dena German Energy Agency

# dena Study
# Integrated Energy Transition

**Impulses to shape the energy system up to 2050**
Report of the results and recommended course of action

Integrated Energy Transition

## Imprint

**Publisher:**
Deutsche Energie-Agentur GmbH (dena)
German Energy Agency
Chausseestrasse 128 a
10115 Berlin, Germany
Tel: +49 (0)30 66 777-0
Fax: +49 (0)30 66 777-699
www.dena.de

**Authors:**
Thomas Bründlinger
Julian Elizalde-König
Oliver Frank
Dietmar Gründig
Christoph Jugel
Patrizia Kraft
Oliver Krieger
Stefan Mischinger
Dr. Philipp Prein
Hannes Seidl
Stefan Siegemund
Christian Stolte
Mario Teichmann
Jakob Willke
Mareike Wolke

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# The dena Study Integrated Energy Transition is structured in two content parts:



*Notice: The complete version of the Expert Report is available in German only.*

# Part A:

## Report of the results and recommended course of action

(dena)

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# Preface

After 18 months of intensive work on the dena Study Integrated Energy Transition, we are now presenting our findings in this report. More than 60 study partners from a variety of industries participated in this dena study. There has been a great deal of analysis and discussion – among the study partners, with a particularly dedicated advisory board and many stakeholders from politics and civil society. Together with the scientific experts and the employees of dena, more than 250 people were involved. I would like to thank you all very much for this extraordinary commitment and excellent work.

Our common goal was to identify the best possible transformation paths to achieve the climate targets and to facilitate them via practical advice and a recommended course of action. At the same time, we wanted to consider the market knowledge and competencies of all those who must, in the end, shape these transformation processes with their companies.

The work was worth it. We can confidently say that this study project sets new standards for the energy and climate policy discourse. It can be required reading for all those who work on the necessary measures to achieve the targets in the various commissions appointed by the Federal Government.

Over the course of the 18 months, the participants have realised: The integrated energy transition involves much more than linking sectors. It revolves around the complex interaction of various infrastructures and markets, customer behaviour, regulatory framework, and a variety of new technologies and business models that go beyond each sector. This also means: We must say goodbye to some rather simple ideas from the past. The energy transition must be fundamentally rethought, especially regarding the current political framework.

The energy transition and climate protection are development projects that offer a multitude of opportunities and new possibilities. But there are also many difficulties that must be overcome and that cannot be ignored. Achieving the targets is anything but a self-propelling success. On the contrary: If we do not finally pick up new momentum in Germany, we face failure. Then other countries will take advantage of the opportunities. And we will still have to cope with the structural change, because energy transition and climate protection have long been a global field of action.

We do not want to use the dena study to say: This is the one right way to manage the energy transition. The task is far too complex for a single study project – no matter how good it may be – to provide the one and only possible solution. However, by selecting the scenarios and pursuing our innovative systemic approach, we are able to provide new guidance and a useful foundation for future discussions and decisions.

This study can be the basis to realign the political settings for the energy transition and climate protection. We will follow the path before us with intent and energetically insert ourselves into the discussion. And to all those who have to make important decisions in the future, let me say: It will not work without courage and determination. And no, we must also not be careless. But with the right dose of judgment, we can achieve a lot. I am convinced of that.

Sincerely yours,

**Andreas Kuhlmann**
Chief Executive
Deutsche Energie-Agentur (dena)
German Energy Agency

# Executive Summary

## The dena study combines energy industry analyses with a comprehensive discourse

The dena Study Integrated Energy Transition develops and compares transformation paths for the energy system in Germany to achieve the climate policy targets of the German government by 2050. It outlines paths using an innovative, cross-sectoral scenario approach. At the same time, it builds on the deep industry knowledge of more than 60 study partners from all relevant sectors as well as on the continuous exchange with key players from politics, society and science. The aim is to review and supplement energy industry analyses with assessments of implementation challenges and social issues.

## With increased efforts in all sectors, the Paris targets can be achieved

Generally speaking, it is possible to reduce greenhouse gas emissions by 80 per cent as well as by 95 per cent by 2050. However, this requires significantly more far-reaching measures in all sectors than previously planned with a high degree of commitment from all participants, an appropriate political framework, as well as a public discussion on the distribution of the costs of the energy transition. It's not enough to simply keep doing what we are doing. Even rigorously pursuing current developments, such as expanding renewable energy, would only reduce greenhouse gas emissions by 62 per cent by the year 2050. Since the possible transformation paths and associated reduction of greenhouse gases in the sectors already clearly differ in 2030 and the upper edge of the corridor requires very far-reaching strategies, a decision on the climate protection targets sought must be made in this legislative period. This is the only way to foster the development and widespread market introduction of the necessary new technologies in the individual sectors in a timely manner.

