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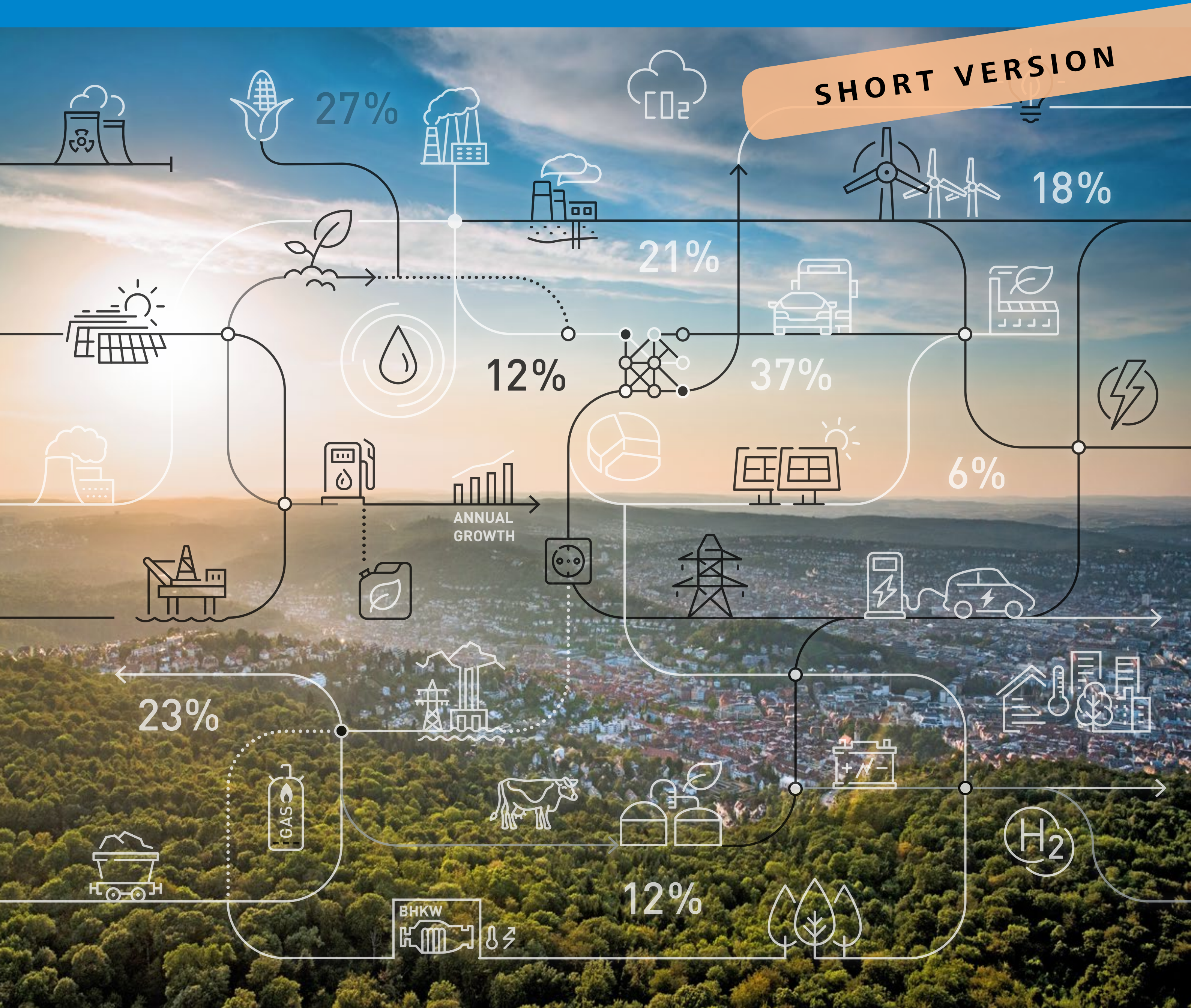
Paths to a Climate-Neutral Energy System

The German Energy Transformation in its Social Context



PATHS TO A CLIMATE-NEUTRAL ENERGY SYSTEM

The German Energy Transformation in its Social Context

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Foreword

The study "Paths to a Climate-Neutral Energy System – The German Energy Transformation in its Social Context" was conducted by the Fraunhofer Institute for Solar Energy Systems ISE as an in-house research project. Part of the work for this study was performed within the Copernicus ENavi project, financed by the German Federal Ministry of Education and Research. The main motivation behind the study was to investigate how specific social behavior and attitudes influence the course of the energy transformation and what effect this has on the investments and costs required to transform the German energy system.

