FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE
ENERGY SYSTEM ANALYSIS

META STUDY ON FUTURE CROSS-SECTORAL DECARBONIZATION TARGET SYSTEMS IN COMPARISON TO CURRENT STATUS OF TECHNOLOGIES

Discussion Paper

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Content

Abstract

To reach the German targets to reduce CO_2-emissions by 80 to 95% in relation to 1990 by 2050 an increase of installed capacity of renewable energy technologies, storages as well as technologies for power-to-X applications is well accepted in research in the field of energy system analysis. However current studies all result in different system compositions, which are due to many reasons. This meta-analysis assesses the bandwidth of technologies in the year 2050, needed for the above mentioned CO_2-emission reduction, and compares the values to an extrapolation of current trend of the technologies. It is the goal to identify technology aspects, which need to be adapted to reach the goals as well as show trends in technologies, which are in line with the CO_2-emission reduction targets.

The results show, that higher emission reduction targets require an accelerated effort to decrease the primary energy demand. On technology side, wind energy, photovoltaics and biomass are mature technologies and show a tendency to reach the installed capacities to meet the emission reduction targets of 80%. Biomass energy and hydropower may not be expanded to a large extent, geothermal usage will either stay in a niche market or needs strong development. A strong increase of the heating technologies heat pumps and solar thermal until the year 2050 is unavoidable. Storages will be massively exploited, especially batteries in vehicles, stationary batteries and power-to-X storages, whereas pumped hydro storages exploitation is limited, due to available land and social acceptance.

1 Introduction

The social and political acceptance of climate change and the entry in the phase of energy transition in Germany led to increasing research in the field of energy system analysis. The demand for system analysis to find solutions for the sustainable energy future rose, also due to the German targets to reduce CO_2-emissions by 80 to 95% in relation to 1990 by 2050 ((Bundesregierung 2010) and (BMUB 2015)).

Several energy system models were developed to find answers if a decarbonized system can be realized and under which conditions. A study by the Federal Environmental Agency found in 2013 that the reduction targets can be reached (Umweltbundesamt 2013). But there is a wide range of possible solutions – in terms of technology mix, infrastructure and the change of behavior and attitude – available to fulfill the emission reduction targets.

The scenarios of future energy systems result in different system compositions. The output is highly dependent on a multitude of factors, such as the used methodology, the model or simulation framework, the granularity of the model, the considered technologies, the input data, future prognosis of technology development path or framework conditions such as costs and prices, or political incentives and in addition on the scenario definition itself. However, the bandwidth of technologies in the different studies can serve as a benchmark to identify where the energy transition process needs to be directed to, for each of the technologies that are identified as system relevant. The results of the meta-analysis on specific energy system topics such as flexibility or transportation are provided by the Forschungsradar Energiewende[1]. They serve as an overview of the different studies provided and a comparison of their inputs and outcome. However, a thorough comparison of the required capacities for each of the energy system relevant technologies in the studies could not be found in literature.

The aim of this meta-study is therefore to identify the need for all energy system relevant technologies by analyzing previous studies which consider all sectors in Germany and different CO_2-emission reduction targets. Therefore a bandwidth of needed capacities of each of the technologies in the year 2050 to be in line with the transition goals is identified from existing studies. In addition, the historical development of the technologies is investigated. If governmental plans for future development exist, those are also included in the comparison. On this basis, it can be concluded which technologies are already on the right path of target achievement and which technologies are still at an early stage of the diffusion process however needed for a sustainable energy future.

In a wider context, this study helps to identify the necessary installed capacity of single technologies to be able to reach the goals of the energy transition in Germany. Furthermore, it can, therefore, serve as a reference for diffusion models of single technologies to identify the need for political regulation.

2 Analyzed Studies

Eight recent important studies, considering all sectors, on the development of the German energy system were analyzed for the comparison with the current technology development (see Table 1). The studies are mainly conducted by research institutions for projects financed by the government. The focus of the studies is the analysis of the future composition of technologies needed in the German energy system by 2050. All of them compare the system configuration based on various greenhouse gas emission reduction goals.

[1] http://www.forschungsradar.de/metaanalysen.html

Table 1: Analyzed studies on the future German energy system

Institutions	Year	Title	Source
Fraunhofer ISE	2017	Study on sector coupling, results of Fraunhofer ISE REMod model are in this study by Acatech ("»Sektorkopplung« – Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems")	(Ausfelder et al. 2017)
Fraunhofer ISI, Consentec, ifeu	2017	Climate change scenarios for the German Bundesregierung	(BMWi 2017a)
Öko-Institut, Fraunhofer ISI	2015	Climate protection scenario 2050 („Klimaschutzszenario 2050")	(Öko-Institut, Fraunhofer ISI 2015)
Fraunhofer ISE	2015	How much does the energy transition cost? Pathways to the transformation of the German energy system („Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems")	(Henning, Palzer 2015)
Fraunhofer IWES, ifeu	2015	Interaction of RE electricity, heat and traffic („Interaktion EE-Strom, Wärme und Verkehr")	(Gerhardt et al. 2015)
BVEE	2014	GROKO – Scenarios for the German energy supply system based on the EEG bill ("GROKO – II. Szenarien der deutschen Energieversorgung auf der Basis des EEG-Gesetzentwurfs")	(Nitsch 2014)
Prognos, ewi, GWS	2014	Development of the energy markets – energy reference prognosis („Entwicklung der Energiemärkte – Energiereferenzprognose")	(Schlesinger et al. 2014)
Umweltbundesamt	2014	Greenhouse gas emission free Germany in 2050 („Treibhausgasneutrales Deutschland im Jahr 2050")	(Umweltbundesamt 2013)

Most studies optimize the energy system by using energy system models to evaluate several scenarios with varying CO_2 emission reduction targets. In this paper, the scenarios are clustered in three groups: CO_2 emission reduction targets below 80%; between 80 and up to 90% and 90% and above. The amount of CO_2 emission reduction refers to the base year 1990. Only energy-related emissions are taken into account. Emissions can also be caused by aviation, shipping, waste, land-use change, agriculture, solvents and industrial processes which are not considered in the analyzed studies. Figure 1 shows the emission reduction for each scenario of all analyzed studies.

