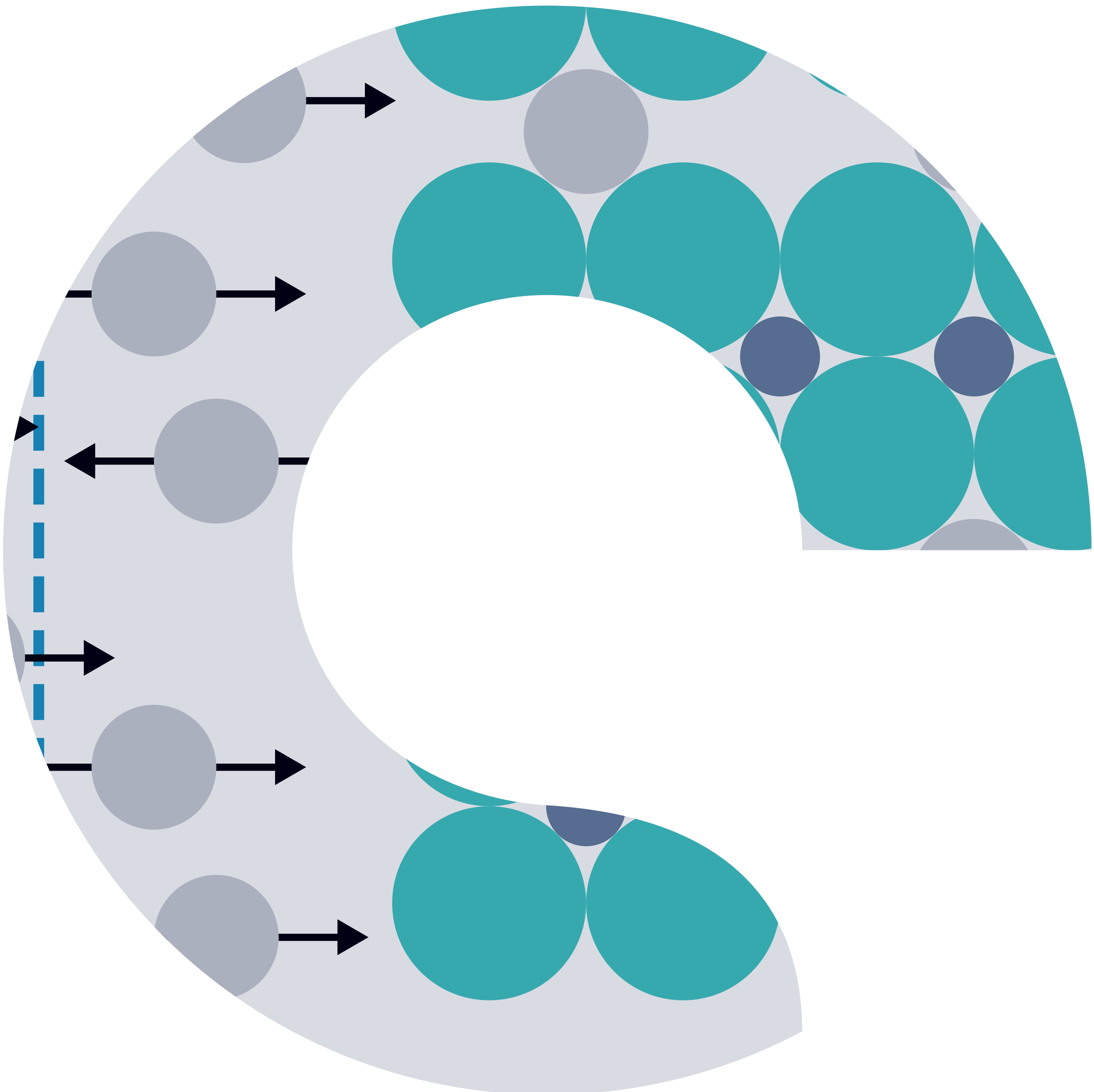
Electricity Storage in the German Energy Transition

Analysis of the storage required in the power market, ancillary services market and the distribution grid

STUDY

Agora Energiewende



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IMPRINT

SUMMARY OF STUDY

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Analysis of the storage required in the power market, ancillary services market and distribution grid

STUDY BY

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Preface

Dear reader,

Power generated by wind and solar power plants depends on the weather rather than the demand for electricity. An intuitive solution to this problem is to collect electricity when the sun is shining and the wind is blowing and then use it later, when the power provided by the sun and wind is insufficient.

Germany has ambitious plans to increase the share of renewable energy in the power sector from its current level of 25 percent to over 60 percent within the next 20 years. In view of such plans, the question arises as to how much storage is required and when.

Agora Energiewende has put this question to a consortium of four leading research institutes.

The focus of the investigation was the cost of the German power system associated with an increase in renewable energies by up to 90 percent.

The results offer striking insights even for experts and encourage further analysis. To facilitate further discussion, all the assumptions used are published on Agora Energiewende's website.

I hope you enjoy the read!

Best regards,
Patrick Graichen,
Director Agora Energiewende

The results at a glance

1. The expansion of renewable energy does not have to wait for electricity storage.
In the next 10 to 20 years the flexibility required in the power system can be provided for by other, more cost-effective technologies such as flexible power plants, demand side management. New storage is required only at very high shares of renewable energies.

2. The market for new storage technologies will grow dynamically.
New markets for battery storage and power to gas technologies are expected to emerge, especially in the transport and chemical sector. Storage developed in these sectors can enable further flexibility for the electricity system as an additional service. Research and development as well as market incentive programs should maximize the system-supporting contribution of new storage technologies.

3. Storage must receive equal access to markets for flexibility.
Storage can already today deliver several ancillary services at competitive costs. Flexibility markets – such as the ancillary services or future capacity markets – should therefore be designed such that they are technology-neutral.

4. Storage should become a tool in the toolbox of distribution system operators.
In specific cases, storage that is used to support a grid can help to avoid grid expansion in the low-voltage distribution grid. The regulatory framework should enable such cost-efficient decisions.

Key Findings and Conclusions

1. The expansion of renewable energies does not have to wait for electricity storage.

With the increasing share of renewable energies, the need for flexibility in the German power system increases. In the next 10 to 20 years, this requirement for flexibility can be covered by other cost-effective flexibility options rather than with new electricity storage, with the share of renewable energy increasing to 40 to 60 percent. In particular, controllable power plants can be turned off during periods of strong wind and sun and used when the power provided by the sun and wind is insufficient. Together with flexible CHP plants, demand side management and European power trading, this option offers sufficient and cost effective flexibility for balancing production and demand over the next 20 years. Investment in new electricity storage for balancing power generation within this period only reduces the cost of power generation to a very limited extent.