We would like to thank all the employees of Fraunhofer ISE who assisted in this study. This group of participants is far larger than the authors named on the title page. The vast expertise on the development of the future costs and performance of significant technologies within the institute was extremely important and helpful and provided a solid basis for the simulations.

With the analysis and results presented here, we hope to make a valuable contribution to an objective, factual discussion on the feasibility of a climate-neutral energy system, based on the use of renewable energy and the provision of higher efficiency for energy conversion and utilization.

Freiburg, Germany   February 13, 2020

Hans-Martin Henning   Andreas Bett

Summary

In this study, potential development paths which lead to at least 95 % reduction in energy-related CO_2 emissions by 2050, compared to 1990 levels, were investigated for the German energy system. Two additional scenarios with aim of achieving 100 % reduction in energy-related CO_2 emissions by 2050 were also considered.

Besides the questions of technical feasibility and costs, societal behavior plays a significant role in determining whether and in what form the energy transformation can be implemented. In order to take this aspect into account, four main scenarios each describing different behavior and attitudes of society were analyzed. The societal aspects play a dominant role in the various scenarios, and thus set the framework conditions for the further course of development for the energy transformation.

The *Persistence* scenario is characterized, in particular, by strong resistance to the use of new technologies in the private sector. The *Non-acceptance* scenario is defined by a lack of acceptance among the population for the further expansion of large infrastructures. On the other hand, the *Sufficiency* scenario describes a development in which changes in conduct are visible in a large majority of the population, resulting in a noticeable decrease in energy demand. These three scenarios are compared to the *Reference* scenario, in which no conditions to either promote or impede achieving the climate targets are specified.

The simulation and optimization of the various scenarios are carried out using the energy system model REMod (Renewable Energy Model). This model was developed almost ten years ago by the Fraunhofer Institute of Solar Energy Systems ISE and since then has been intensively further developed and optimized.

The most important results and findings derived from the simulations are as follows:

1.
From a technical and systemic point of view, the achievement of the climate protection targets in the German energy supply is feasible based on renewable energy sources.

Using dynamic simulations carried out in hourly time steps up to 2050, the model showed that a secure energy provision is guaranteed hour-by-hour in all consumption sectors despite a high share of fluctuating renewable energy sources in the electricity mix. At the same time, the results from the various scenarios demonstrate that the differences in expenditure and costs are strongly dependent on the framework conditions.

2.
Electricity from renewable energy sources will dominate the energy supply, with wind and solar being the largest primary energy sources.

In the scenarios considered, the total installed capacity of wind and photovoltaic power plants combined lies between 500 GW_{el} and over 750 GW_{el} in 2050, or about five to seven-fold of the installed capacity today. All of the development scenarios considered show that solar and wind power plants shall cover between 50 and 60 % of the primary energy demand in 2050.

3. Due to lower losses in the conversion chains, mostly as a result of sector coupling, the primary energy consumption decreases significantly.

In the investigated scenarios, the primary energy consumption for the energy sector lies between 1750 TWh (*Sufficiency* scenario) and 2500 TWh (*Persistence* scenario) in 2050, thus appreciably lower than today's value (almost 3400 TWh). This is despite the assumed increase in useful energy consumption over time considered in most of the scenarios. The reduction is mostly due to a more or less pronounced displacement of combustion-based technologies (boilers, thermal power plants, internal combustion engines) by electricity-based technologies and the resulting improvements in conversion efficiency throughout all sectors. Therefore, sector coupling, i.e. the increased direct – or in the case of synthetic energy carriers produced by renewable electricity – indirect use of electricity, is a key element of the energy system transformation throughout all consumption sectors.
Considering the above (points 2 and 3), it can be concluded that the core building blocks needed for reaching the CO_2 emission targets in the most cost-effective manner are: the successive reduction of fossil fuel use in the heat (building, processes) and transport sectors in conjunction with a greater use of electricity and an accelerated reduction in specific emissions in electricity generation.