## A broad mix of energy sources enables more cost-effective and robust transformation paths

The transformation paths explored in the dena study assuming a broad mix of technologies and energy sources are under the assumptions made more cost-effective by up to €600 billion until 2050 than those that focus more heavily on electricity-based applications. The use of existing energy infrastructures in their diversity allows these transformation paths more flexible approaches to solutions paths, such as capitalising on technological developments by 2050 that cannot yet be foreseen.

## The expansion and integration of renewable energies must be accelerated

Until 2050, an expansion of renewable power generation capacities averaging up to 8.5 gigawatts annually (GW/a) is required. In order to make this possible, the existing expansion corridor must be enlarged and availability of the necessary land areas has to be ensured by the federal states. The further development of the market design and grid regulation is the basis for optimally integrating renewable energys into the system on a regional and national level.

## Synthetic renewable energy carriers complement energy efficiency and the expansion of renewable power generation

The reduction of final energy consumption through comprehensive energy efficiency efforts in all sectors (efficiency gains in industry alone 26 to 33 per cent until 2050) as well as the expansion of renewable energy are two key facts to achieve the climate targets. The third decisive factor is the use of synthetic renewable energy carriers, most of which are imported into Germany. In 2050, these energy carriers will cover between 150 and 900 TWh/a in all areas of application where cutting emissions by using renewable electricity directly is either impossible or very difficult. At the same time, these 'Green Power Fuels' close gaps that could arise in the future due to implementation obstacles (such as acceptance for new wind turbines).

## A reliable planning horizon turns the necessary structural change into an opportunity to modernise

In addition to the much-discussed changes in the coal industry, the structural change associated with the transformation will also affect many other sectors and industries in the future. For example, ambitious climate targets might fundamentally change the highly integrated value-added network of the basic chemical material industry. In the automotive industry, the change in propulsion technologies will not only affect the major vehicle manufacturers, but also a large number of small and medium-sized suppliers.

It therefore requires a political framework that provides longterm reliable incentives for reducing carbon emissions and enables a marketbased innovative optimisation across sector boundaries that is open to a range of technologies. The necessary policy decisions on energy infrastructures must be made in good time, to, for example, further develop the gas infrastructure or to build an infrastructure for hybrid trolley trucks.

## Building stock and energy sector require the highest investments

A successful energy transition will require continued high investments by all building owners over the next three decades when it comes to refurbishing their building stock, along with increasing the refurbishment rate from 1.0 to at least 1.4 per cent.Stimulating and consolidating this investment dynamics requires a carefully selected mix of incentive-focussed instruments, which emphasise stimulus over compulsory regulations, must be constantly reviewed and, if necessary, adapted.

Extensive balancing effects within Germany and the European integrated grid will be required for an efficient electricity system with very high proportions of renewable energy sources. In order to achieve this, investments must be made in the transmission and distribution grids beyond the existing network development plan by 2030. In addition to the continuous expansion of renewable power generation, new investments in gas-fired power plants are needed in alignment with neighbouring European countries. They ensure security of supply when the secured capacity from nuclear power plants is no longer available and the secured capacity from coal-fired power plants is only available to a limited extent.

## The energy transition in transport is based on several pillars

The electrification of propulsion technologies is a major driver of the energy transition in the transport sector – but it is not alone. A major factor is the reduction of the specific energy consumption of transport in order to reduce total energy consumption and significantly increase the proportion of renewable energy in the transport sector. Electricity as well as gaseous and liquid fuels must be 100 per cent based on renewable energy sources in the future. At the same time, new mobility strategies are needed to curb the further increase in traffic and, at best, reduce traffic altogether. Overall, the transport, energy and IT infrastructures must be planned in a much more integrated manner across the sectors and the fee and taxation systems must be aligned with the energy transition targets.

## A successful energy transition is embedded in international developments

A sustainable energy system in Germany requires balancing possibilities of a further-developed common European electricity market, an international trade for synthetic renewable energy carriers (Power Fuels) and a further decrease in cost of key energy transition technologies due to global demand.