With very high shares of renewable energies, of 90 percent in any case, full integration of renewable energy into the power system without new power storage will be increasingly difficult. In the scenario with 90 percent renewable energies in Germany consideredhere in this study, about ten gigawatts of electricity storage could contribute to the reduction of the total cost of electricity supply. The optimal quantity and the best mix of different storage systems in Germany will especially depend on the development of capital costs for new storage systems, the availability of alternative flexibility options (such as new flexible power consumers) as well as the type and speed of the expansion of renewable energies.

2. The market for new storage technologies will grow dynamically.

In addition to balancing power generation from wind and solar power plants, significant markets will develop beyond the electricity system for both battery technologies and power-to-X (i.e. Power-to-Heat, Power-to-Gas, Power-to-Chemicals). Besides the use of thermal storage to improve the flexibility of CHP and Power-to-Heat, such new markets will develop particularly in the transport and chemical sector. Due to the falling cost of these technologies, the replacement of fossil fuels with electricity from wind and solar power plants will be increasingly attractive in these sectors in the future. The speed and in which order these markets will develop is not currently clear, and will depend, amongst others, on the ambition with which the targets for renewable energy are pursued beyond the power sector. In the long-term, however, new energy storage technologies from other sectors such as heating, transport, chemistry is likely to dominate the German electricity system with installed capacities in dimensions of over 100 gigawatts. Additionally, a market for storage systems installed together with PV systems will develop, driven by the preference for self-consumption of electricity produced as well as the regulatory environment. Future regulations should enable such a market to develop while at the same time preventing new storage systems being solely financed by avoiding the necessary common costs.

All new energy storage systems will be able to provide flexibility to the electricity sector as an additional benefit in addition to their primary application. To use this flexibility potential fully in the medium to long-term, existing and future research and development as well as market incentive programs should be aimed at maximizing the contribution of new storage technologies in terms of supporting the power system.

3. Storage must receive equal access to markets for flexibility.

Due to the declining contribution of controllable power plants in terms of power generation, other flexibility options including storage will become more and more important with regard to balancing power generation and demand. Energy storage is already able to provide some ancillary services cost-effectively. Because of their ability to respond quickly, battery storage systems are used in the market for primary control power in Germany today. Storage devices are technically well suited to contribute in some hours to security of supply, provided that sufficient energy is stored at the time of use.

In order to allow technology-neutral and open competition, it is important to create a level playing field with other flexibility options in the markets for ancillary services as well as in potential future capacity markets.

4. Storage should become a tool in the toolbox of distribution system operators.

It may be necessary to adapt the distribution grid when connecting new wind and solar power plants. In such case, in addition to building new grid infrastructures, one can also consider using battery storage to smooth out production peaks from renewable energy. In low-voltage distribution networks, a combination of battery storage and / or curtailment of production peaks can be cost-effective in certain cases. To enable the distribution system operators to minimize cost, it should be possible to use storage systems to permanently or temporarily avoid the need to expand low-voltage networks. A case-by-case analysis is essential here.

Battery storage to optimize self-consumption in combination with solar systems can relieve the distribution network when used in a manner that supports the grid. Appropriate design and parameterisation enables this kind of use without having to invest in communications technology.

In the medium and high-voltage distribution grid, the use of battery storage is however not a cost-effective solution to avoid network expansion. The very large amount of energy storage required in these cases would result in very high investment costs that far exceed network expansion costs in all the cases considered.

5. The results are sound, but indicate that future research is also necessary

The results are based on extensive scenario analyses using simulation models. As for all models, the assumptions have a major impact on the results. The scenarios in this study were discussed intensively and complemented by sensitivity analyses. Emphasis was placed on analysis of the most likely future developments: A European electricity market using existing and moderately expanded cross-border connections and other flexibility options (in particular gas-fired power plants and demand-side management) were assumed. A significant expansion of renewable energies both in Germany (according to the government targets) and in the neighbouring countries (assuming a slower expansion than in Germany) was also assumed. A much-discussed assumption of this study is that network expansion within Germany will not be delayed. The results from other studies (for example, the Optimization Study by Agora Energiewende in 2013 and the Roadmap Storage from Fraunhofer IWES / IAEW / SUER 2014) show, however, that delays in grid expansion by several years have no significant effect on the results. In principle, a delayed grid expansion would not affect the conclusion that the resulting need for flexibility of a power system with 60 percent renewables can be met cost-effectively by alternative flexibility options other than new electricity storage systems. It remains to be determined, however, what the long-term optimum is between grid expansion within Germany and other flexibility options. „Grid expansion until the last kWh" would be more expensive than an ideal mix of all flexibility options and is likely to be realized only with delay due to lack of acceptance.

This study does not consider scenarios where renewable energies in Germany or Europe undergo more rapid expansion than expected. For example in the event of a breakthrough of photovoltaic technology, or scenarios in which cost effective flexibility options such as grid expansion, the construction of new gas turbines and demand side management are not available at all in the long-term. The simulations also did not consider the effects on the power system that the large amount of energy storage technologies driven by market developments in other sectors would have on the power sector. Analysis of respective future market development shows that further research is needed here.

Content

1 Summary of Findings

This section describes the insights generated by this study. In the first part, we elucidate our research questions, explain important terminology, and present key assumptions. As the results of any study have to be understood in relation to its underlying assumptions, we conclude the section by examining the interrelationships between assumptions and results. Finally, the need for further research is addressed.

The research question and terminology
How much and which kinds of storage capacity are required for the energy transition in Germany? This study aims to contribute to answering this question. We focus on the power sector, and we examine the issue primarily from the perspective of overall system costs. A separate analysis of the markets for storage capacity, including other energy sectors and investment motives, expands upon this main focus.

In the context of this study, the phrasing **storage needs at the level of the transmission network** designates the amount of *electrical* storage which – through integration in European energy and reserve markets, and in conjunction with other flexibility options for balancing power generation and consumption – can contribute to a reduction in overall system costs. In the context of the study, **storage needs in the distribution network** designates the amount of *battery* storage capacity that can avoid the need for network expansion in a cost-effective way, if investments are solely directed at this goal and if deployment is undertaken in a way that "serves" the network.

The need for electrical storage capacity explicitly **leaves out of consideration other energy storage in the system**, as may be used, for example, in the transportation, chemicals, and heating sectors (electric vehicles, plants that convert power to gas/liquids/chemicals, heat accumulators for power-to-heat facilities and CHP systems, cold accumulators in large scale cooling systems, etc.).

