expanding the knowledge base for the debate in society

Ensuring that energy transition planning and approval procedures are widely **understood among the general population** ("planning policy workshops") can create greater understanding and so be of benefit to all kinds of infrastructure planning. Having some expertise in planning policy, citizens can then communicate in their own spheres and so contribute to a constructive debate about the options available for the energy transition. One question which undoubtedly arises is the extent to which the complex technical, legal and social interrelationships can be communicated to the general public. Not every citizen will be willing and able to familiarize themselves with all the interrelationships for example not only in planning law but also in climate protection and tax law.

Not only science journalists, but also scientists and planning experts, have an important role to play in communicating a basic understanding of these complex interrelationships. They have already been contributing to the energy transition debate but there has previously been a lack of opportunities for local experience and discussion. Such discussions can be organized and documented in the context of **informal participation processes**. The knowledge gathered in this way can be disseminated via conventional media and social networks.

5.4.4 Initial and in-service training for specialists

New technologies and grid structures also entail corresponding **initial and in-service training for specialists**. Various studies have accordingly concluded that secure and reliable operation of the energy supply grid of the future is dependent on experts and specialists who have a higher level of interdisciplinary training.[255] For example, new challenges are arising in relation to control concepts, data management or IT security in the course of digitalization of the energy transition. Safe operation of new grid structures such as protective systems or stability in the event of decentralized feed-in must also be ensured. This requires knowledge about not only centralized (transmission grids, HVDC transmission, large-scale/long-term flexibility etc.) but also decentralized structures (self-consumption, consumption optimization or coordination of numerous stakeholders and plants).

An understanding of how the two types of structure interact is also becoming ever more important. This relates for example to the reversal of power flow, overall system stability and macroeconomic optimization. In all cases, specialists will have to work

254 Hildebrand et al. 2017.
255 HMWEVL 2019; Gremienverbund zur beruflichen Qualifikation 2017; Öko-Institut 2018-3.

together in a more **interdisciplinary** way. Grid experts need knowledge about the underlying control structures, forecasts (weather, load), business administration and economics (energy market) and technologies (generators, transmission, storage systems, load). Less complex innovations will tend to be required for a centralized system than for a highly decentralized one. New occupational profiles are arising which depend to a greater extent on interdisciplinary working and are so creating a link between different energy systems (heat, gas, electricity etc.) and energy consumers. Precisely with regard to the greater role of prosumers, flexibilization of energy demand and energy saving, it is important to understand consumer and prosumer behaviour, for example what prompts people to invest in solar power systems, storage systems or electric cars or to provide flexibility for the overall system with their electric car's battery. An understanding of social processes (e.g. what motivates people to resist wind turbines or power routes) is likewise essential. Knowledge in the social sciences and humanities, for example in environmental psychology and political science, is therefore becoming increasingly important in order to shape the transformation of the energy system.

6 Conclusion

When it comes to developing and comparing possible transformation pathways for the energy system, establishing a "centralized – decentralized" dichotomy is ultimately not of great help. It is instead vital to know how various more centralized and more decentralized installations and coordination mechanisms can be brought together to create a functional overall system which is as environmentally friendly, competitive and secure as possible. The question as to what degree of decentralization is appropriate can therefore only be answered in the overall context of the transformation of the energy system, which gives rise to the following fundamental challenges against which both more centralized and more decentralized approaches must be measured:

- Huge time pressure applies to the transformation of the energy system, making the speed with which a climate protection measure can be implemented an important criterion.

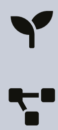
- Expansion of renewable energy sources requires large areas. Conflicts with nature conservation and with people who consider themselves to be harmed by the facilities are therefore on the rise. Reducing these conflicts to the greatest possible extent and securing the population's ongoing consent to the energy transition are thus essential for achieving climate protection targets.

- The increasing share of renewables, the necessary flexibility and increasing sector coupling mean that the energy supply will become more complex. Coordinating the overall system and ensuring security of supply are becoming more challenging as a consequence.

- reliable framework which encourages all the various stakeholders, from private households to major energy supply companies, to make the greatest possible contribution to the energy transition. This framework should also ensure an energy transition at the lowest possible cost.

Major **gaps in knowledge** still remain, in particular with regard to **comprehensively decentralized energy systems**, in which a large share of both energy and flexibility is provided locally in small units. There is thus a **need for research** into the operation of energy systems in which **security of supply** is ensured **by decentralized installations**. Reliable estimates regarding the **costs** of comprehensively decentralized systems, taking account of system services and effects on distribution grid expansion, have also not yet been made available. Investigating a broader **range of scenarios** in energy system studies and **taking greater account of impacts on people and the environment**, with the aim of responsible land use for instance with regard to species conservation and landscape, could provide a better basis for comparing more centralized and more decentralized energy systems.