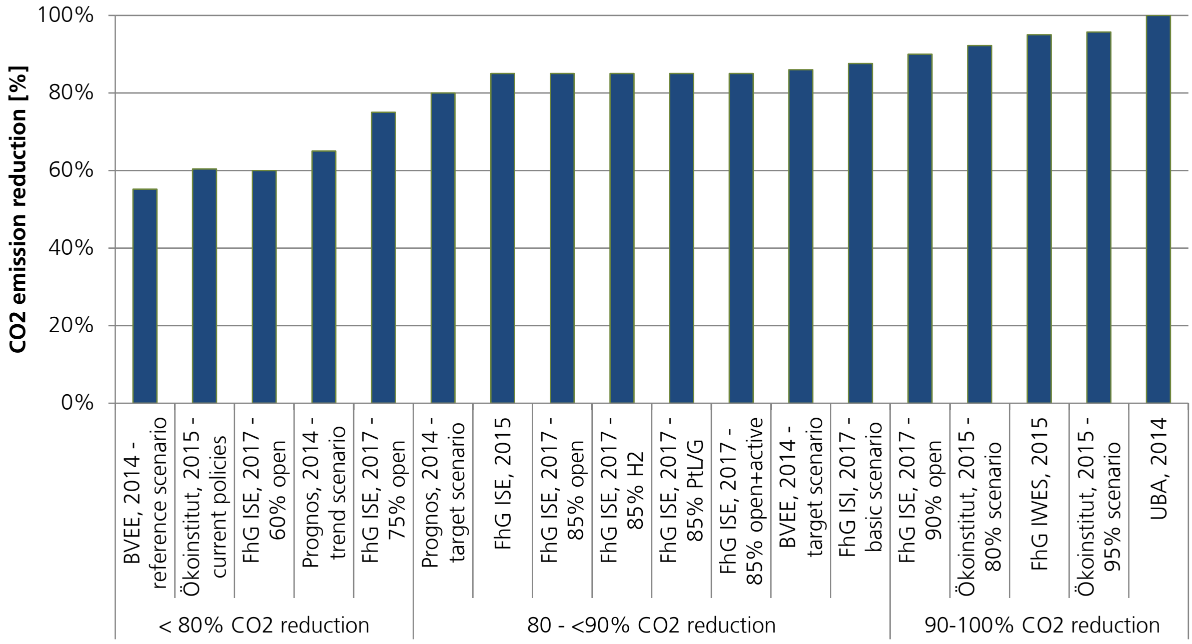


Figure 1: CO_2 emission reduction assumptions for the energy-related CO_2 emissions in the scenarios of the analyzed studies

The lowest analyzed emission reduction among the studies is 55% in the reference scenario of the BVEE study. The section with less than 80% emission reductions consists of five scenarios in four different studies. The largest analyzed group targets between 80 and 90% emissions reductions, where eight scenarios are found in all studies. Five scenarios are analyzed with emission reduction targets above 90%. Only the scenario UBA 2014 (Treibhausgasneutrales Deutschland im Jahr 2050) includes an approach to completely decarbonize the energy system.

Figure 2 shows the composition of renewable energy (RE) technologies according to the studies. In all scenarios, photovoltaics (PV) and onshore wind play a major role in terms of installed capacities in the power sector. Except for four scenarios, PV has the largest installed capacity. Offshore wind energy is also expected to have a large market share. In terms of generated electricity, the increase in market share will be even higher due to higher full load hours compared to PV. In the high emission reduction target scenarios, up to 60 GW of installed capacity of offshore wind turbines is found to be a potential solution to reach the emission targets. Hydropower, biomass and geothermal energy will play a smaller role with a maximum of 30 GW of installed capacity per technology throughout all studies. This fact might also be a result of the political discussions concerning the role of biomass, as a competitor to food production and therefore a rather conservative consideration of the potential, within the models. The role of geothermal energy is still uncertain and therefore it is not fully considered in each of the investigated studies, which needs to be considered when analyzing the meta-study results.