Key assumptions
This study considers three future time points: 2023, 2033, and the point in time when renewable energy comprises 90 percent of Germany's electricity supply. A series of assumptions were made about these three time points.

The **scope of consideration for the analysis** at the level of the transmission network is the European power generation system, which is made up of various market areas that are linked to each other through limited cross border interconnections. We assume that the European market areas will maintain their current structure. Thus, we do not include in our consideration any network bottlenecks within Germany resulting from delayed grid expansion in Germany. Electricity storage is evaluated based on its benefits for balancing electricity production with demand.

Due to the European wide analysis, both the **share of renewable energy** in German electricity generation and the **share of renewable energy in Europe** are of relevance. It is assumed that the European percentage will continue to be lower the German percentage:

- → **2023:** 43 percent share of renewable energy in Germany; 23 percent in Europe as a whole
- → **2033:** 60 percent share of renewable energy in Germany; 40 percent in Europe as a whole
- → At the time of a **90 percent** share of renewable energy in Germany: 60 percent in Europe as a whole

Scenarios with a renewable energy share of 90 percent in both Germany and Europe as well as scenarios that project full supply from renewable energy were not considered in this study.

The impact that will be exerted by the expansion of **alternative flexibility options** on needs for storage at the level of the transmission network are examined in the 2023 and 2033 scenarios by considering alternative scenarios. The scenarios vary in particular with a view to the expansion of **demand side management, flexibility of production facilities with heat and power cogeneration,** as well as the **expansion of cross border interconnections**. Our assumptions are based on previous studies by the co-authoring institutes and on discussions with experts from industry and academia. The effect of potentially high penetration by new power consumers, such as electric vehicles and power-to-gas, which can add flexibility in the electricity sector as an additional benefit, is not examined.

The assumptions regarding the **development of power plant fleet and electricity demand** are based on scenarios developed by the German Federal Network Agency and by the European transmission network operators. These scenarios include an expansion of gas power plants to cover the required peak load. The economic evaluation of storages at the level of the transmission network is done based on scenarios to which several predetermined variants of additional storage are added, whereby savings from then no longer required gas power plants are credited to the storage. The study is not based on any optimization model that would jointly evaluate the necessary power plant fleet considering storage capacities as well as alternative flexibility options. Given the approach selected, the investment costs for alternative flexibility options have no impact on the results because only savings and additional costs from additional storage capacities are taken into account.

1.1 Findings on the classification of energy storage facilities

There are many kinds of energy storage facilities with different functions and purposes. A clear differentiation between electricity storage technologies and cross-sectoral energy storage solutions is essential in the discussion of storage.

A meaningful discussion of storage within the energy system requires a classification that distinguishes between electricity storage devices, heat accumulators, fuel accumulators, and gas storage facilities. Sector-specific energy storage technologies, such as electricity storage units, are assigned to a sector. Cross-sectoral technologies for energy storage, such as power-to-gas and power-to-heat, as well as batteries for electric vehicles, interconnect different energy sectors (see Figure 1-1).

Currently, over 80 percent of the power generating system is based on stored chemical energy, such as coal and gas. Thus, there has always been a need for energy storage in the form of coal stocks and gas storage tanks. These energy storage systems are classified as primary energy stores, and they are "charged" only once, for example, through photosynthesis, and the natural transformation into hydrocarbons, and they are only capable of being "discharged" one time by means of combustion technology. By contrast, secondary energy storage technologies can be chargedand discharged many times (including, for example, pumped storage plants or battery systems).

An energy storage technology is generally a means of energy storage that incorporates the following three processes: charging , storage, and withdrawal (discharge).

Electricity storage technologies are a sub-category of energy storage technologies. They take in electrical energy and store it directly, either electrostatically or electromagnetically, or they reversibly transform electrical energy into some other physical form of energy.

Increased feed-in from renewable energy has created a need for flexibility, which includes a need for technologies to store electrical power. There are numerous flexibility options that are derived from primary and secondary energy storage (and which may involve other sectors – for example, heat storage).

The feed-in of renewable energy does not lead directly to an increased need for energy storage. Rather, it creates the need for flexibility to deal with fluctuating input and to compensate for both temporal and spatial fluctuations. The requirements for electricity storage as such arise from an assessment of the trade-offs between technically and economically advantageous flexibility options.

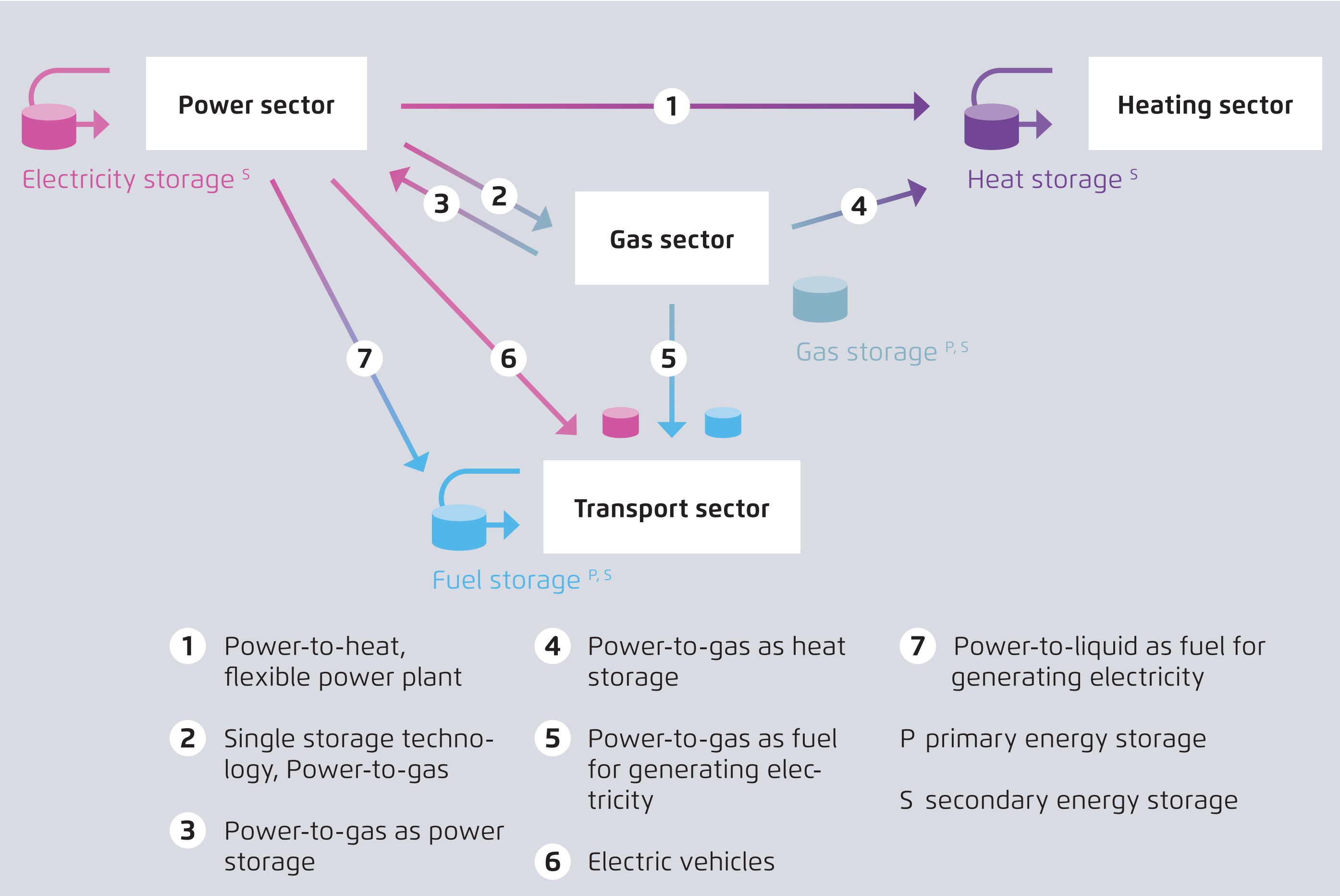
Flexibility options in each segment include:

- → Generation: power plant flexibility, cogeneration plants, renewable energy plants (including curtailment)
- → Network: network expansion, network conversion
- → Storage technologies: sectoral energy storage, cross-sectoral energy storage
- → Consumption: demand side management in the electricity sector and across sectors

Overall, there is little competition between electrical grids and electrical storage technologies, because electrical grids are res-ponsible for the spatial compensation of differences between generation and consumption, whereas electricity storage technologies are responsible for temporal compensation.

Major flexibility in Germany can be achieved at relatively low cost by coupling the electricity and heating sectors in the form of heat accumulators. Heat accumulators enable operation of cogeneration plants focused on electrical power generation, making this form of generation more flexible and thereby reducing the proportion of "must-run" plants. In combination with fluctuating renewable energy input, must-run plants can result in excess production and negative electricity prices in the power system. In addition, by using power-to-heat with heat accumulators and heat grids, high gradient fluctuations in the electricity sector can be

Sectoral and cross-sectoral storage in the energy supply system, including differentiation into primary and secondary energy storage — Figure 1-1



Sterner, et al., 2014

stored in the heat sector. Both applications are cost-effective, easily achievable from a technical point of view, and underscore the importance of heat accumulators for a successful energy transition.

1.2 Findings on the medium-term need for electricity storage capacities at the level of the transmission network

From the perspective of the electricity market, there will be no absolute need for additional storage capacities in the 2020s and 2030s, as long as the European transmission grid is expanded (even if expansion is delayed), and that other flexibility options are activated in the European market areas (even if this activation is delayed).

To analyze the question of storage capacity needs at the level of the transmission network, we considered numerous scenarios. In the basic scenarios for the years 2023 and 2033 (e.g. "flexible scenarios"), we assumed that many obvious flexibility options will be realized, including parts of the cross-border network expansion planned by the transmission network operators, and the potential for demand side management identified in third-party studies. In order to take into account the possibility that technically and economically sensible options might be delayed or not implemented at all (for example, because of a lack of societal acceptance), these scenarios were varied to consider a roughly ten-year delay in the implementation of additional flexibility options, and a more than ten-year delay in network expansion (e.g. "inflexible scenarios").

Despite this conservative approach, even in the inflexible scenarios, no reduction of overall system costs will take place in the medium term through the use of one to eight gigawatts of short-term or long-term storage capacities, given renewable energy shares of 43 percent in Germany and 22 percent in Europe overall (see Figure 1-2).

In the 2030s, a small expansion in long-term storage capacities (approx. three gigawatts) would make macro-economic sense, in the case of delay in the expansion of the

Additional costs/savings for storage variants in millions of euros per year in the *43 percent/22 percent inflexible scenario*

Figure 1-2

Authors' graphic

European transmission network, a delay in the activation of other flexibility options, and a favourable costs development of storage technology.

If renewable energy shares reach 60 percent in Germany and 40 percent in Europe in combination with a delayed deve lopment of flexibility options (inflexible scenarios), small amounts of additional electricity storage capacities approach economic viability (see Figure 1-3).

If investment costs for storage technologies develop favourably and high opportunity costs for non-integratable renewable energy generation appear, additional three gigawatts of long-term storage capacities would make macro-economic sense. In the other cases, even assuming lower storage costs, additional storage for balancing of generation and demand will continue to entail additional macroeconomic costs due to the pre-dominance of the investment costs for new electrical storage technologies.

Additional electrical storage systems will stabilize the base-load share of the residual load and reduce the demand for peak load. In the scenarios considered here, the electrical storage capacities operating in the electricity market integrate only small quantities of additional feed-in from renewable energy during the 2020s and the 2030s.

The influence of increased flexibility is relatively small in the scenario 2023, even a generation system without further flexibility (i.e. the 43 percent/22 percent inflexible scenario) has sufficient flexibility options for the efficient integration of renewable energy, given a renewable energy share of 43 percent. Similarly, for a renewable energy share of 60 percent in Germany and 40 percent in Europe as a whole, the amount of renewable energy that could not be integrated in the power generation system would be relatively small, even in the inflexible scenario considered here. In the 60 percent/40 percent inflexible scenario only 1.6 percent of the feed-in from renewable energy would have to

Additional costs/savings for storage variants in millions of euros per year in the *60 percent/40 percent inflexible scenario*

Figure 1-3

Authors' graphic

be curtailed (in the 60 percent/40 percent flexible scenario, curtailment would equal 0.3 percent).

Moreover, greater flexibility for balancing generation and demand in this scenario year leads to a shift from peak load generation by natural gas to base load generation by coal-fired plants. In the considered scenario, the coal-fired plants will continue to rank ahead of the gas-powered plants in the merit order, due to the presumed prices for emission certificates in the study (27 euros per tonne of CO_2 in 2023; 45 euros per tonne of CO_2 in 2033). Thus, barring any other measures or a major increase in CO_2 prices, no CO_2 intensive electricity generation will be displaced from the electricity mix simply by virtue of additional flexibility for balancing generation and demand.

1.3 Findings on long-term needs for electricity storage at the level of the transmission network

From a long-term perspective, electrical storage technologies will reduce overall system costs in every case if the cost of storage technology develops favourably, even if one assumes a system with many other flexibility options, a German renewable energy share of 90 percent, and a European renewable energy share of only 60 percent.