The energy transition can only succeed if it is also a success in terms of industrial and economic policy. On the one hand, this requires instruments to protect German industry from competitive disadvantages due to German climate protection requirements (carbon leakage protection), which are higher than in other countries, and international agreements for global trade. On the other hand, the growing global demand for energy transition technologies also offers export opportunities for the German companies.

## Leeway to make decisions and participation promote social acceptance

The next phase of the energy transition will affect citizens more than today – through distribution issues of energy transition costs as well as structural changes and how they affect each person’s own working and living environment. They are challenged to muster the necessary private investments as well as to accept and accelerate the changes with energy applications, such as in the field of mobility. Politicians now face the task of continuously tracking and highlighting the opportunities of the large-scale energy transition project. Citizens themselves need sufficient leeway to take action as well as participate and design options for their investment decisions.

# 1. The integrated energy transition as a holistic approach

The dena study examines the guiding concept of the integrated energy transition. The integrated energy transition refers to how the various technical facilities, infrastructures and markets from the energy, industry, building and transport sectors are coordinated and integrated into an optimised and intelligent energy system. This integration takes place in balance between the local, regional and supra-regional levels. In addition, markets and infrastructures must be considered together and brought into harmony.

The dena study pursues a holistic view of the energy system and a socially broad dialogue via realistic transformation paths under this guiding concept.

## Sectors in transition and with increasingly indistinct borders

Each sector is characterised by its own features and framework: The specific technologies, infrastructures and markets are synchronised and optimised within the respective sector. Legal framework conditions have grown over decades along with the sectors, shaping them. Business models and value chains have developed specific to each sector. Customer requirements and expectations vary by sector and are influenced by different sociological factors. All this contributes to making each sector work differently.

The energy transition is causing new, strong forces of change to affect the structures that have developed. The expansion of renewables, especially in the electricity sector, increases the need for flexibility in the system. Production is no longer determined solely by consumption; consumption also responds to fluctuations in production. Those who adapt their electricity demand to the situation in the electricity grid can turn their flexibility into a service – be it with a production or heat storage facility or an electric vehicle. More and more consumers also have decentralised power generating plants and can even feed energy into the system. For example, buildings are increasingly becoming units that not only consume energy, but also generate, store and deliver energy.

Digitisation makes it possible to control and coordinate different components in production and consumption – even beyond the borders of your own company or house. In all sectors, data on consumption patterns can provide the basis for new business models. Algorithms make it possible to intelligently control the operation of technical facilities for the benefit of their owners as well as to improve the stability and efficiency of the overall system. As a result, the traditional value chains of the energy industry are changing and new value creation networks are emerging – across sector boundaries.

The sectors as we know them are changing. Borders are becoming less rigid, interactions are increasing. The term 'sector coupling' therefore fails to paint the whole picture. It gives the impression that the idea is to connect existing, self-contained units. But the idea is more about integrating the growing number of energy system components from all the sectors into a single system, recognising interactions, taking advantage of optimisation and innovation potentials, further developing markets and infrastructures. It would therefore not be enough to tackle the challenges from the perspective of the individual sectors. Achieving the climate targets requires a holistic, cross-sectoral approach. And that is what the term 'integrated energy transition' stands for.

## Integration at several levels – from local to international

For a successful integrated energy transition, every level of action is important: from individual energy production, conversion and storage facilities, to consumption systems, all the way to buildings and local areas. From the city to the regional level and the supra-regional balance to the national energy system and its integration into international markets and structures. There are already many points of reference here, which are essential for achieving the climate targets. Thus, local cooperative agreements between companies or a district management body can help implement small-scale but important aspects of the integrated energy transition. There is also great potential at the regional level, for instance cities working together with their surrounding rural areas to use renewable energy.

The consideration of the many possible course of action is already complex at the national level. However, the integrated energy transition must also take into account the European and global levels. The European energy markets are interconnected. Their interdependencies are likely to increase rather than decrease as the EU energy market continues to develop. These European energy markets and infrastructures, as well as the global markets and trade relations, offer special opportunities for the successful implementation of the energy transition via the favourable availability of renewable energy and the provision of balancing effects, as well as the joint approach to improving security of supply.

Furthermore, global developments cannot be ignored. Important parameters that affect this include the competitiveness of industry or simply technological developments.

