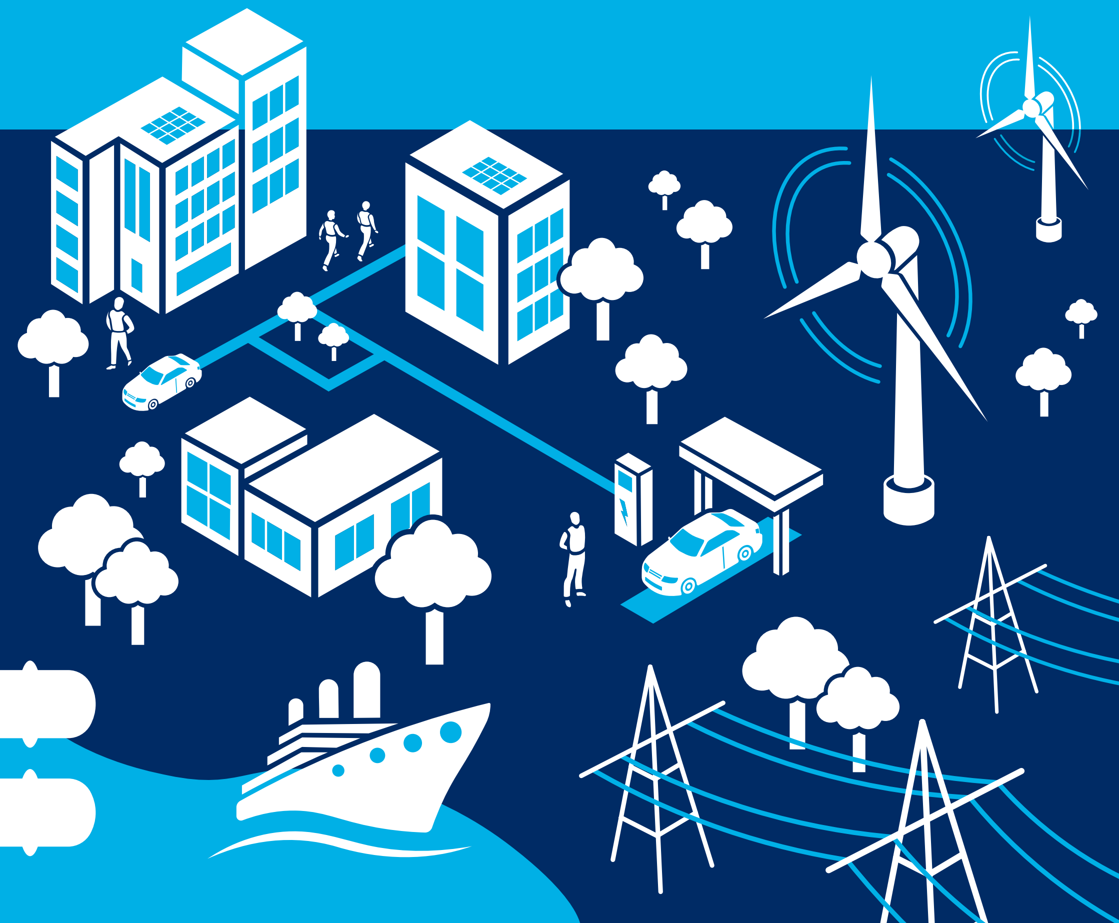
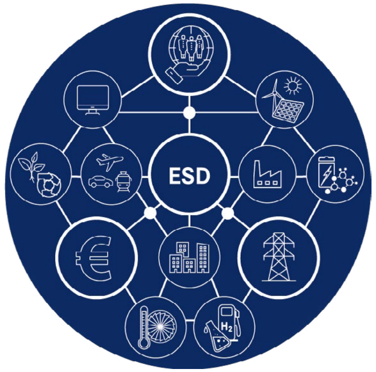
HELMHOLTZ Energy

Energy System Design – Policy Brief

Integrative Considerations on Energy Transition





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Hinweis:
The Policy Brief can be downloaded.
The Policy Brief includes an attachment, which presents the findings in more detail.