If the costs for storage technologies develop favourably, the greatest reduction in overall system costs will stem from 16 gigawatts of long-term storages and 7 gigawatts of short-term storages (see Figure 1-4). This would limit the necessary curtailment of feed-in by renewable energy on the electricity markets to approx. 3 percent. For renewable energy shares of 90 percent in Germany and 60 percent throughout Europe, additional storages will result in savings in electrical generation costs and lead to the substitution of conventional power plant capacities. At the same time, additional storage capacities will result in more renewable energy being integrated in the generation system. Nevertheless, the need for electrical storage capacities will remain in the low gigawatt range in the scenarios considered here.

Findings from other studies (see bibliography) show that with an even higher share of renewable energy in Germany and/or Europe (for example, a share of renewables greater than 90 percent), the need for storage capacity would increase very significantly.

Short-term storage is more exposed to competition from other flexibility options than long-term storage. Long-term storage capacities can reduce the overall system costs in the long run, even in the case of unfavourable development of storage costs.

About eight gigawatts of long term storage, for example, through power-to-gas as electricity storage, will reduce overall system costs in the 90 percent/60 percent scenario, even assuming higher storage costs and disregarding the opportunity costs of curtailed generation from renewables. This measure alone could reduce the curtailment of renewable energy in the electricity market from 7.2 percent to 5 percent. The variants with a greater share of long-term storage plants tend to show the greatest savings potential due to the long-term shift potential.

The use of additional short-term storage capacity for balancing production with demand of about seven gigawatts would only reduce the overall system costs in the considered 90 percent/60 percent scenario in the event of favourable storage price development. By itself, short-term storage could limit the curtailment of feed-in by renewable energy in the electricity markets to 6.2 percent. However, its capacity utilization and macroeconomic advantage are less marked than long-term storage due to the competition with other forms of flexibility within the same time frame as short-term storages. Especially notable among these forms of flexibility are demand side management and flexible power plants based on combined heat and power (CHP) with heat accumulators.

1.4 Findings on the need for electricity storage at the distribution network level

At the low voltage level of the distribution grid, the use of storage technologies can help avoid or delay the need for

Additional costs/savings for storage variants in millions of euros per year in the *90 percent/60 percent scenario*

Figure 1-4

Authors' graphic

network expansion in some cases and thereby result in cost savings.

Unlike at medium and high voltage levels of the transmission grid, the use of battery storage at the low-voltage level can be more cost efficient than network expansion.

Based on typical grids, we investigated the costs of using different flexibility options (see Figure 1-5). We compared the combined use of battery storage (including cost bandwidths) and conventional network expansion (scenario 6) to the following scenarios:

- → conventional network expansion (scenario 1)
- → adaptation of technical connection guidelines (elimination of the two or three per cent voltage criterion, scenario 2), and
- → the use of controllable local network stations (RONS, also RONT, scenario 3).

These scenarios were analyzed for two variants of additional photovoltaic cell expansion: namely, an increase in predicted photovoltaic production levels to 60 percent and to 80 percent at the low-voltage level. Whereas the first case (60 percent) clearly favours combined expansion of battery storage and the network, once one examines higher proportions of increased photovoltaic production at the low-voltage level, the use of a controllable local network station is the least expensive, if we assume maximum costs for power storage.

A very rough projection of these findings to Germany as a whole shows that in 2033, about 0.7 gigawatts in storage capacity could make a cost-effective contribution toward avoiding the need for network expansion at the low-voltage level. This projection is based upon typical networks, which were chosen on a regional basis and only represent a small proportion of all distribution networks in Germany. The findings only allow us to impute trends and options. Accordingly, analysis of each individual case is essential. However, we can say that at the low-voltage level, battery storage systems could be a cost-effective option as part of the toolbox of measures for enhancing networks.

Storage technologies must be deployed "in the service of the network" for network expansion to be avoided. If storage technologies are deployed based on electricity market needs, they might actually result in distribution grid expansion under certain circumstances.

We use the expression "in the service of the network" (viz. *netzdienlich*) to refer to the use of energy storage technologies to stabilize network load. To the extent that battery storage systems are installed for reasons other than preventing the need for network expansion (for example, household storage to optimize self-consumption), one must ensure that the form of operation does not significantly increase the load situation in the grid.

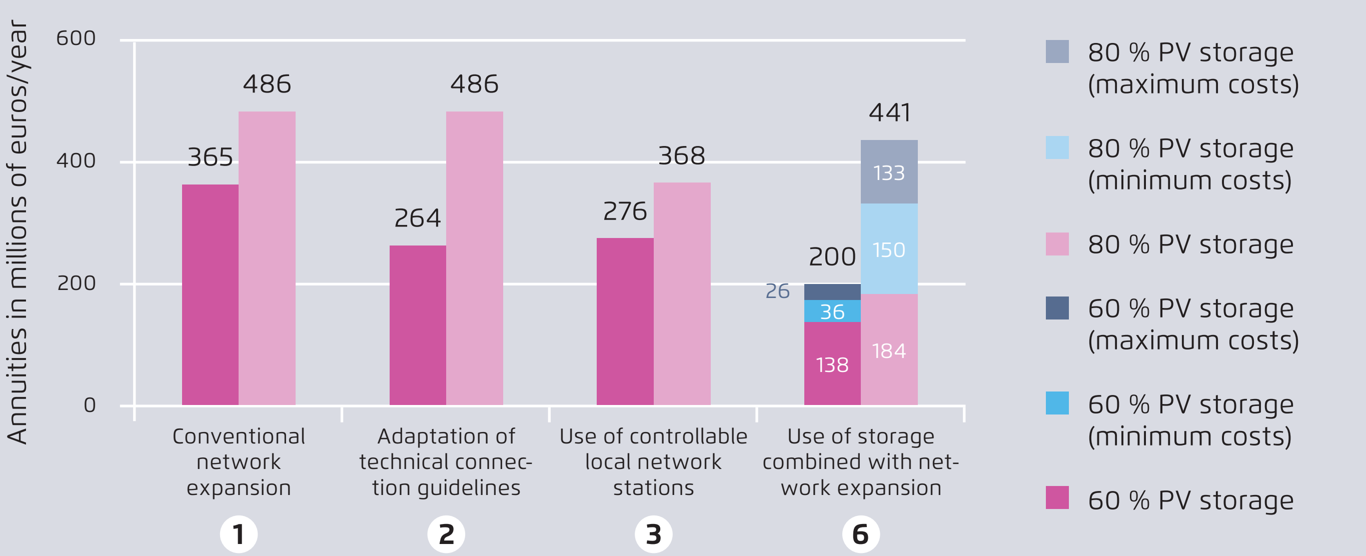
If storage technology expansion is determined by the electricity market and does not take place "in the service of the network," battery storage plants and other energy storage technologies could generally aggravate network load under certain conditions or cause network bottlenecks, and, in this way, ultimately increase the need for network expansion.