## The integrated optimisation of the market and the grid

The integrated energy transition requires, in particular, the optimisation of the markets and infrastructures. For example, with the further renewable energy expansion, the necessary transport infrastructure must also be available. As the different sectors continue to merge, their previously separate markets will also increasingly converge. Infrastructures must be optimally designed so that all sectors can make best use of the structures and energy carriers they need.

Thus, the integrated energy transition connects much more than separate sectors and energy infrastructures. It also connects various levels of action – from local to national and European to global. And it connects the stakeholders active in all these sectors and at all these levels, often giving them new roles. This also creates a variety of possibilities and opportunities for new business models.

## Interactions in the integrated energy system

A holistic view of the energy system reveals complex interactions. This can be seen in the example of the increasing electrification in all sectors. Renewable energy capacities can be most significantly expanded in the electricity system, where wind and solar power plants play the starring role. This electricity should be used as efficiently as possible. Electricity-based applications are increasing, such as in the form of electric arc furnaces or various electrolysis-based processes in industry, heat pumps in buildings and electric vehicles in transport. But electrification is also reaching its limits. It is not possible to electrify every industrial process. The refurbishment demand for buildings is also increasing, because heat pumps operate at low supply temperatures and small differences in temperature; for efficient operation, it is therefore important that the building envelope has a high thermal quality.

In the transport sector, there are major challenges in long-distance freight transport as well as in shipping and air traffic. This raises many questions about the use and relationship of electricity, gaseous and liquid energy carriers in the energy system of the future.

Technically, it would be possible to electrify trucks using overhead lines. But is it worthwhile to develop this electrification infrastructure in the transport sector? How sensible is it to propose more ambitious building refurbishment rate targets when we have fallen short of the previous target level for years? How and where must the energy system be developed to meet the additional demand for electricity? How does the system react in extreme situations, such as the annual peak load, i.e. the highest demand in the year, or the 'dark doldrums' when hardly any wind or solar power is available? What is meant by the term 'dark doldrums' and how long will it take for the system to be safeguarded against it? How will the infrastructures for gaseous or liquid energy carriers develop if their utilisation changes? And would it be more practical, less expensive, and more useful for the stability of the system in some cases to use renewable electricity to produce synthetic renewable energy carriers rather than directly? These and other questions are explored in various scenarios in the dena study.

## Social acceptance as a target factor

In addition to the goal of the most efficient and environmentally friendly use of energy, other factors come into play: economic costs, security of supply and, last but not least, social acceptance. There are currently objections to the construction of wind turbines or electricity transmission lines. The willingness or ability to invest in new, energy-efficient technology is not self-evident among companies, municipalities and private citizens, although investments in energy efficiency – be it the modernisation of a production plant, the refurbishment of a building or the purchase of an energy-saving household appliance or vehicle – usually pay off sooner or later thanks to the energy cost savings. This has considerable implications for the feasibility of individual transformation paths. The dena study therefore considers social acceptance as the fourth target factor alongside the established target factors of security of supply, economic efficiency and environmental sustainability.

## Integrated energy transition in dialogue

The starting point, requirements and opportunities must be optimised on different levels for the holistic approach of the integrated energy transition. This leads to many dependencies and a very high level of complexity. Evaluations from the point of view of a single sector or a single industry are not enough. A cognitive process in the interdisciplinary, cross-sectoral discourse and great openness to future developments are required. Due to the high dynamism of the energy transition, it is important that all parties react flexibly to mindset and process changes. The dena study is itself an example of just such a broad dialogue in which industry experts are prepared to learn from each other, beyond the borders of their own industry and sector, and to bear the system in mind while they view things from their own perspective. It is not a pure research and study project. It consciously builds on the industry knowledge of more than 60 study partners from every relevant sector and continuous dialogue with stakeholders from politics, society and science. The preparation of the results and ideas has been designed to further stimulate discussions as much as possible.

## Scenario analyses rather than optimisation analyses

The dialogue-oriented approach of the dena study also includes the discussion of various transformation paths as possible course of action. The quantitative analyses performed are not comprehensive optimisation analyses in which all supply and demand side features are mapped in a mathematical model and the mutual interactions of balancing structures are optimised to a specific target point.

The provision was not to determine the one optimal way to successfully implement the energy transition and describe it in detail as a roadmap for politics and industry. On the contrary, the dena study consists of a scenario analysis. From the outset, fundamental scenarios were agreed upon with the partners and then, for each study module, specific transformation paths were developed to meet the scenario requirements and achieve the related climate targets. These paths were used to analyse which applications, technologies and energy sources can be used to achieve the climate targets. This approach made it possible to optimally integrate the expertise of the study and module partners and develop transformation paths that would be considered feasible.