4. Greater flexibility in the provision and use of electricity becomes a key element of the system development

The growing share of fluctuating renewable energy sources for power generation necessitates a paradigm shift in the supply model. The predominantly demand-based power supply relying on large power plants is being increasingly replaced with a system in which continuous energy balancing is carried out between a provision of supply from renewable energy sources, characterized by limited controllability and forecastability, and a consumption that should be as flexible as possible. This results in a complex interplay between energy provision and a time-adjusted (through load shifting, demand response) energy consumption, including the stronger coupling of the electricity, heat and transport sectors as well as the temporary use of flexible production systems such as electrolyzers for hydrogen production and storage systems of all types.
Multi-modal heating networks fed from different generators in combination with large heat storage units have also proved to be an effective measure for flexibility and load management, especially in dense urban areas.
Stationary battery storage facilities are another important element of flexibility. For the scenarios investigated, the installed capacity of battery storage in 2050 lies between 50 GWhel and 400 GWhel.
And last but not least, controllable power generators are also needed in the long term, especially highly flexible gas turbines with an installed capacity totaling between 100 GW_{el} and over 150 GW_{el}.

5. Electrolysis combined with hydrogen utilization for various applications is a key building block of the future energy supply.

Electrolyzers can be used to produce electricity-based energy carriers such as hydrogen, methane or liquid fuels, making them an important option for renewable electricity use. Although these plants achieve higher full-load hours at locations with a higher renewable power availability than Germany, their installation in Germany was shown to be advantageous in the context of a cost-optimized energy system transformation. There are three

main reasons for this: Firstly, the secondary energy carriers produced can be used in applications where a direct use of electricity is difficult to implement. Examples of this are liquid fuels for maritime transport, air traffic or heavy-duty transport as well as hydrogen and hydrocarbons for the chemical industry.
Secondly, those electrolyzers which enable fast start-up and shut-down, can be used as flexible loads, thus furthering the potential for integrating renewable electricity into the energy system.
Thirdly, these processes offer the possibility of producing electricity-based energy carriers from renewables during times of high feed-in of electricity. These secondary energy carriers can then be stored nearly loss-free over a period of several days or months. Subsequently they can be used, for example, in dispatchable power plants when grid feed-in from renewable electricity is low. Thus, a reliable power production is guaranteed without the use of fossil fuels. For the scenarios investigated, the installed capacity of electrolyzers ranges between around 50 GW_{el} and 120 GW_{el} in 2050.

6.
The efficient use of energy resulting from implemented technical measures leads to an accompanying reduction in consumption and contributes significantly to reaching the climate targets, especially in the area of heat provision.

In all of the investigated scenarios, increasing the rate of energy retrofits in buildings was shown to be an important factor in decreasing the space heating requirement. This goes hand in hand with changing many heating systems over to a lower temperature level, which accommodates the use of heat pumps and solar thermal systems. There are also numerous possibilities in the industry for a more efficient energy utilization, which in part can be realized by the direct use of electricity.

7.
Behavioral changes in a majority of the society which result in more energy conservation can have a significant effect on the restructurization of the energy system and reduce costs substantially.

In the *Sufficiency* scenario, a development was investigated in which behavioral changes in a large part of society resulted in considerable reductions in energy consumption. A shift in values, driven by a growing awareness of the dangers posed by climate change, could, for example, bring about such behavioral changes. If this were to occur, a significantly smaller amount of technical systems for the conversion, storage, distribution and consumption of renewable energy would be required. As a result, the necessary investments and costs would be lower. With a value of about 50 € per ton CO_2 on average over the next thirty years, the carbon avoidance costs in this scenario are far lower than for all of the other models calculated in this study. At the same time, it can be assumed that lower expansion of renewable energy plants and other technical facilities in the energy system would also lead to a greater acceptance of the changes associated with the energy system transformation.