This Policy Brief was prepared within the Helmholtz Program Energy System Design (ESD).

Executive Summary

The creation and analysis of energy scenarios is an unquestionably essential methodology to support the necessary sustainable transformation of the energy system, and must do justice to the complex socio-technical character of this system. Therefore, technical, ecological, economic, institutional, and organizational as well as social aspects must be taken into account.

In the Helmholtz Program Energy System Design (ESD), researchers from the German Aerospace Center (DLR), Forschungszentrum Jülich (FZJ), and the Karlsruhe Institute of Technology (KIT) have developed and applied an integrative scenario approach with the aim of meeting these requirements better than the energy scenarios that have dominated discussion to date. The approach essentially consists of two elements: 1) the development of so-called socio-technical scenarios, and 2) the estimation of the impacts of these scenarios with regard to their effects on sustainability indicators relevant to the energy system. The aim is to enhance the basis for decision-making regarding the sustainable transformation of the energy system.

The analyses show the need to consider the range of possible developments in population and economic performance, as key drivers of energy and infrastructure requirements, in a more systematic way than previous scenario analyses. Irrespective of population development or future economic performance, the electrification of production and transportation processes should be at the heart of suitable transformation strategies. This requires comprehensive spatial and temporal flexibility in the electricity sector. For technical reasons, electrification must be supplemented by the use of defossilized hydrogen. However, three-quarters of this would be imported. The transformation of the heating sector, on the other hand, requires a concerted interplay between energy-efficient building refurbishment, a change of energy source, and the expansion of electricity and heating grids. The transformation of energy supply and use involves the use of critical resources. Therefore, suitable strategies are essential to reduce geopolitical risks and use these resources efficiently.

The transformation of energy supply and use is a necessary condition for achieving a climate-neutral energy sector, but not a sufficient one. The establishment of an infrastructure for effective CO_2-management is indispensable in order to compensate for unavoidable greenhouse gas emissions (GHGs). However, the goal of a sustainable energy system also requires consideration of non-climate-related environmental effects. If the macroeconomic effects of a transformation are included in the development of suitable strategies, it can be seen that the transformation strategies lead to an increase in domestic value added, but do not lead to a substantial change in the overall economic demand for labor. On the other hand, additional burdens on low-income households are possible.

This depends largely on socio-economic boundary conditions, which are closely linked to energy-related variables. Finally, the degree of internalization of external costs, as an important condition for the success of a sustainable transformation, is significantly influenced by political and economic developments, as well as by the innovative capacity of the system.

Introduction

Energy is of central importance for the functioning of modern economies and societies. However, the provision and use of energy could be also associated with significant climate and environmental impacts. The energy system therefore plays a key role in the necessary sustainable transformation. Converting technical infrastructures to achieve energy and climate policy goals therefore always affects economic and social options for action. At the same time, social groups were and are key drivers of this transformation. However, they can also take critical or even hostile stances towards it.

The energy transition must therefore be conceived and implemented holistically, i.e., also taking into account the interests and options for action of different stakeholder groups. Discussion of suitable measures therefore includes not only the technical challenges but also social, institutional, and organizational factors, as well as national and international political and economic developments. These factors and their interactions are central to decisions regarding the energy system transformation.

Today, energy scenarios make an important contribution to supporting the necessary decisions for the transformation of the energy system. It is essential that the energy system is not only understood as a technical and economic construct, but that its embedding in and interaction with society is also taken into account. In order to support a sustainable transformation in a broad sense, it is therefore essential to analyze the social prerequisites of the transformation and its effects on the environment, economy, and society. As part of the Helmholtz Program Energy System Design (ESD), the German Aerospace Center (DLR), Forschungszentrum Jülich (FZJ), and the Karlsruhe Institute of Technology (KIT) have set themselves the task of developing energy scenarios that meet as far as possible the requirements described above. The basic idea of the developed integrative scenario approach consists of two elements: 1) the creation of so-called socio-technical scenarios by combining the possible developments of the social, political, economic, and technical contexts of

the energy system with techno-economic modeling, and 2) the estimation of the impacts of these scenarios with regard to their effects on sustainability indicators relevant for the energy system.