## System boundaries of the dena study

The dena study pursues a holistic approach, but it is, of course, not possible to fully examine every aspect. As with any study, it is important to know and name the system boundaries. Only then the statements made can be understood and assigned to proper meaning. And, at the same time, this makes it possible to deduce which questions require subsequent, more far-reaching studies.

All greenhouse gas emissions are balanced according to the so-called 'source principle' in the dena study – as is internationally customary and is the case in the 'Federal Government's Climate Action Plan 2050', for instance. The source principle allocates emissions to the place where they are generated. Thus, the emissions generated within the national (i.e. territorial) borders of Germany are balanced in the context of our study. Furthermore, emissions are allocated to the sector where the combustion and thus the release of greenhouse gases takes place.
The more integrated the energy system and connected the sectors, the more debatable it is that the source principle fulfils its purpose. An example is imported fuels that are synthetically produced from renewable energy sources using carbon from the air or from exhaust gases. Deviating from the source principle, emissions from the combustion of such imported Green Power Fuels are considered to be climate-neutral in the dena study, since this is an example of a carbon cycle: The emissions generated by the combustion were previously extracted from the atmosphere at another location. Consequently, synthetic fuels with a $CO_2$ factor of zero are included in the national carbon balance.

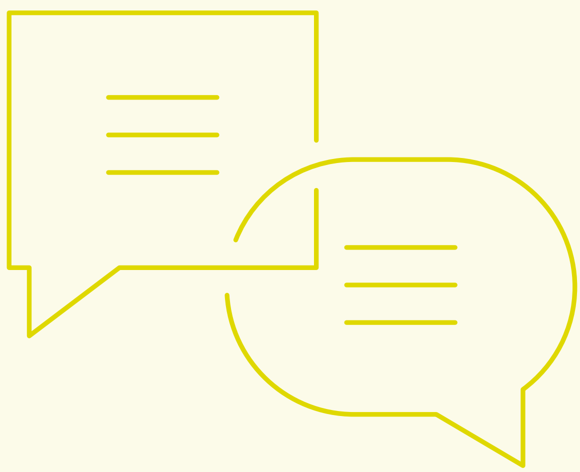
The study is also importantly limited regarding possible statements on the costs of the energy transition. It examined the additional costs of various transformation paths in the sector of energy generation and in the energy-consuming sectors to achieve the climate targets compared to a reference scenario whereby the targets were not achieved. It was possible to evaluate and compare the transformation paths on this basis, but not to make any statements about the cost optimisation of the overall system.

It was also not possible to realistically estimate investments in the industrial sector in the context of the dena study. On the one hand, facilities in the industrial sector are usually very individually designed, which makes it difficult to determine standard investment costs. On the other hand, some of the technologies have not yet been developed or their further development is fraught with uncertainty.

It is therefore not possible to make a scientifically founded declaration on the necessary investment costs. Nor can the study make any statements about the positive economic effects of a successful energy transition, such as how many jobs the investments will create, how the added value of German industry will develop, or which subsequent costs for people and the environment will be avoided.

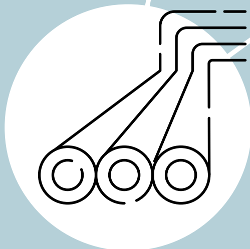
All the calculated costs for the transformation of the energy system were considered from an economic perspective. It was not examined whether measures are worthwhile from a microeconomic perspective and what redistribution effects will arise. Further studies must follow to evaluate the transformation paths along with their societal and macroeconomic effects. This would then make it possible to examine the economic implementation of the transformation and the concrete effects on citizens, especially on their housing and energy costs, but also employment effects and the domestic added value. Such a further analysis would be crucial for the successful implementation of the energy transition, which will ultimately be executed by individual stakeholders, i.e. by companies and private consumers.

The intent of the dena study is to encourage the further pursuit of the integrated energy transition approach – also and especially where further discussion and research is required. The broader and more diverse the dialogue, the more likely a joint decision will be made regarding Germany's transformation path.