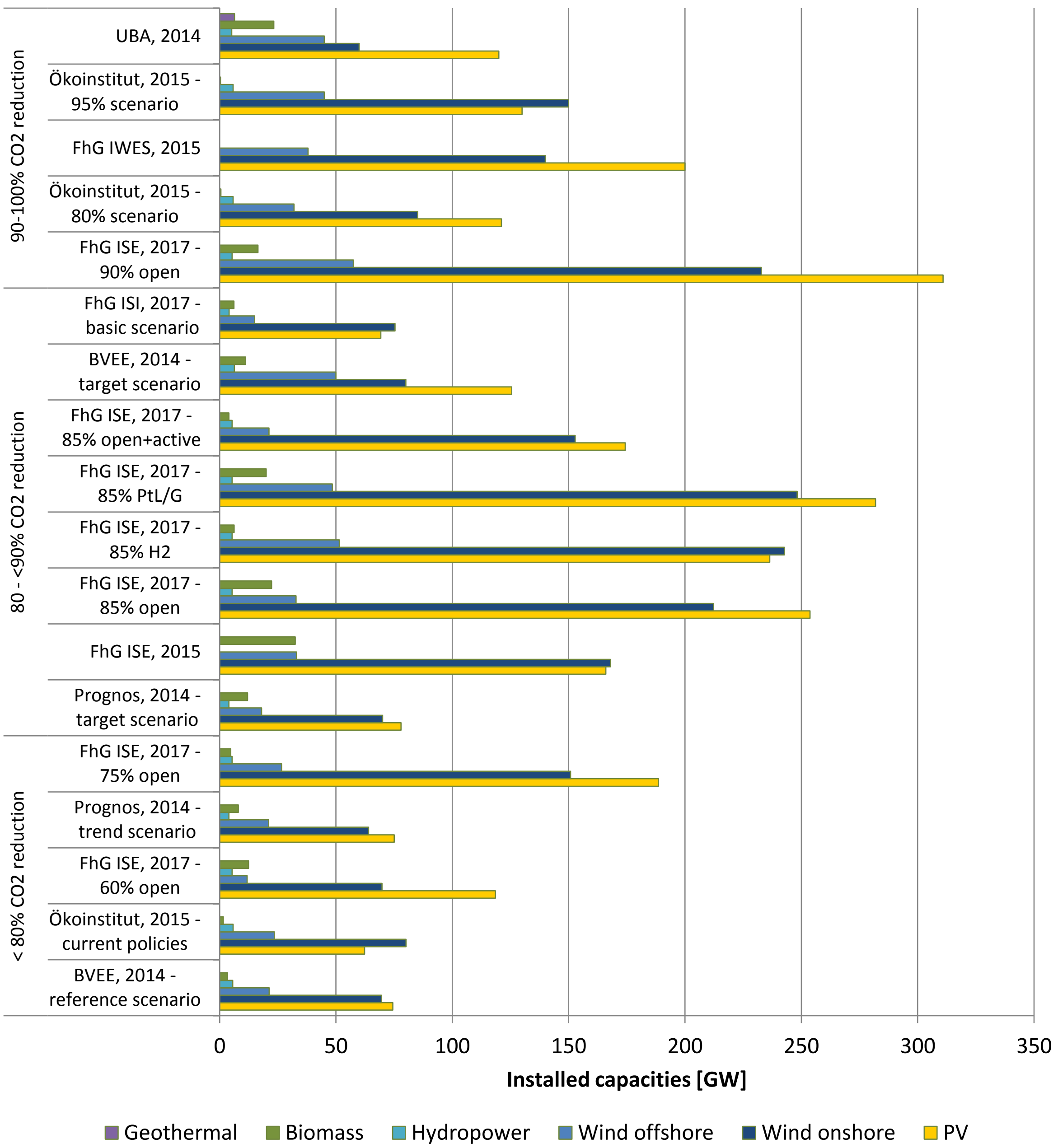


Figure 2: Installed capacities of RE technologies in the scenarios

Figure 3 shows the study results for sector coupling or power-to-X technologies. These include power to heat, power to liquid, power to gas and electric vehicles. In all studies, sector coupling plays a major role compared to today's situation. The composition of technologies however and their contribution to the energy system differ to a large extent. Based on the meta-analysis there is no clear observable correlation between emission targets and use of power-to-X technologies, except that with increasing emission target scenarios the sum of all technologies increases. Electromobility is considered with about 40 to 200 TWh per year in almost all scenarios. The results have to be viewed with caution, as in many cases the use of the technologies is not optimized but goes into the model as an assumption.

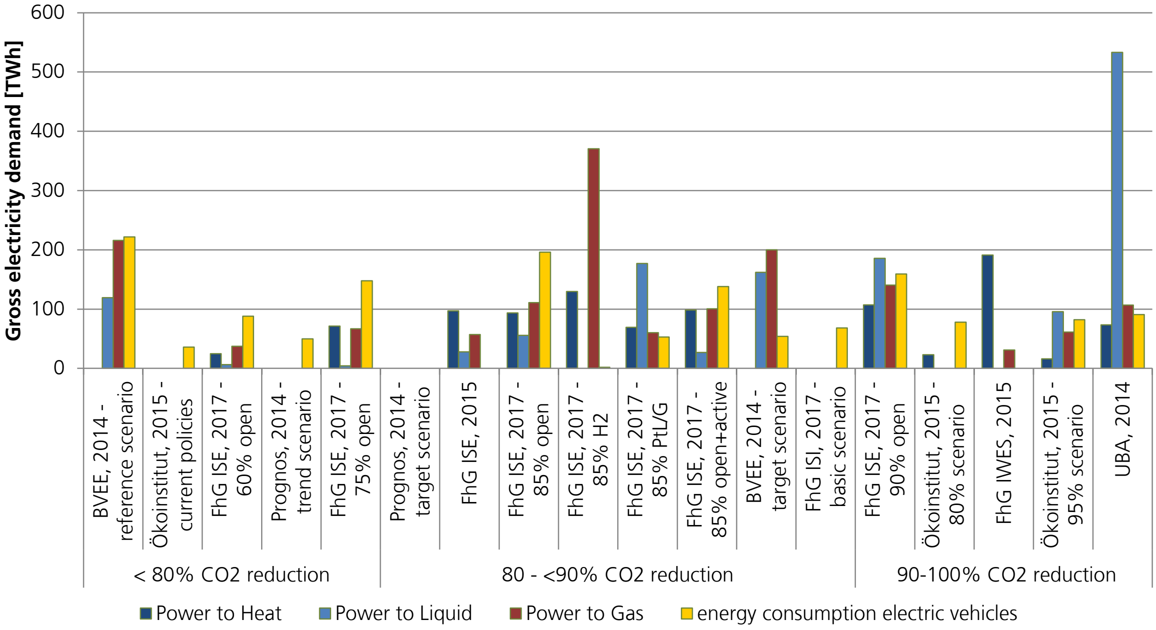


Figure 3: Power-to-X technologies in the analyzed scenarios (Remark: Not all analyzed studies are considering all Power-to-X technologies)

3 Historical and future primary energy demand

Figure 4 shows the historical development of the yearly primary energy demand in Germany between 1990 and 2016. The energy demand in these years has decreased from about 15 EJ to 13.5 EJ (BMWi 2017b). If a linear trend line is inserted, the decrease is about 8% over the whole 26 years. On the right side of the graph, the results of the analyzed studies are shown in the grey area. The primary energy demand calculated in the three emission reduction target groups are shown separately. The studies show that to achieve an emission reduction of up to 80%, the primary energy demand needs to be decreased to about 8.8 to 10.3 EJ. This corresponds to a reduction of 24 to 34% compared to today's value. An emission reduction between 80 and 90% requires primary energy reductions by 37 to 51%, emission reductions above 90% result in primary energy reductions by 41 to 56%. The primary energy demand can be reduced by reinforced energy efficiency measures and by the implementation of generation technologies with a low primary energy factor, such as renewable energy technologies or combined-heat and power production.