The combination of different perspectives on the transformation of the energy system enables a range of results that is essential for the design and implementation of suitable energy policy measures, but which cannot be found in the energy scenarios that have dominated the discussion to date. Only such a broad basis for decision-making will make it possible to develop viable strategies for a sustainable transformation of the socio-technical energy system.

The main findings from the energy scenarios developed by the Helmholtz Program ESD and the impact analyses and assessments are summarized below.

Socio-technical Energy Scenarios

The socio-technical energy scenarios considered combine context scenarios with techno-economic energy scenarios. Context scenarios describe possible developments in the social, political, economic, and technical conditions of the energy system. They are determined using the Cross-Impact Balance approach, and form the framework for the techno-economic scenarios, which were created using a cost-optimizing energy system model.

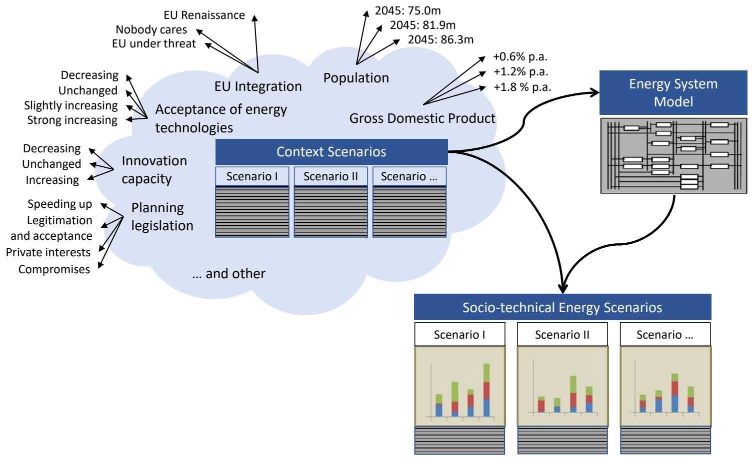

Figure 1: Socio-technical energy scenarios

The created energy scenarios assume that a climate-neutral energy system can be realized in Germany by 2045. In order to be able to depict a range of possible developments in the overall economy that will have a direct influence on the technical design of the energy system, different development paths were assumed with regard to Gross Domestic Product and population. For the Gross Domestic Product, paths between a cautiously pessimistic (+0.6 % p.a.) and an optimistic development (+1.8 % p.a.) were examined; the assumed population development varies between a sharp decline in the population (75.0 million in 2045 compared to 84.7 million in 2023) and a moderate increase in the population (86.3 million in 2045).

The scenarios with low economic growth and a declining population are characterized by a tendency towards political and economic fragmentation of the world order and stagnating cohesion of the EU. These developments, but also domestic one, put pressure on domestic innovation capacity. Furthermore, these scenarios are characterized by a stagnating income of private households with increasing inequality. Despite the rather unfavorable economic environment, the state can count on the general approval of the population with regard to the transformation policy.

The economic and political environment in the scenarios with high economic growth and moderate population growth is characterized by an integrated world order and enhanced EU integration. This environment also favors domestic innovation capacity and improves the income of private households. In these scenarios, too, the state receives fundamental approval. It should be noted that the government relies heavily on participation and legitimization in these scenarios.

Requirements and Effects of Climate-neutral Transformation Pathways

Uncertainties regarding economic and population development needs more consideration than has previously been the case when planning future energy and infrastructure requirements

Germany's future energy demand, and thus the necessary infrastructural conversion and expansion of the energy system, will be largely determined by economic and population development in the coming decades. The present scenario analyses show that, due to uncertainties in Gross Domestic Product (GDP) and population development alone, it can be expected for the year 2045 that final energy demand, electricity demand, installed capacity for electricity generation, and hydrogen demand can vary between 10 and 25 %. A premature determination of a possible (generally moderate) development of GDP and population therefore harbors the risk of underestimating or overestimating future energy and infrastructure requirements.