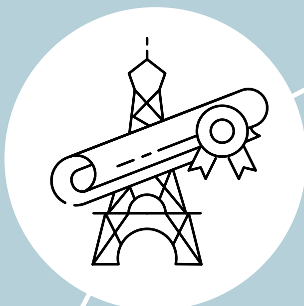


# 2. The central findings of the dena Study Integrated Energy Transition

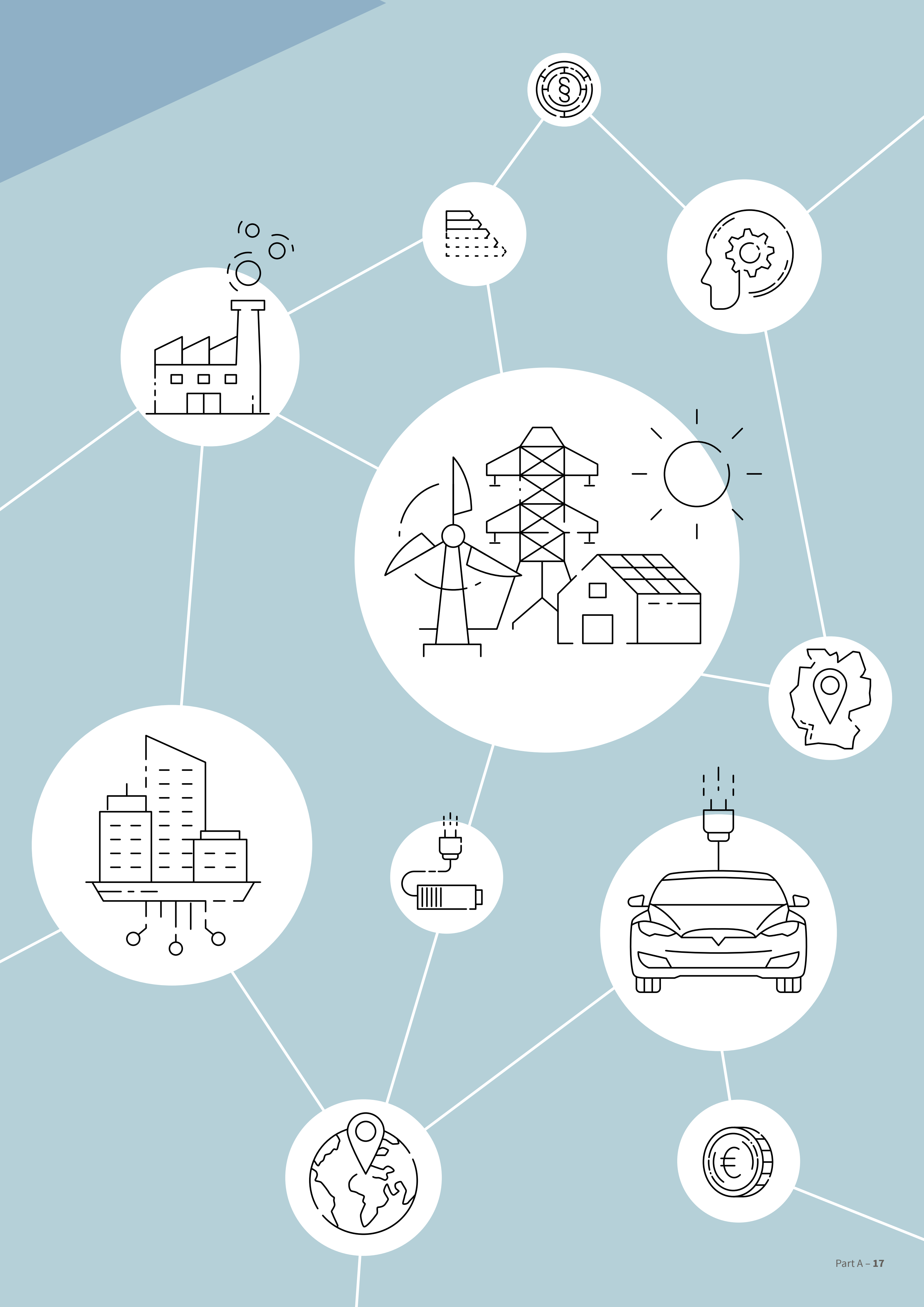
1. Which regulatory framework and investments does an integrated energy transition require?
2. How and when do the transformation paths diverge from each other as well as with regard to the 80 and 95 per cent climate targets?
3. What role does energy efficiency play in achieving the climate targets?