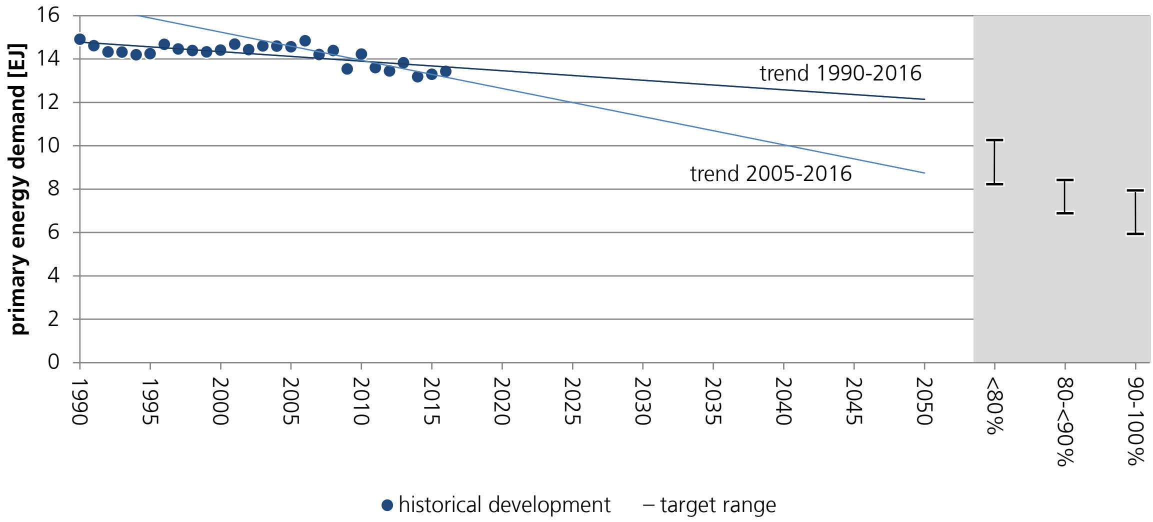


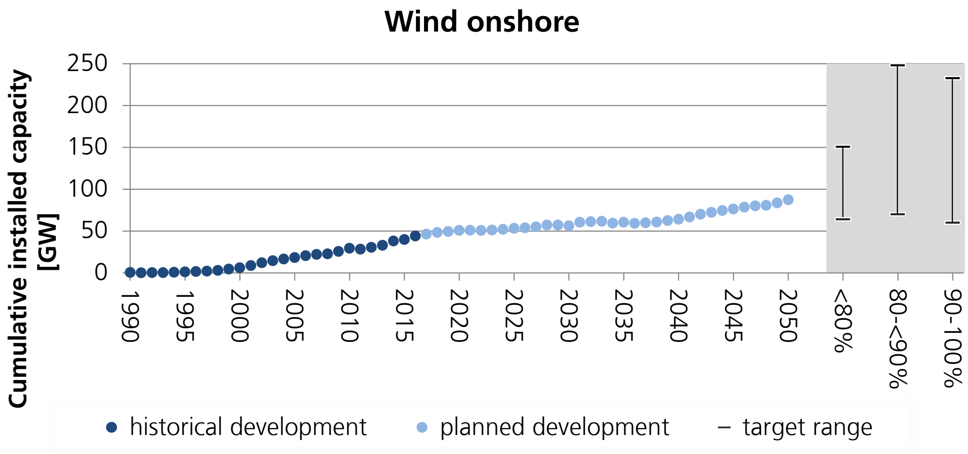
Figure 4: Primary energy demand in Germany: historical development (based on data from (BMWi 2017b)) and targets according to the emission reduction targets of the analyzed studies.

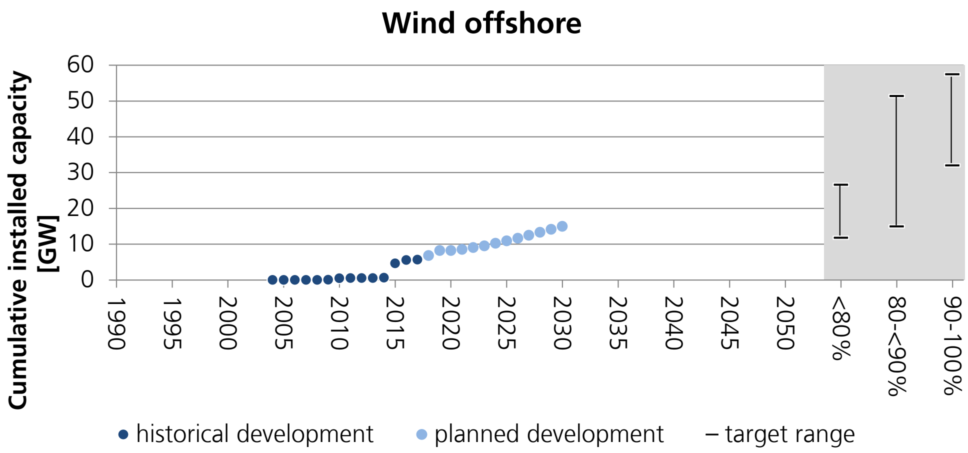
The long-term trend (1990 to 2016) leads to a minor reduction of the energy demand in 2050. If a trend line for the values from 2005 on is analyzed (the year in which the Kyoto Protocol came into effect), the projected linear decrease will lead to a reduction down to about 9 EJ in 2050, neglecting effects such as a declining cost-benefit ratio to achieve primary energy reductions. If the trend continues, this may, in combination with other changes in the energy sector, allow emission reductions to about 80% in comparison to 1990. To reach more ambitious emission reduction targets in 2050, the reduction needs to be accelerated.

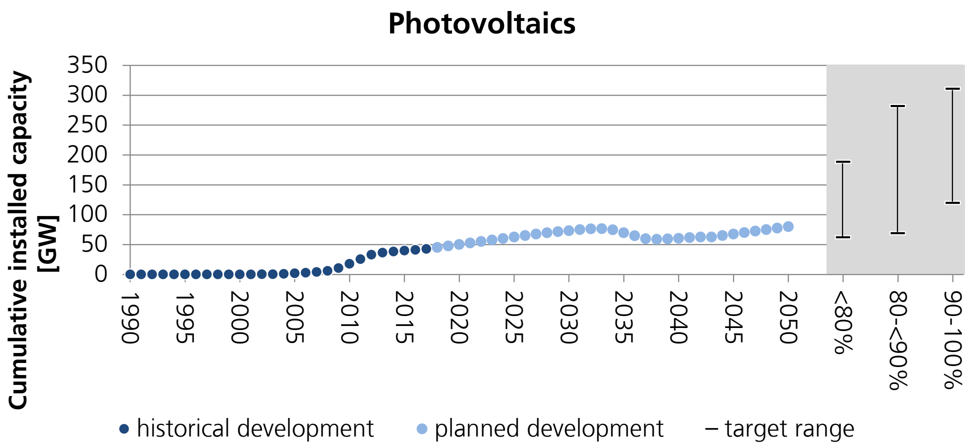
4 Development needs for energy technologies

Electricity generation technologies

The following figures show the historical development, future plans according to the EEG 2017, and target ranges of each technology according to emission reduction targets related to the analyzed scenarios for RE technologies. The target values are shown to the right of each figure for all three emission reduction target groups (below 80%, 80-<90% and 90 to 100%). The range is usually wide, even within the groups. This is due to the varying emission reduction targets within the groups (e.g. 80 or 85%), but also due to different assumptions and inputs in the studies and resulting technology compositions. The results, therefore, have to be seen in comparison to each technology: If one technology reaches the lower bound of the required installed capacity only, it may be sufficient for meeting the emission targets if other technologies are installed in larger amounts, meeting the upper bound of the requirements. Figure 5 shows the data for wind energy, photovoltaics and biomass electricity.


Wind onshore
Cumulative installed capacity [GW]
250
200
150
100
50
0
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
<80%
80-<90%
90-100%
historical development
planned development
target range


Wind offshore
Cumulative installed capacity [GW]
60
50
40
30
20
10
0
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
<80%
80-<90%
90-100%
historical development
planned development
target range


Photovoltaics
Cumulative installed capacity [GW]
350
300
250
200
150
100
50
0
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
<80%
80-<90%
90-100%
historical development
planned development
target range