Spatial and temporal flexibility in the electricity sector are essential for the electrification of the overall system

Due to the increasing direct and indirect electrification of the energy system, the demand for electricity will rise continuously to around 1,100-1,300 TWh per year by 2045 – depending on the scenario. Key drivers are "new" consumers such as the production of synthetic energy sources (electrolysers for H_2), electromobility, heat pumps and other electrical heat generation. On the generation side, wind power plants (onshore and offshore) and photovoltaic power plants (rooftop and ground-mounted systems) will form the backbone of Germany's electricity supply, accounting for more than 90 % of the electricity generated.

Technology	Installed power in GW
Wind onshore	211-223
Wind offshore	53-70
Photovoltaic ground-mounted	~255
Photovoltaic rooftop	115-180
Controllable power plants (Hydrogen, Biomass, Biomethane)	145-160

Controllable power plants will provide peak load coverage as backup capacity in the event of prolonged dark doldrums, among other things.

Table 1: Range of installed electrical power in 2045

The spatial and temporal disparity of electricity generation and demand requires a further expansion of the electricity grid at all grid levels, an expansion of the electricity storage infrastructure, and the realization of economic flexibility potential in industry, commerce, households, and in the conversion sector (e.g., in the operation of electrolysers). Germany's integration into the European interconnected grid, taking into account the transformation of other EU member states, is an important element in ensuring a high level of security of supply.

Electrification and hydrogen use are crucial for the success of the industrial transformation

The transformation of the energy system must be accompanied by an industrial transformation. The primary starting point is the electrification of industrial processes. In the paper and glass industry, for example, fossil-based combustion processes must be completely replaced by biomass-based combustion processes and electrification. Where direct electrification is not possible, hydrogen can play a central role in industrial transformation. This is the case, for example, in steel production, where hydrogen is used to provide heat or for direct reduction. With the additional melting of steel scrap in electric arc furnaces, the steel industry can thus be almost completely defossilized by 2045. The industrial hydrogen demand can achieve up to 335 TWh in the scenario of a high increase of economic performance and increasing population. The most important driver is methanol production. Methanol is required for highly refined chemicals such as ethylene and propylene.

Electrification is a core component of the defossilization of the transport sector – even if hydrogen-based fuels are indispensable for specific transport modes

Electrification of the transport sector will nearly double its energy efficiency from almost 30 % currently to about 60 % in the year 2045. Accordingly, in the scenarios the final energy demand in the transport sector would decrease from currently approx. 600 TWh to approx. 250 TWh, without any significant modal shift. As a consequence, the direct greenhouse gas emissions will drop to nearly zero. Contrary to that, the opportunities for electrifying shipping, air traffic, and heavy load traffic is limited. A complete defossilization is only possible with hydrogen-based fuels.

Hydrogen imports are essential for an economically sound defossilization of industry and specific transport modes

Industrial hydrogen demand, including the demand from shipping and air traffic and as long-term storage for reconversion of electricity, will amount to between 450 and 570 TWh per year in 2045, depending on the scenario. Around a quarter of this will be covered by domestic production; the rest will be imported mainly by pipeline. The timely development of a corresponding international infrastructure for hydrogen transport, national distribution and storage, but also domestic production, is therefore essential. Care must be taken to minimize geopolitical dependencies by diversifying supplier countries and establishing long-term energy partnerships with politically stable countries.

The heating transition in the building sector requires a concerted interplay between energy-efficient building refurbishment, energy source switching, and the expansion of electricity and heating grids

The heating transition in the building sector requires the concerted interaction between energy-efficient refurbishment of existing buildings, energy-efficient new buildings, and a complete conversion of the heating supply to renewable sources by 2045. According to the scenarios, the dominant technology will be the electrically powered heat pump. However, a good third of the heat demand in the building sector can be provided by grid-connected heat, which in turn is largely supplied by central biomass Combined Heat and Power (CHP) plants and large central heat pumps. Parallel to the change in energy source, the specific energy demand per living space must be reduced from the current approx. 120 kWh/(m²*a) to an average of approx. 62 kWh/(m²*a) through an ambitious energy-efficient refurbishment of the building stock (~2 %/year). The additional electricity demand resulting from the massive use of electric heat pumps (in addition to electromobility) requires the distribution network infrastructure to be upgraded in line with demand. Heating networks must also be expanded – where it makes energy and economic sense to do so – in order to achieve the targeted increase in the share of grid-connected heat in building heating. Necessarily, sufficient amount of renewable energy sources for heating have to be available.