4. What can and must be the contribution of renewable energy expansion in Germany?
5. What is the significance of synthetic renewable energy carriers and raw materials?
6. How do we ensure security of supply and meet demand, even during the 'dark doldrums'?
7. How will the energy infrastructure change?
8. Which parameters influence the energy transition in transport?
9. How can buildings become more energy-efficient and climate-friendly?



10. What changes can be expected in the industrial sector?
11. How must development in Germany be embedded in the international energy transition?



## The central findings of the dena Study Integrated Energy Transition

Germany has set itself the goal of reducing its national greenhouse gas emissions by 80 to 95 per cent by 2050 compared to 1990. At the same time, Germany is one of the signatories of the Paris Agreement, which aims to limit global warming to well below 2°C above the pre-industrial levels, preferably 1.5°C.

The aim of the dena Study Integrated Energy Transition is, together with the expertise of more than 60 study partners from many relevant industries, to develop realistic transformation paths to reach the target corridor for 2050 and have them evaluated by scientific experts in a cross-sector energy industry model.

For this purpose, four scenarios which had the aim of achieving the German climate targets by 2050 were examined in two groups. Furthermore, a reference scenario with no specified climate targets was modelled as a basis for comparison.

This chapter summarises the key findings of the dena study in '11 questions on the energy transition'. They present the discourse, which is very intense – and in part controversial – on the individual topics that dena moderated among the group of study partners as well as in continuous exchange with other key stakeholders from politics, society and science. In addition, each question gives rise to a concrete recommended course of action that, according to dena and the study partners, are necessary for the successful implementation of the energy transition.

## The climate target scenarios: Electrification and technology mix, each with a climate target of 80 or 95 per cent

They describe the way toward a new, climate-friendly energy system where greenhouse gas emissions will be reduced by 80 or 95 per cent by 2050 compared to 1990 across all sectors.

### Reference scenario (RF)

The reference scenario (RF) was modelled as a comparison with no specified climate targets. It assumes a continuation of current political and technological developments up to 2050, albeit at a quite ambitious level. It makes moderate assumptions regarding carbon certificate prices. No greenhouse gas reduction target is specified in the scenario.

## Electrification scenario (EL80)

### with 80 per cent climate target

The electrification scenario with an 80 per cent climate target assumes an increase in energy efficiency and widespread electrification in every sector, resulting in a significant increase in electricity demand. Synthetically generated renewable energy carriers are taken into account when they become mandatory. The scenario is analysed with a view toward the target of reducing greenhouse gases by 80 per cent compared to 1990.

## Electrification scenario (EL95)

### with 95 per cent climate target

The electrification scenario with a 95 per cent climate target assumes an increase in energy efficiency and widespread electrification in every sector, resulting in an even greater increase in electricity demand. Synthetically generated renewable energy carriers are taken into account when they become mandatory. The scenario is analysed with a view toward the target of reducing greenhouse gases by 95 per cent compared to 1990.

## Technology mix scenario (TM80)

### with 80 per cent climate target

The technology mix scenario with 80 per cent climate target also presupposes an increase in energy efficiency, but deliberately allows for wider diversity in the technologies and energy sources used. In the model, this scenario is analysed with a view toward reducing greenhouse gases by 80 per cent compared to 1990.

## Technology mix scenario (TM95)

### with 95 per cent climate target

The technology mix scenario with 95 per cent climate target also relies on an increase in energy efficiency, but deliberately allows for wider diversity in the technologies and energy sources used. In the model, this scenario is analysed with a view toward reducing greenhouse gases by 95 per cent compared to 1990.


# 2.1
# Which regulatory framework and investments does an integrated energy transition require?

The energy transition is an incredibly complex project with enormous implications that affect all of society. This is particularly evident in the current legal framework and its specific regulations. It is characterised by a multitude of individual measures, which are continuously improved and refined. However, this practice of continuously correcting details does not provide sufficient stimulus to achieve the Federal Government's energy and climate protection targets. Achieving those targets requires a broader, sustainable political strategy.

## Guarantee technology mix and planning security

The dena study shows that the future cross-sectoral energy system should be based on a broad mix of energy sources and technologies. This would allow the climate targets to be achieved via more realistic transformation paths with greater overall economic benefits. Which in turn requires a regulatory framework that guarantees openness to a range of technologies and promotes innovation.

The investment cycles for developing new technologies vary widely by industry and may span two to three decades for new industrial process and manufacturing techniques. Economic stakeholders therefore need long-term planning security to invest in the development and market introduction of new, innovative technologies.