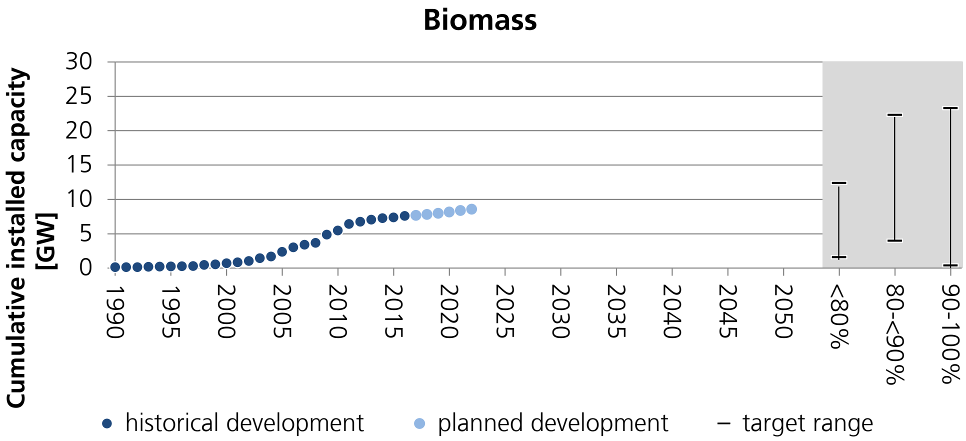


Figure 5: Historical and planned development compared to the targets of the analyzed studies. Historical data based on (BMWi 2017b), planned development as stated in (EEG 2017, revised 12/22/2016, § 4). Dismantling is assumed to be after 20 years for wind energy turbines and after 25 years for PV systems.

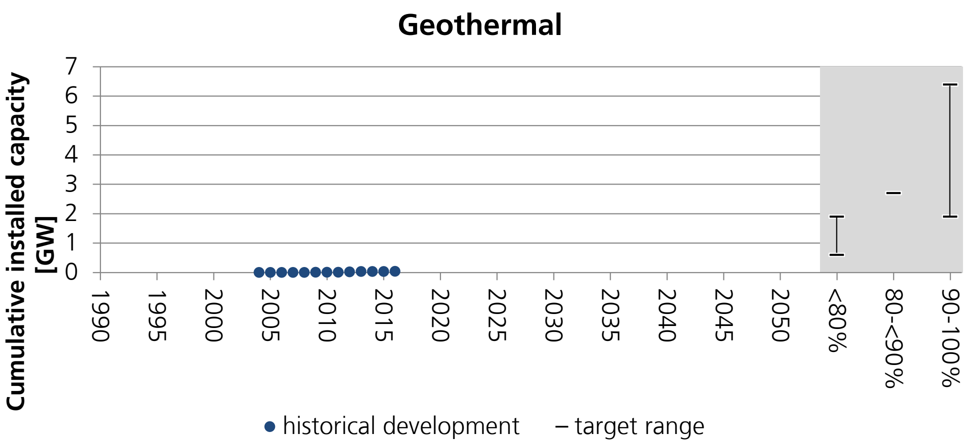
Onshore wind energy has seen a steady increase in the installed capacity up to today's 50 GW. The planned increase of 2.8 to 2.9 GW per year, with an assumed dismantling of the plants after 20 years of lifetime, will lead to an amount of about 87 GW of installed onshore wind power in 2050. The range of onshore wind energy projected to be necessary for an emission reduction in all analyzed categories may, therefore, be reached. However, to reach the emission reduction targets, more wind energy installations may be needed. Depending on the study, an amount of up to 250 GW of onshore wind energy will be necessary.

Offshore wind energy is a relatively new technology, which started with the first wind parks in 2009. An increase of today's 4.1 GW to 6.5 GW in 2020 and 15 GW in 2030 is planned (EEG 2017, revised 12/22/2016, § 4). If a linear increase is expected, the amount of the emission reduction targets below 80% will be fulfilled before 2050. If higher emission reduction targets are to be reached in 2050, the amount might not be enough. The analyzed studies project a necessary installed capacity of up to 58 GW of offshore wind power.

The installed capacity of photovoltaics shows a steep increase between 2009 and 2013. Today about 43 GW of PV capacity is installed in Germany. For the next years, an annual installation of 2.5 GW is planned (EEG 2017, revised 12/22/2016, § 4). If this trend is to be continued and considering the dismantling of 25-year-old plants, about 80 GW of PV will be installed in 2050. This amount is within the range of necessary capacity for up to 90% emission reductions. However, it is rather at the lower end of the installed capacity needed. For higher emission target values, the currently planned installed capacity of PV systems is not sufficient.

The installed capacity of electricity generation by biomass has increased strongly between 2005 and today. The current level is 7.4 GW (BMWi 2017b). For the next years, an increase of 150 (up to 2019) and 200 MW per year (from 2020) is planned. The amount of biomass plants necessary to reach the emission reduction targets varies strongly among the studies. This is due to the different assumptions made for the technology. The Öko-Institut, for example, calculates only the sustainably growing amount of biomass to be able to be used in the future, resulting in a decreasing amount of installed biomass plants (Öko-Institut, Fraunhofer ISI 2015, p. 259). A high number of installed capacity is calculated by Umweltbundesamt (2013). If the installation of biogas plants is continued with 200 MW per year, 14 GW will be reached by 2050. This is higher than the upper bound necessary for reaching 80% emissions reduction and is within the range of necessary installed capacity for higher emission reduction targets.

Figure 6 shows the historical development of geothermal energy for power generation and hydropower in comparison with the emission reduction targets. 330 MW of installed geothermal capacity were in operation in 2015. The technology is still young, and future studies either assume an installed capacity of up to 6.5 GW in the case of 100% emission reduction (Umweltbundesamt 2013) or consider the potential to increase their use as limited (e.g. Henning, Palzer (2015)). If geothermal energy for power generation is to reach the 2050 targets according to the studies, either the number of projects or the size of the power plants need to be increased considerably.



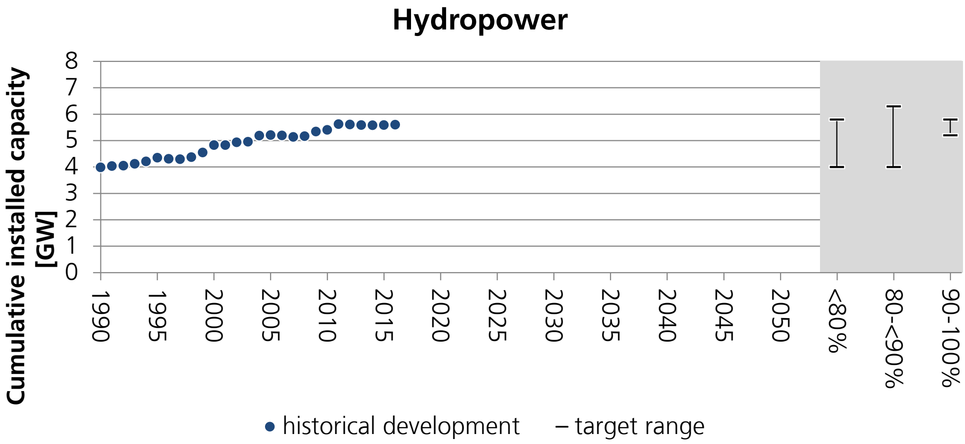


Figure 6: Historical development of geothermal and hydropower compared to the targets of the analyzed studies. Historical data from (BMWi 2017b).