8.
The import of energy in the form of electricity and synthetic chemical energy carriers produced abroad with renewable electricity is an important part of reaching the German climate protection targets.

In the scenarios investigated, the amount of imported synthetic chemical energy carriers produced with renewable electricity abroad and consumed in 2050 varies between ca. 75 TWh (*Sufficiency* scenario) and 500 TWh (*Persistence* scenario). Naturally these values are strongly dependent on the assumed price development for such energy carriers. Although the absolute quantities are certainly subject to a great deal of uncertainty, the large difference resulting from different social behavior and attitudes is clear. In particular, an adherence to the use of familiar combustion-based technologies for heat supply and transportation (*Persistence* scenario) results in large import quantities of such energy carriers.

9.

From a system perspective, it would be possible to increase the use of photovoltaics if the wind capacity does not expand to its optimal level. However, this leads to a greater need for energy storage and also higher CO_2 avoidance costs than would be the case for a cost-optimal development.

In the *Reference* scenario , which assumes a cost optimization without external intervention, the total on and offshore wind capacity amounts to around 40 % (263 GW_{el}) and the photovoltaic capacity around 60 % (414 GW_{el}) of the total installed capacity of plants generating electricity from fluctuating renewable energy sources. This means about two thirds of the total electricity generated by these plants is from wind turbines and around one third from photovoltaics. On the other hand, in the *Non-acceptance* scenario, which is characterized by a strong resistance to further expansion of large infrastructures, the total installed wind capacity (on and offshore) is 115 GW_{el} while the photovoltaic capacity increases to 645 GW_{el}. As a result, a number of different measures are required to integrate this solar power into the energy system in a useful way also for times of high solar radiation in Germany. For example, the orientation of photovoltaic installations shall be distributed from east to west in order to widen the feed-in profile throughout the course of the day and avoid an extreme midday peak. At the same time, with 400 GWhel of installed capacity, considerably more stationary battery storage units will be installed by 2050 than in the *reference* scenario (150 GWhel). Furthermore, 300 TWh of imported chemical energy sources, i.e. around twice as much, will result and the average CO_2 avoidance costs will increase from around €150 per ton (Reference scenario) to €162 per ton over the entire period under consideration.

10.

The transformation of the energy system involves additional costs compared to a development that is not oriented towards compliance with climate protection targets. A large part of these additional costs are for investments which are necessary to set up and reconstruct the energy system.

Compared to a Business-as-Usual scenario, the net additional expenditures range between €440 billion for the *Sufficiency* scenario and €2330 billion for the *Persistence* scenario. These results underline that societal behavior and attitudes have a significant influence on the costs associated with the transformation of the energy system towards a climate-neutral energy supply. In the scenarios, the annual additional expenditures range from 0.4 % (*Sufficiency* scenario) to around 1.5 % (*Reference* and *Non-acceptance* scenarios) to around 2 % (*Persistence* scenario) of the Germany's 2019 gross domestic product (GDP) respectively. Another comparative measure for the annual additional costs is the turnover attributed to the Christmas business, which for 2019 in Germany was just under €102 billion, i.e. about twice as high as the average annual expenditure for the energy system transformation in the *Reference* and *Non-acceptance* scenarios.

The results show that in almost all scenarios far more than half of the additional expenditure is incurred for investments, which are necessary for restructuring the energy system. When this system transformation is completed (for the most part) in 2050, the investments will decrease significantly, since from then on only replacement investments will have to be made.

When considering costs, it should also be noted that the analysis carried out here did not consider external costs for the different scenarios, nor did it consider the total economic costs, which include value added analyses and employment effects. In particular, it does not take into account the follow-up costs associated, for example, with a sharp rise in atmospheric temperature that would result if climate protection targets are not met.