The development of an infrastructure for effective CO_2-management is essential in order to compensate for unavoidable greenhouse gas emissions, e.g., from industry and agriculture

All scenarios show that from 2040 onwards, unavoidable greenhouse gas emissions from agriculture and industrial processes determine the climate relevant greenhouse gas emissions. The most important carbon dioxide (CO_2) emission sources are industry and agriculture: in 2045, approx. 90 million t CO_2. These emissions have to be removed permanently from the atmosphere. In addition, in 2045, approx. 26 million t CO_2 are bounded in chemicals, which will be emitted at the end of their use phase.

Carbon Capture and Storage (CCS) is seen today as a relevant technology to dispose greenhouse gases permanently. However, CCS is energy demanding as well as cost intensive. Furthermore, German society and politicians are skeptical. Therefore, the size of an appropriate CO_2 transport network (e.g., pipelines, including converted natural gas pipelines) and storage facilities shall be limited by the volume of unavoidable CO_2 emissions, to impede incentives to store avoidable CO_2 emissions.

The energy transition requires suitable strategies to reduce the demand for critical resources and counteract potential raw material shortages

In all scenarios, the transition of the energy and transport system is accompanied by a significant increase in the demand for strategic mineral raw materials. These are e.g., lithium, cobalt, nickel and vanadium (in batteries), neodymium and dysprosium (in wind turbines and electric motors), silver, tellurium, selenium, gallium, indium (in certain types of photovoltaic modules). However, the demand for industrial metals such as steel, copper, and aluminum will also rise sharply as a result of the energy transition. The domestic requirements compete with a globally rapid increase in demand. The required fulfillment of worldwide requirements has to be compensated by a corresponding increase in extraction of deposits that are not competitive under current market conditions. Finally, the supply of many raw materials is subject to geopolitical risks. As a consequence, there could be supply bottlenecks with corresponding price increases. Technical developments (e.g., material efficiency, recycling, use of other functionally equivalent materials) as well as a forward-looking raw materials policy that also addresses geopolitical concerns may help to reduce supply risks.

A sustainable energy transition must consider non-climate-relevant emissions, including those generated in the upstream chains

Transformation strategies for the energy and transport system generally aim to reduce greenhouse gas emissions from the operation of plants and vehicles in Germany. In doing so, other environmental impacts occur that significantly impair living conditions, such as particulate matter or nitrogen oxide emissions. Furthermore, environmental impacts also arise during the manufacture of required technologies, and the provision of raw materials and energy sources, etc., which are often released via upstream chains abroad.

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The life cycle-based analysis of environmental impacts in the scenarios describing energy systems shows on the one hand that impacts from upstream chains can in some cases significantly exceed the impacts from the operation of a technology, as is the case with photovoltaic modules or electric cars, for example. On the other hand, the transformation to a climate-friendly energy and transport system is generally accompanied by positive side effects in the quality of ecosystems and many indicators related to human health. But the consumption of mineral resources and land use will increase compared to today. Whether the energy system transformation will lead to increased impacts of some human-health related factors, such as carcinogenic and non-carcinogenic effects, is still uncertain.

Overall, the transformation will increase the domestic value added, but will not lead to any substantial change in labor requirements

The sectors that are important for the transformation of the energy system, such as mechanical engineering and the production of electrical equipment, can compensate for other sectors that are losing importance, such as conventional car manufacturing, so that there is no clear net change in domestic employment. But the structural change increases the domestic gross value added. The development of labor demand depends on the development of international competition in the manufacture of intermediate- and end-products. Internationally, the lack of coordination national climate policy measures decreases the international price competitiveness of domestic companies, which could increase the risk of drifting for companies that are exposed to strong international competition. In fact, according to the investigations of the scenarios, compliance with domestic climate policy targets is compatible with maintaining a robust industrial base while achieving the goals of creating domestic jobs and promoting economic growth. As expected, the effects are higher in the scenarios with higher growth rates than in the scenarios with low growth rates. However, the differences in terms of structural effects are only slight.