The installed capacity of hydropower was 5.6 GW in 2015 (BMWi 2017b). As the potential in Germany is almost fully exploited, most studies assume that no further expansion will take place in the future or if, only very limited. Prognos et al. (Prognos AG, EWI, GWS 2014) assume an installed capacity below today's value which is probably due to a different method of splitting run-of-river power stations and pumped storage power plants. According to the analyzed studies, only a limited or even no further exploitation of the hydropower potential will be needed in order to achieve the 2050 emission reduction targets.

Heat generation technologies

For thermal energy generation, no development paths have been defined by the government yet. Also, the results of the studies in the heat sector vary much more than in the electricity production sector.

Figure 7 shows the historical development of solar thermal energy and biomass energy compared to the emission reduction targets for both technologies in terms of generated heat. Solar thermal energy has been increasing in the last decades to an amount of 28 PJ of heat produced in 2015 (BMWi 2017b). The analyzed studies show that at least 76 PJ of heat production is expected in 2050, which in combination with the other technologies will lead to only 55% emission reduction (BEE 2014). If emissions are to be reduced, the solar thermal energy potential needs to be further exploited. 80 to 90% emission reductions, for example, will need about 250 to 500 PJ of solar thermal energy. To reach this amount in 2050 an exponential expansion of solar thermal energy will be needed. For 90 to 100% emission reduction, the studies propose 340 to 470 PJ solar thermal heat generation per year.

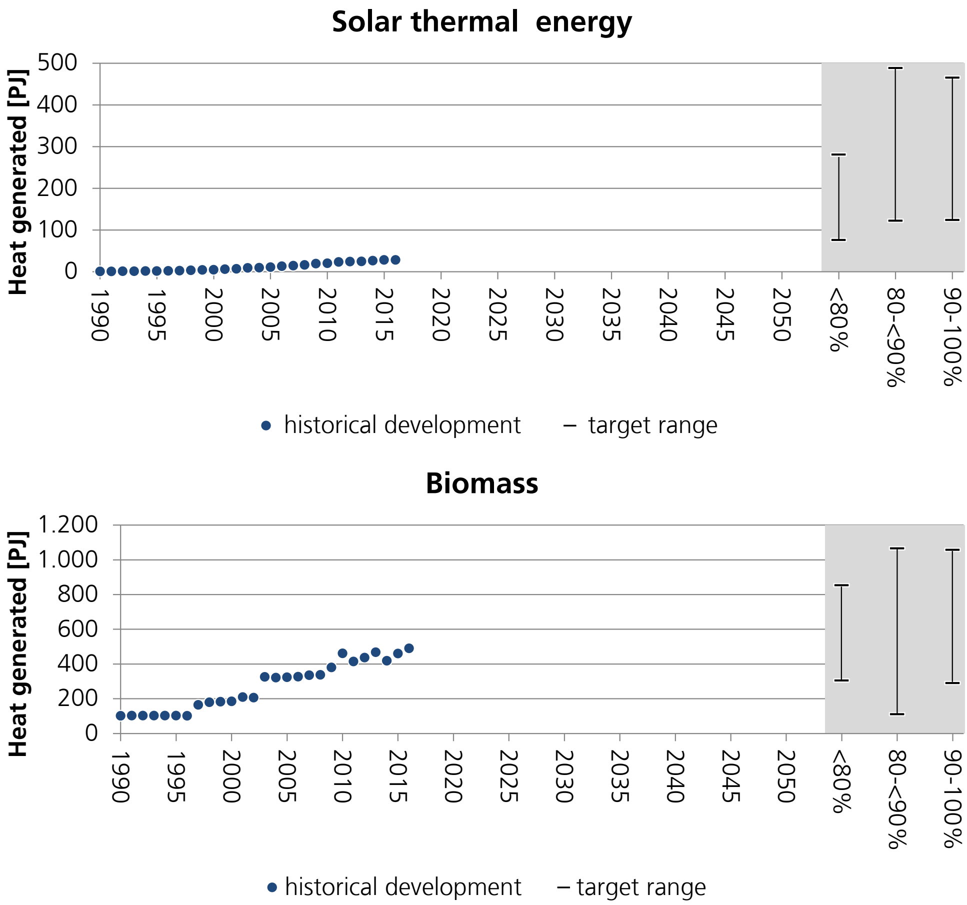


Figure 7: Historical development of solar thermal and biomass-based heat production compared to the targets of the analyzed studies. Historical data from (BMWi 2017b)

Heat from biomass has been extended stepwise to today's 460 PJ heat production per year (BMWi 2017b). The amount varied strongly within the last years. As explained before, some studies propose no further extension of biomass due to the limits of production, while others expect a stronger growth of the technology.

Figure 8 shows the historical development and future technology needs for geothermal energy and heat pumps in terms of generated heat. Also for these two technologies, no development plans have been published. The generation of heat from geothermal energy has been growing only slowly in the past and was at 3.5 PJ in 2015. As explained in the electricity section, some studies do not consider geothermal energy at all while other studies propose a strong extension of the technology. The results of the studies which take geothermal energy into account vary from 10 to almost 130 PJ.