With a view to storage capacity for maximizing the self-consumption of PV energy, the appropriate dimensioning and parameterization of systems can allow storage technologies to be operated "in the service of the network" without the need for additional investment in communication infrastructure.

Findings from the sensitivity analysis of the distribution of predicted photovoltaic production at different voltage levels: Annuity costs in the low voltage network in 2033

Figure 1-5

Projections based on typical networks



Authors' graphic

1.5 Insights concerning the need for electricity storage capacities for ancillary services

Battery storage systems are particularly suitable for providing primary control power. As battery prices fall in the future, the provisioning of primary control power by battery storage systems can be macroeconomically reasonable.

Battery power plants are quicker at providing reserve power than conventional thermal and hydroelectric power plants. Furthermore, as investments costs fall in the future, they will be able to provide this in an economically efficient manner. In special situations in which fossilfuel power plants alone are used to provide reserve power, energy storage can replace "must-run" capacities and thereby contribute to a reduction in CO_2 emissions in the power system.

Energy storage technologies can offer ancillary services, and thus improve their economic efficiency.

There are further market opportunities for storage systems with a view to the provisioning of ancillary services as well as in control power markets. Energy storage technologies can contribute to the following:

→ Frequency stability (control power markets)
→ Voltage stability (reactive power provisioning)
→ Secured capacity
→ Resumption of supply (black start-up ability, only electrical storage technologies)
→ Redispatch

When energy storage technologies provide such dual benefits, their economic efficiency is improved.

However, over the mid- to long-term, additional possibilities for providing ancillary services, as flexible generation units of today and tomorrow, additional flexibility options and network operating equipment, are available for the transmission network operators.

Electricity storage technologies can substitute conventional power plants and can contribute to secured capacity.

Over the long term, electricity storage can replace thermal power plants when the share of renewable energy in the power system is high. Thus, with a renewable energy share of 90 percent/60 percent, thermal power plants can be substituted in the power generation system by additional storage which leads to a reduction in total system costs.

In addition, within the scope of their technical capabilities (e.g. storage capacity, availability), electricity storage can contribute to provision of secured capacity and thus replace further thermal power plants that would otherwise be necessary to provide sufficient secured capacity

1.6 Insights concerning markets for battery storage and power-to-gas outside of the power market

The use of battery storage in decentralized applications will develop independently from the power market and will establish itself over the long term both in German and internationally. Newly installed photovoltaic systems, existing photovoltaic systems for which subsidy eligibility is expiring, and electric vehicles are all decisive markets.

Alongside the established markets for uninterruptible power supply and off-grid battery systems, significant new applications are currently being developed. With a view to electric vehicles as well as the optimization of self-consumption, substantial markets are emerging. Key drivers of this development are the legal requirements for vehicle CO_2 emissions in Europe in combination with rising electricity costs for small consumers. At the same time, batteries are experiencing considerable cost and price reductions thanks to production in evergreater numbers.

Over the long term, electric vehicles and batteries for self-consumption are two particularly relevant areas. Germany currently has some 10,000 PV storage installed. This corresponds to a cumulative capacity of 30 to 40 MW (if we assume each system has a capacity of 3 to 4 kilowatts). While the installation of battery units for new PV systems is increasingly interesting for small electricity consumers, so too is the installation of battery units for existing systems: As soon as the subsidies that are provided under the German Renewable Energy Act (EEG) expire for a large number of PV systems in the 2020s and 30s, the market for battery systems will considerably expand. A similar dynamic development can be expected in the deployment of battery systems used in electric vehicles. Figure 1-6 shows the estimated battery capacity connected to the grid in Germany in the next decades. Our forecasts show that in 2050, the markets taken into consideration here will comprise approx. 40–170 gigawatts, and will thus play a considerable role in the German power system. In comparison to the other two markets, the market for balancing power will be small from a long-term perspective.

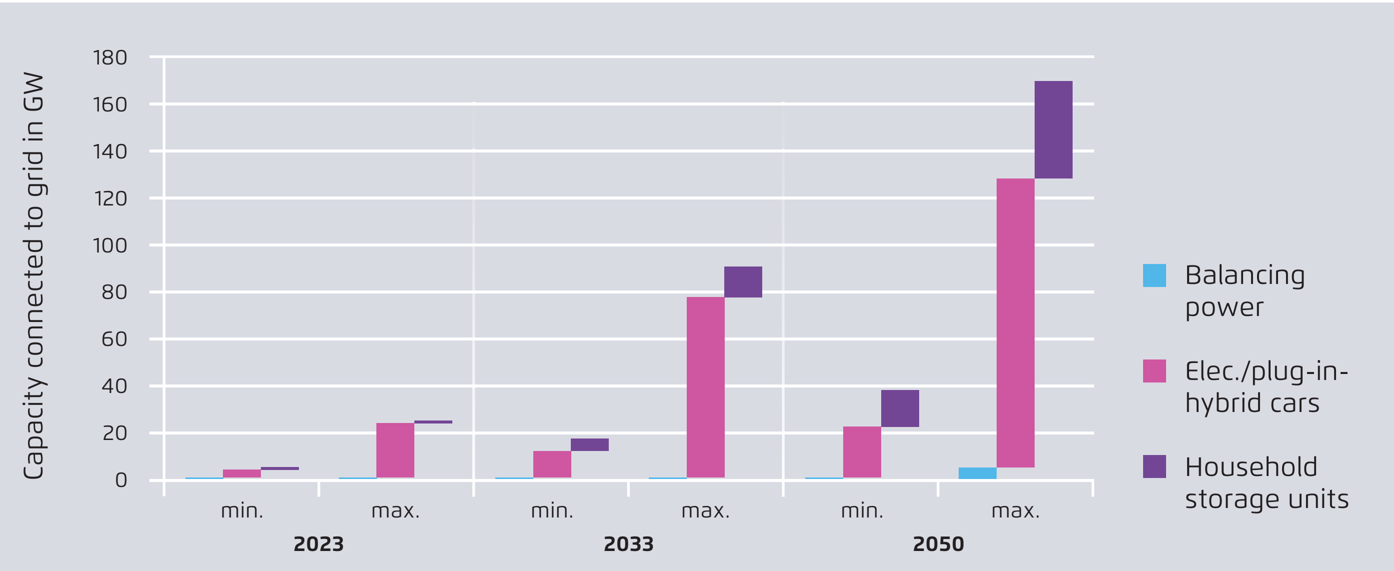
The segments of the transportation market that cannot be electrified and the chemicals industry represent the lead market for "power-to-X," in which power is transformed into power fuels. This is because (1) there are few alternatives for these sectors that are based on renewable energy, and (2) the revenues for stored energy in these markets are higher than in the electricity market.