The development of key socio-economic framework conditions influences the opportunities for low-income private households to deal with the transformation-related burden

The burden on private households with low income is significantly influenced by the development of a number of socio-economic conditions. These obviously include the development of income, the situation on the labor market (low or high demand for low-income earners), the basic structure of the social insurance system (high or low importance of personal responsibility in social insurance provision), and the value orientation of society (low or high importance of solidarity or post-materialism in society). In each scenario, relieving factors, such as income development and the labor market situation, compete with burdening factors, such as the high importance of personal responsibility in social insurance provision. However, it can be seen that the situation of low-income earners tends to deteriorate in scenarios with low economic growth and population decline, while the situation tends to remain unchanged in scenarios with high economic growth and population growth.

The internalization of external costs is a key condition for the success of the sustainability transformation

The aim of internalizing external costs is to allot the environmental and social follow-up costs arising from production or consumption activities, which normally have to be carried by the general public, to the polluter, so that these costs are included in their decision-making process. This can be achieved through regulatory measures (bans, prohibitions, limits, etc.), market-based measures (taxes, levies, etc.), mixed forms (e.g., certificate trading), and informational measures (labeling, stakeholder events, etc.).

It can be seen that in a relatively poor economic situation with increasing social inequality, rather confrontational and disintegrative global and EU-wide political and economic development, as well as weak innovative actors, the conditions for internalization are particularly unfavorable in terms of social acceptance of corresponding measures and the willingness of politicians to implement them. Positive factors such as a stronger government focus on climate policy, and a population with a fundamentally positive attitude towards the energy transition and energy sufficiency are thus overcompensated. In a better economic and social environment at a national, European and global level, the conditions for internalization are much more favorable. In addition to the positive factors mentioned above, this is due in particular to higher economic development accompanied by less inequality, greater innovative strength in the economy and a society that is more oriented towards values such as a sense of community and post-materialism.

Conclusion and Outlook

The scenarios considered are intended to represent a range of possible developments. What all the scenarios have in common is that the climate policy goal of climate neutrality is achieved by 2045. However, the scenario-specific challenges for energy policy – as well as for economic, social, labor market, environmental, and foreign trade policy – differ significantly.

Integration of diverging but consistent socio-economic developments into the scenario design and analysis to identify suitable transformation pathways enables disclosure of the complexity of the energy system transformation that is necessary for a holistic discussion. This also reveals possible conflicts between the objectives of the sustainable transformation in the scenario analyses. An example of this includes the necessary investments in new transformation-promoting infrastructures and the resulting additional burdens – without compensatory measures – on private households. The most affected are the already heavily burdened low-income households. The same applies to the economic prosperity required for the willingness to support the energy transition and the associated environmental burdens and higher raw material requirements. Such an extended scenario analysis and assessment makes it possible to identify the need for action at an early stage, which is often not (or cannot be) seen in a purely techno-economically dominated analysis.

Building on this, science can offer policymakers and society tools to develop suitable measures in societal discourses at an early stage, before costly decisions are made that ultimately make little or no contribution to the necessary transformation.

An integrative scenario analysis methodology that has been further developed and improved in the manner outlined goes hand-in-hand with increased complexity and therefore increased effort. A variety of pictures arise from positive and negative effects of a climate neutral pathway on various aspects of sustainability. A major methodological challenge is to derive valid action-guiding statements in this multi-criteria decision-making situation. The continued development of the methodology will therefore primarily involve expanding and adapting the set of factors which address changing geopolitical, social, and technical conditions, as well as improving the assessment methodology, for example by systematically integrating methods of multi-criteria decision analysis involving relevant stakeholders.

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