The following six pillars would appear to be essential to a successful energy transition:

Pillar	Considerations for implementation / approaches	Challenges
Boosting renewable energy source expansion: All potential renewable energy sources, whether centralized or decentralized, will have to be exploited and utilized to the full if the power needs of the future are to be met climate neutrally.	More stringent spatial planning, the use of already built-up areas (roofs, car parks), dual use (e.g. wind energy/PV and agriculture), offshore wind energy and energy imports can **alleviate land-use conflicts**. **Storage systems** and other **flexibility options** will also have to be expanded, with research and development still being capable of achieving considerable reductions in cost. Reducing energy consumption by modified user behaviour and more efficient use and conversion technologies is essential for meeting energy demand in an environmentally and socially responsible way.	
Implementing grid expansion: Considerable expansion of both the transmission and distribution grids will be necessary by 2050, even if renewable energy sources are put to decentralized use.	If transmission grid expansion is delayed, **decentralized PV systems** in combination with grid-beneficially operated storage systems and power-to-gas technologies can assist in nevertheless meeting climate protection targets. The more decentralized the system, the more important will **smart distribution grids** become.	
Shaping digitalization: Secure and smart information and communication technologies are essential to the coordination of the energy system of the future. There is still a great need for research and development in particular with regard to more decentralized systems with numerous different stakeholders and plants.	The demands placed on decentralized installations to contribute to system stability will grow over time. Plants should therefore be equipped from the outset with the necessary hardware in order to enable **rapid adaptation to new requirements** through software updates. Approaches should be developed to **ensuring stability through decentralized installations**, while taking account of **risks due to cybercriminals**.	
Strengthening the CO_2 price: A stronger CO_2 price signal as a key instrument would assist in achieving climate protection targets as inexpensively as possible.	There are various possible approaches to CO_2 pricing: extension of European emissions trading to other sectors with the optional addition of a minimum CO_2 price, introduction of a separate Emissions Trading System for those sectors which have not previously been included, or introduction of a CO_2 tax or duty. Above and beyond the CO_2 price, further instruments will be required to model external effects other than CO_2 emissions (e.g. land use-related conflicts).	
Streamlining regulations: A new, simpler regulatory system should support the market as a "marketplace of ideas" and so facilitate the development and commercial introduction of new products and services. At the same time, the market and grid operation should be better coordinated.	The profusion of individual regulations should be reduced to the greatest possible extent. Incentives can also be provided by reforming markets, fees and surcharges, to • enable **system-beneficial prosumption** (individual and collective), • **grid-beneficially expand renewable energy plants** (e.g. by regional components in the remuneration model in calls for proposals under the EEG or limitation of compensation for lost revenues for curtailed volumes of energy), and • **grid-beneficially operate renewable energy plants** (e.g. by local markets for congestion management or node-specific, time-variable pricing). **These aims could also be supported by the introduction of grid fees for feed-in suppliers and restructuring grid fees** for consumers.	
Strengthening participation: The energy transition can only succeed if it is shared and actively supported by the population. Opportunities for political and economic participation may be of assistance here.	**Economic participation** ensures that local stakeholders can share in the wealth creation arising from renewable energy sources, for example through a countrywide Citizens' and Local Authority Participation Act. **Opportunities for political participation** in formal and informal participation processes can be improved (for instance by lay planning assessors), enabling citizens to play a part in shaping the transformation process in line with their ideas.	

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The Academies’ Project

With the initiative “Energy Systems of the Future”, acatech – National Academy of Science and Engineering, the German National Academy of Sciences Leopoldina and the Union of the German Academies of Sciences and Humanities provide impulses for the debate on the challenges and opportunities of the German energy transition. In interdisciplinary working groups, some 100 experts from science and research develop policy options for the implementation of a secure, affordable and sustainable energy supply.

“Centralized-decentralized energy supply” working group

The interdisciplinary working group investigated how centralized and decentralized components in the energy system can be combined to create a secure, affordable and climate-compatible energy supply. This involved elucidating the advantages and drawbacks of more centralized and more decentralized systems from technical, economic, spatial planning and social standpoints and, on this basis, drawing up options for action as to how energy policy can make use of the opportunities offered by more centralized and more decentralized components to the benefit of the overall system and mitigate risks.

The results of the working group’s efforts have been made available in two formats:

- The **Position Paper** “*Centralized and decentralized components in the energy system. The right mix for ensuring a stable and sustainable supply*” presents the results in compact form and indicates energy policy options for action for integrating more centralized and more decentralized technologies and coordination mechanisms to the greatest possible benefit for the overall system.

- The “*Technical scenarios*” **Materials**, which are available online in German, contain a more detailed characterization of centralized and decentralized energy systems from a technical standpoint, and an evaluation of energy scenarios from studies which examine various aspects of decentralization. The presented results formed the basis for further interdisciplinary examination.

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Framework

Project duration

03/2016 to 02/2020

Funding

The project is funded by the Federal Ministry of Education and Research
(funding code 03EDZ2016).

The German Position Paper was approved on 27 September 2019 by the Board of Trustees of the Academies' Project.

The Academies would like to thank all the authors and reviewers for their contributions. The Academies bear sole responsibility for the content of the Position Paper.

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Series on Science-Based Policy Advice
ISBN: 978-3-8047-4061-7