Power-to-X is a versatile energy storage technology and much more than a method for storing electricity. This technology will make it possible to decarbonise the transportation and chemical sectors. According to our projections, the first markets for power fuels and electricity-based feedstock will arise in these sectors. Power fuels will be in demand in areas that require fuels with high energy density, such as the air and maritime transport sectors, as well as in some heavy duty applications. Meanwhile, in the chemicals industry, renewable electricity- and CO_2-based input materials will be in demand.

Both sectors are dependent to a very high degree on oil and natural gas, and the alternatives are restricted by technical limitations. Accordingly, as fossil hydrocarbons become increasingly scarce and/or decarbonisation requirements are legislated, a market for power-to-X will arise in these sectors.

The terminology surrounding power-to-gas is expanded to include three additional terms – which, taken together, are subsumed under the term "power-to-X". Power fuels are fuels that derive their energy from electricity, such as hydrogen, methane (wind gas), methanol, Fischer-Tropsch diesel, and Fischer-Tropsch kerosene. "Power-to-chemi-

Bandwidth of installed battery storage capacity (market for battery storage units) — Figure 1-6



Authors' graphic

cals" or "power-to-products" are processes used to create input materials in the chemicals industry, such as hydrogen, methane, or methanol, which can be produced with water electrolysis and power-based synthesis processes.

Together with the power sector, there are thus three markets, which are shown in Figure 1-7 as forecast ranges.

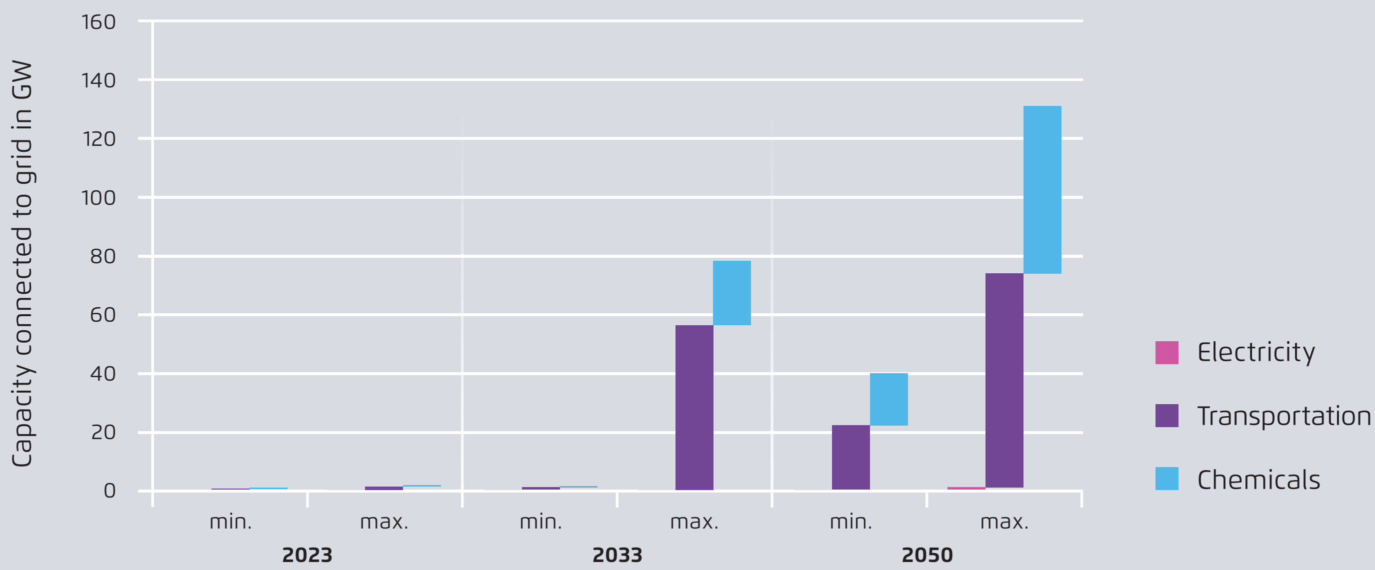
- → Markets for power-to-gas as a method of storing electricity
- → Markets for power fuels (power-to-gas, power-to-liquid)
- → Markets for chemical input materials (power-to-chemicals, power-to-products)

For all three markets there is a wide range of possible installed capacity, as the development of these markets will depend on many factors, such as resource availability, raw material prices, and regulatory conditions. Accordingly, it is difficult at present to provide precise forecasts (see Figure 1-7).

With early market development and falling investment costs for power-to-X facilities, it could be cost-effective to produce power fuels as early as the mid-2020s, provided electricity from renewables can be purchased by power fuel production facilities for over 4,000 to 5,000 hours annually at a price of 3 to 5 euro cents per kWh. Up to 2050, the conditions for power fuel production will continue to improve: production facilities will be in a position to pay up to 6 to 7 euro cents per kWh. In addition to the direct cost of power fuels, from a macroeconomic perspective their impact on the overall climate balance is important. In this connection, the sources of electricity used for electricity-based transportation will be decisive.

The markets for energy storage technologies outside of the power sector will lead to an increase in electricity demand as well as to greater flexibility in the power generation system. These storage systems will be in a position to offer additional services (beyond their actual value to the grid) at low marginal costs.

Bandwidth of installed capacity for power-to-gas, -liquids, and -chemicals — Figure 1-7



Authors' graphic

According to our forecasts, battery storage systems and power-to-X will develop initially outside of the power sector, first and foremost in the transportation sector. These markets could contribute to accelerated development trends, leading to cheaper energy storage technologies for demand side management or generation balancing, as well as greater technological maturity and availability (which could also benefit the power sector).

Furthermore, it will make sense to leverage the potential offered by these energy storage technologies to provide system services to the power sector. These technologies offer additional potential for flexibility. Batteries installed in household PV systems, in industrial systems for self-consumption, in systems to manage peak loads, and in electric vehicles can all serve a dual function and provide a valuable service to the power market at low marginal costs.