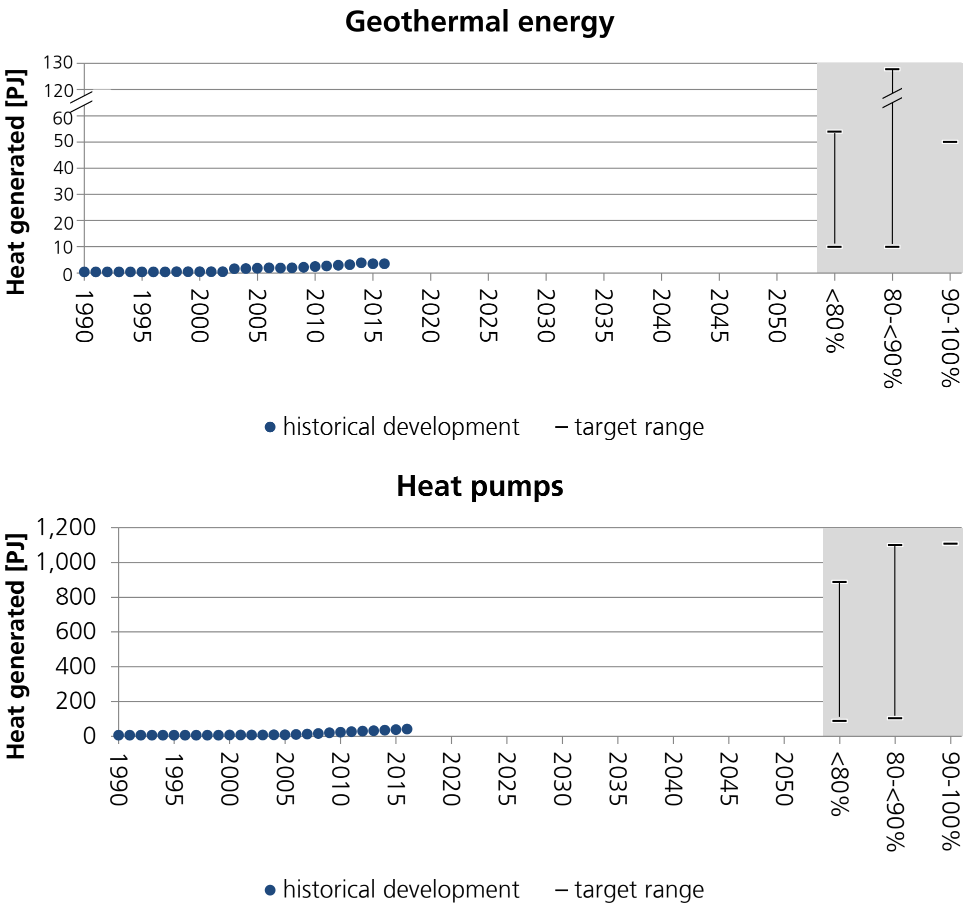
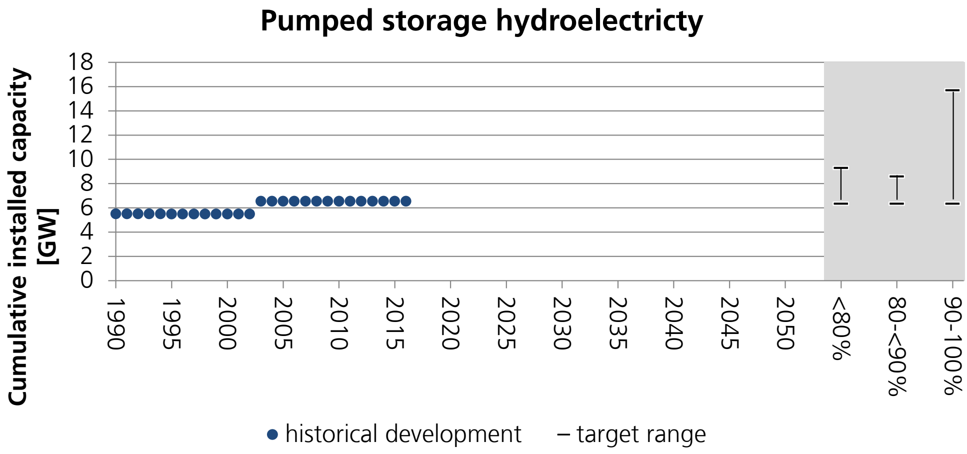


Figure 8: Historical development of geothermal energy and heat pumps compared to the targets of the analyzed studies. Historical data from (BMWi 2017b)

In 2015, 37 PJ of heat was generated by heat pumps in Germany. The trend scenarios by BEE (Nitsch 2014) and Prognos (Schlesinger et al. 2014) show that in 2050 about 90 to 130 PJ will be provided by heat pumps based on the current situation. If emissions are to be reduced further, at least 200 PJ of heat from heat pumps will be needed. The upper end of the studies' proposes that 1,100 PJ from heat pumps as necessary.

Storage technologies

With higher shares of electricity in the energy system, energy storage technologies are gaining importance. Figure 9 shows the historical development and the target ranges for emission reduction for pumped storage hydroelectricity (PSH) and stationary batteries. Most PSH plants have been in operation for several decades. Today, all PSH plants together have a power of about 6.6 GW with a storage capacity of about 40 TWh. The increase in 2003 is due to the Goldisthal power plant starting operation. The potential for PSH in Germany is exploited to a large extent. Therefore in the studies the installed capacity (or power) is not optimized, but fixed to the current status or including some further increase. Overall the studies see no potential for extension of PSH.



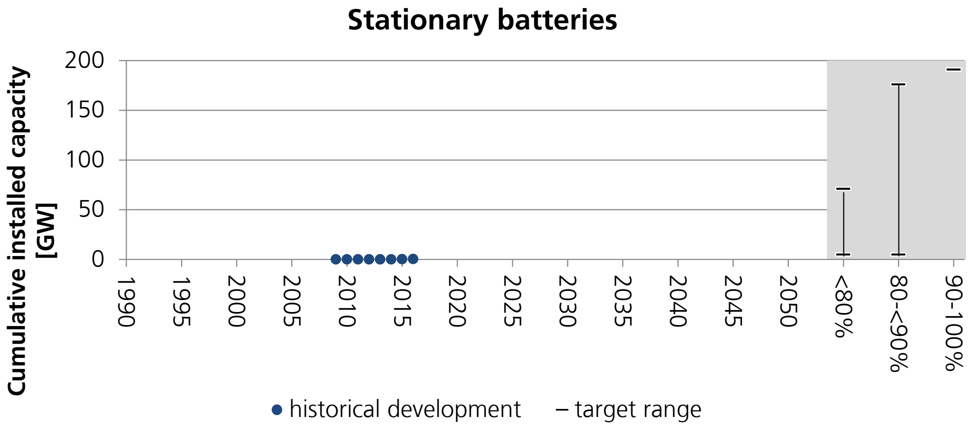


Figure 9: Historical development of PSH and stationary batteries compared to the targets of the analyzed studies. Historical data of PSH based on operator statements; historical data of stationary batteries based on (Kairies et al. 2016) and (Department of Energy (DOE) 2017)

The market for stationary batteries has just started several years ago. The amount of installed capacity was about 230 MW in 2015. The analyzed studies assume a moderate (about 5 GW) or steep increase up to 65 to 75 GW installed capacity in 2050, to reach 80% CO_2 emission reductions, or even up to 170 GW for 80 to 90% emission reductions. In a highly decarbonized system the battery capacity needed is around 190 GW based on (Ausfelder et al. 2017). Compared to the needed capacities to achieve the emission targets, the amount of installed battery capacity today is still low. However, due to fast price decreases in the last years, a strong growth is possible.

Power-to-X technologies

Figure 10 shows the historical development of energy consumption by private electric cars compared to the energy consumption expected in the analyzed studies. Most studies do not optimize the number of electric cars but rather assume a certain demand. In light blue, the electricity demand of the former target of 1 million electric cars in Germany in 2020 is indicated. The electricity demand of private electro mobility was about 150 GWh in 2016. Even with the assumed 1 million electric cars, the demand would still be below 2 TWh/year. This is very low compared to the expected 35 to 200 TWh which will be needed if emission targets are between 55 and 100%. The very low value in the 80 to 90%-scenario range is caused by the hydrogen scenario of the acatech study, which assumes large amounts of hydrogen cars and only few electric cars.