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Conclusion

This study analyzes the influence that key societal behaviors and attitudes have on the progress of the energy transformation and how this affects the necessary investments and costs of restructuring the energy system. The results show that from a technical and systemic point of view it is feasible to reach the climate protection targets for the energy supply based on renewable energy sources. The model calculations, carried out on an hourly basis for the next thirty years, show that a secure energy supply throughout all consumption sectors is guaranteed for each hour, despite the high share of fluctuating renewable energy sources in the electricity supply.

The different scenarios also illustrate that the differences in the expenditure and costs required to achieve the goals depend strongly on the framework conditions, which are largely determined by societal behavior and attitudes. For example, if large parts of society change their behavior to a more economical use of energy, this would have a considerable impact. As a result, the necessary amount of facilities for the conversion, storage, distribution and use of energy and the associated costs would then be substantially lower than in all other scenarios considered. In contrast, adhering to the use of combustion-based technologies for the heat supply and transport would lead to substantially higher capacity requirements for renewable energy power plants and other related technical facilities. Also, the import of synthetic, chemical energy carriers, produced abroad on the basis of renewable electricity, increases. Such persistent behavior would make the energy transformation more expensive. Strong resistance to the expansion of large infrastructures such as wind turbines and grids can be partially compensated by a modified path, albeit at slightly higher costs than in the case of cost-optimal development. Greater installments of photovoltaic systems and battery storage are elements of such a path.

An essential prerequisite for a comparatively cost-effective achievement of the climate targets is the continuous development of all relevant technologies for the conversion, storage, distribution, use and system integration of renewable energy. Only then will it be possible to achieve the projected reductions in costs and the increases in performance and service life. The study has also made it clear that the use of thermal and electrical storage systems in Germany is just as meaningful as establishing domestic production, processing and the use of hydrogen in a wide range of applications. The development of domestic markets is important for all technologies and furthermore contributes significantly to successful technology development. On the one hand markets for local manufacturers are created and on the other hand experience can be gained across the board with the corresponding plants and their system integration. These are also essential prerequisites for achieving the desired improvements in costs and performance. At the same time, knowledge of these technologies and confidence in their reliability grows. This is also an important factor for export.

However, applied research and development does not end with component development, rather it also can make important contributions to increasing market integration. The concept of integrated photovoltaics is an example of this. It is foreseeable that a massive expansion of large open space photovoltaic systems could lead to conflicts and possibly acceptance problems. On the other hand, with the integration of photovoltaics into building envelopes, vehicle bodies and roads as well as agricultural land and water surfaces, huge areas already used for other purposes will open up for the dual use of solar power generation. Creating the appropriate products and solutions for these applications will be an important task in the further development of photovoltaics and will present new opportunities for domestic production. Electric heat pumps are another example. The investigations carried out underscore the important role of heat pumps in achieving a cost-effective transformation in the heat sector. Especially in urban areas, however, regulations that limit the exploitation of heat sources are in place; also noise emissions can cause acceptance problems. Here, too, applied research and development in close cooperation with manufacturers and users is needed to address the arising problems and to develop new solutions. These are just two concrete examples of the many questions that need to be answered in order to develop customized solutions, which are highly relevant for the successful implementation of the energy transformation.

The future energy system will be characterized by a large number of interconnected systems. These will interact with each other and operate so as to provide as much dynamic support to the system as possible. Photovoltaic systems, heat pumps, stationary battery storage systems and charging stations for electric vehicles, but also technical systems, many in the small power range, are particularly important here. In the coming decades, the number of these systems is expected to reach the double-digit millions. Against this background, the development of solutions for the efficient, stable and reliable system integration and operation of these many components plays a decisive role. This can be achieved, however, only by using modern concepts from the information and communications technology (ICT). Application-oriented system research is just as relevant for the development of feasible solutions and business models as for energy system analysis, which serves as a compass for the successful development of the total energy system towards a climate-neutral energy supply.

With this study, we hope to contribute valuable input to the discussion on the feasibility of achieving a climate-neutral energy system, which is essentially based on two main pillars: renewable energy use and high efficiency in energy conversion and utilization.

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