The situation is similar with a view to power-to-X. It will not be possible to use batteries to electrify large segments of the transportation sector (including air, sea, freight, and long-distance transport). Accordingly, the transportation sector will have to rely on power fuels, as the alternative (i.e. biofuels) suffers from limited public acceptance as well as limitations with a view to sustainability. As a result, electricity demand will be considerably higher, and the nature of the demand will change, providing additional flexibility for the power sector.

In this study we did not examine the market developments in the power sector that have been described in the foregoing, nor did we assess the consequences on the need for power storage capacities in the power system.

1.7 Selected recommendations for action and prospects for the future

With a renewable energy share of over 90 percent in Germany and over 60 percent in Europe, additional energy storage capacities will be required for decarbonisation in all markets and sectors. In order to have the required storage technology available at this point in time, a technology and market development process as well as a commercialization process will be necessary in the preceding years to allow the production costs for storage technologies to fall. Furthermore, in order to realize the full benefits of energy storage, it will be necessary to conduct research and development activities concerned with their integration and standardization.

Aside from the electricity power market, there are additional markets that can drive the development of energy storage technologies. Despite the very low demand for energy storage, a technological and a market development of energy storage are advisable, as energy storage technologies will be needed over the mid-term in other sectors for decarbonisation, for example the transportation sector. In addition to the testing and research of new storage technologies, research will be needed concerning their system integration. In the future, a large number of decentralized units will be able to fulfil roles in the power system previously fulfilled by centralized units. This process of transforming the power system needs to be accompanied by researchers as well as authorities involved in setting standards. In addition, the further development of storage technologies to higher flexibility is desirable. For the financing of the required programmes, revenues from CO_2 certificate trading could continue to be used in the future.

As with all flexibility options, it is advisable to ensure that the utilisation of energy storage systems does not lead to an increase of CO_2 emissions through the increased generation of electricity by fossil fuel-based power plants. This is an elementary concern both with regard to electric vehicles and with regard to power fuels, which can lead to CO_2 reductions in the transportation sector.

The use of battery storage and power-to-X should take place in coordination with the availability of wind and sun in order to integrate the highest possible share of renewable energy and to generate climate-neutral products. Otherwise, the use of these energy storage options in the transportation sector can lead to higher CO_2 emissions than the use of conventional fossil fuel-based transportation technologies. The same applies to the use of heat storage units via power-to-heat, flexible CHP plants as well as electricity storage technologies.

The development and implementation of flexibility options will not take place solely according to economic criteria. A broad spectrum of flexibility options can help to compensate the deficit of some cost-effective options due to a lack of social acceptance.

As flexibility options are developed and assessed in the future, beside economic criteria is also important to take socioeconomic and societal acceptance into account. While some key options are inexpensive, the implementation will be difficult due to social reasons. As a substitute for these non-viable options, other options can provide flexibility, such as energy storage technologies. While these options are more expensive, the risks associated with their implementation are lower.

1.8 Discussion of the interrelationships between assumptions and findings

The delayed (or accelerated) **expansion of network interconnections to neighbouring countries of Germany** may lead to an increased (or decreased) need for energy storage in Germany. In comparison to the network development plans of the European transmission network operators, this study assumes an approximate ten-year delay in expansion efforts. This implies that transmission capacities between market areas continue to rise, even if this increase is slower than planned by the transmission network operators. If it is not even possible to achieve the (delayed) network expansion assumed in our study due to a lack of social acceptance, a larger need for energy storages at the level of the transmission network than predicted in this study may result.

In the analysis we undertook at the level of the transmission network, the European power generation system is modelled on the basis of various market areas which are connected to each other by limited interconnections. Though, we assume that the **European market areas will retain their current structure**. Accordingly, network bottlenecks within Germany that could result from the delayed network expansion have not been taken into account. If these potential bottlenecks were taken into account, however, there could be a higher need for energy storages. In general, battery storage units and other forms of energy storages can be set up quickly in the case of network bottlenecks and potentially moved to other locations at a later date once the bottlenecks have been eliminated.

An even more rapid rise in the **renewable energy share in Europe** could lead to an accelerated need for energy storage in Germany. This study assumes that the European renewable energy share will remain low in comparison to Germany in the future. Thus cost-effective flexibility options in the European power generation system can provide additional flexibility. If there is more uniform growth in the share of renewables throughout all of Europe, the need for flexibility would be higher, and this would lead to a greater need for flexibility and energy storage at the level of the transmission network than predicted in this study.

In order to determine the need for energy storage, this study draws on scenarios developed by the European transmission network operators when making assumptions about the power plant fleet. These scenarios assume that additional natural gas power plants will be constructed in order to ensure the balance of generation and demand even in extreme situations. The advantages of energy storage may be reduced as scenarios are used as a basis for analysis that assume the existence of a large and **flexible fleet of power plants** designed to ensure sufficient secured capacity. While possible savings in investment costs for power plants that are not need in the scenarios with additional energy storage are considered, no endogenous optimization model of power generation system expansion, particularly with a view to the most cost-efficient mix of power plants and energy storage, was applied. If such an optimized expansion of both natural gas power plants and energy storage was analysed, there could be a larger need for energy storage at the level of the transmission network, particularly if electricity storage was necessary for the provisioning of secured capacity.

In this study, we drew on various existing studies to make assumptions concerning the expansion of flexibility options (e.g. demand side management, flexible CHP), considering both a probable development path as well as one that is ten years behind schedule. The slower (or faster) **expansion of alternative flexibility options** could lead to a higher (or lower) need for electricity storage in Germany. If the expansion of flexibility options is not achieved in the scope assumed due to technical challenges or a lack of sufficient regulatory incentives, the need for electricity storage at the level of the transmission network could be higher than predicted. This applies in particular to short-term storage capacities, as this storage technology is similar to demand side management in its flexibility features (in contrast to long-term storage capacities).

A high penetration of **cross-sectoral energy storage technologies**, such as electric vehicles and power-to-X, or battery storage units in uninterruptible power supply systems or for the optimization of self-consumption, could lead to a lower need for electricity storage in Germany. The modelling performed in this study does not consider a significant market penetration of these technologies; our market analysis was undertaken separate from the modelling performed at the level of the transmission networks. If the above technological applications achieve significant market penetration, they could provide double benefits, by making a contribution to demand side management in the power sector and/or function in the service of distribution networks. Through their dual usage, all of these energy storage systems can offer the power system additional flexibility at low marginal costs, as they are primarily paid for through another sector.

The analysis undertaken in this study with a view to markets for battery storage units and power-to-X technologies clearly indicate that additional research should be undertaken to examine the impacts to the power sector that will result from increasing interaction between the transportation, heating, and chemicals sectors, as well as to analyse the contribution this could make to achieving the objectives of the energy transition.

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