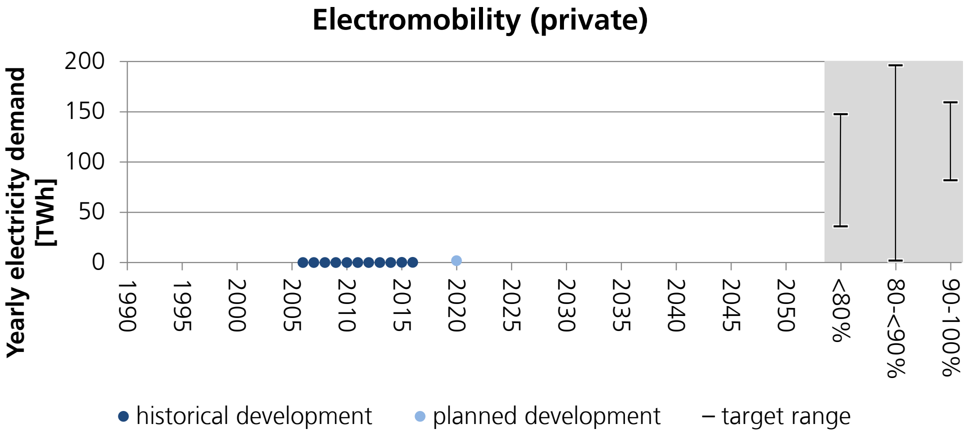


Figure 10: Historical development and planned development of private electro mobility compared to the target ranges of the analyzed studies. Historical data based on (Kraftfahrtbundesamt 2017), assuming 50 kWh battery capacity per car and 120 cycles per year

Figure 11 shows the range of emission target results for power to heat, power to gas and power to liquid depending on the scenario group. The current energy demand for these technologies is comparatively small and without long history, therefore a different format is chosen for the comparison. In 2014, about 225 MW_{el} of power to heat plants were installed in Germany (Agora Energiewende 2014, p. 3). Power to gas plants amount to 21 MW in 2016 (EnergieAgentur.NRW 2016, p. 10). Power to liquid is still at pilot project and demonstration status with a very low installed capacity. The low minimum need for power to X technologies shows that not all studies consider these technologies as necessary for a successful energy transition at the date of publication, which could be a result of the very early market phase of those technologies today. Only power to heat is considered as relevant for CO_2 emission reduction, in all analyzed studies. Nevertheless, those studies considering power to X technologies as relevant, expect a required energy demand of up to 700 PJ for power to heat production (90-100% reduction), 1,300 PJ for power to gas production and 1,900 PJ for power to liquid.

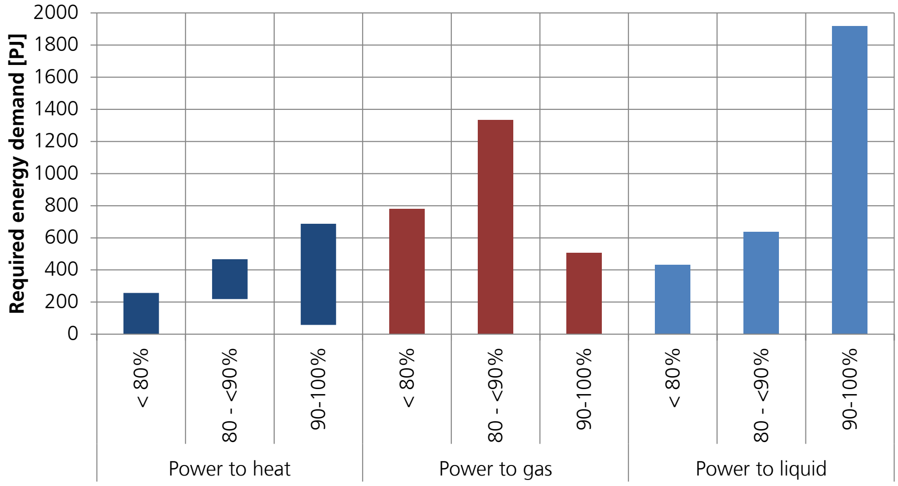


Figure 11: Range of expected energy demand by power to X technologies for different CO_2-emission targets

5 Conclusions on technology needs

Several conclusions can be drawn from the analysis: The current reduction in primary energy demand between 2005 and 2016 shows that the CO_2 emissions target of 80% reduction in the year 2050 may be met if the current reduction trend continues. However, the trend is very unstable, as data of the last three years show even an increase in CO_2 emissions. Higher emission reduction targets require an accelerated effort to decrease the primary energy demand. In addition, the development is dependent on a multitude of factors, including political decisions and socio-economic aspects.

Wind energy and photovoltaics are mature technologies. If the historical trend is extrapolated, these technologies show a tendency to reach the installed capacities at the lower end necessary to meet the emission reduction targets of 80%. It is therefore questionable, whether this will be enough to reach the emission-reduction target. Biomass energy may not be expanded to a large extent due to limitations in the resources. Hydropower is a mature technology which will probably not be further exploited in the future due to the fact that the potential is almost fully exploited. Geothermal usage in Germany is promising, but there is no widespread use up to now. There are different scenarios on the development of geothermal energy; the studies either propose a large extension of the installed capacity or do not consider the technology at all. The technology may therefore either stay in a niche market or needs strong development.

According to the analyzed energy scenarios future heat generation will rely mainly on heat pumps and solar thermal energy. Heat pumps up to now are installed in very limited numbers and a strong increase up to 2050 is needed in order to reach the emission reduction targets. The same conclusion is valid for solar thermal energy.

Pumped hydro storages are mature and well developed in Germany. Due to a limitation in available land and social acceptance, a further development of pumped hydro storages is not foreseen. All studies show a massive development of usage of batteries for electric vehicles. In the studies where stationary batteries are analyzed, a massive increase of installed capacities is proposed. Power-to-X technologies are at pilot project or demonstration project status and are expected to play a major role in the energy sector with high shares of renewable energy technologies. However, due to the currently small numbers of installed capacities the projection of future development comes with an even higher uncertainty.

The meta-study can provide benchmarks for future technology needs and show the gaps that need to be closed to fulfill the emission targets. It is based on a top-down approach, grouping the resulting technology needs by the emission targets of the studies. For some technologies, the German government has defined a development path for the near future. The actual development of the technologies, however, depends on the individual decisions by the investors. A model for the technology diffusion, based on investment decisions, is developed in the project "Sozio-E2S", which is funded by the federal ministry for economic affairs and energy BMWi[2].

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[2] https://www.ise.fraunhofer.de/de/forschungsprojekte/sozio-e2s.html

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