## Consider the international context

The success of the energy transition in Germany is heavily dependent on the international implementation of the energy transition. Firstly, the future German energy system will continue to be part of the European energy market and be closely linked to international energy markets. Energy self-sufficiency is not a goal of the energy transition. Not only does Germany need a high domestic production of renewable energy, it also requires intense power exchanges with other European countries – depending on the scenario and the year, the import balance is between −62 and +155 TWh/a[1] – and imports synthetic renewable energy carriers from other European and non-European countries range from 25 to 744 TWh/a in 2050[2].

[1] ewi Expert Report (2018), p. 211.
[2] ewi Expert Report (2018), p. 240.

Secondly, the timely and cost-effective availability of energy transition technologies depends on international markets being created for them. New technologies are not being developed solely by German companies and Germany is also not the only sales market. In order for the necessary economy of scale to be achieved, international markets for energy transition technologies must emerge.

Thirdly, industrial sectors and product categories with international competition require binding trade agreements in order to balance the climate protection requirements on companies from different countries.

## A broad mix of technologies leads to lower additional costs

The scenarios modelled in the dena study that reach the target corridor of 80 to 95 per cent less greenhouse gas emissions by 2050 require considerable additional investments compared to a reference scenario where greenhouse gas emissions are only reduced by 62 per cent. These investments, which are necessary to achieve the climate targets, create a multitude of opportunities for the companies that successfully offer the required new products and services with innovative technologies and business models. Other companies, however, would face major challenges in these scenarios.

The scenario with the lowest additional cost is the one that achieves the 80 per cent target with an energy system encompassing a broad mix of technologies – amounting to about €1.2 trillion in all by 2050[3]. The scenario with the highest additional cost (€2.2 trillion) is the one that achieves the 95 per cent target with an energy system encompassing a high degree of electricity-based applications in all sectors. An energy system with a mix of different energy sources, infrastructures and applications (including an already extensive use of electricity-based applications) is thus less expensive than a system with a particularly high proportion of electrification in all consumption sectors.

In the scenarios that achieve the climate targets, the capital cost of investing in energy efficiency and the conversion of application technologies by 2050 totalled between €1.1 and €1.9 trillion. This includes investments in building refurbishment and heating systems, in new vehicles and transport infrastructures such as charging stations and in power plants, power-to-x facilities and renewable energy plants. In addition, the costs for the further expansion of the electricity grid beyond today's plans will amount to between €80 and €110 billion at the transmission grid level and between €140 and €250 billion at the distribution grid level[4]. In the 95 per cent scenarios, the use of synthetic renewable energy carriers costs an additional €450 to €810 billion. By contrast, the cumulative additional costs dip to between €670 and €790 billion due to the reduced additional costs for primary energy as a result of increased energy efficiency[5].

The additional costs for the 80 and 95 per cent scenarios identified here only relate to energy production, including distribution and storage, as well as imports and energy use, including investments in energy efficiency and the conversion of application technologies. Implications on jobs or industrial policy effects as well as the emergence of new business models for the national or international market have not been investigated. The scenarios in the dena study, therefore, do not allow any economic conclusions to be drawn. Likewise, it is not possible to carry out individual economic assessments or make statements on the distribution of costs to citizens and social systems.

Furthermore, investment costs required by industry to specifically achieve the energy transition targets are not quantified. These additional investments would have to be allocated to every scenario and the cost difference between the technology mix and the electrification scenarios would tend to increase.

## Investment needs span all sectors

The aforementioned additional capital costs compared to the reference scenario, of between €1.1 and €1.9 trillion for a successful energy transition by 2050, illustrate the dimension of the investment needs to achieve the targets over the years. This is particularly visible in the building sector. In this sector, the additional investment required is around €450 billion in the technology mix scenarios and up to €1 trillion if the degree of electrification is high[6]. A key factor is the annual refurbishment rate, which varies from 1.4 per cent in the technology mix scenarios to around 2 per cent in the electrification scenarios. Taking into account every sector, the average additional investment required per year is up to €30 billion in the most favourable scenario and up to €50 billion in the most investment-intensive scenario.

[3] ewi Expert Report (2018), p. 244.
[4] ewi Expert Report (2018), p. 217 et seq.
[5] ewi Expert Report (2018), p. 246.

## Citizens play an important role as partners and investors

Regardless of the chosen transformation path, it is important to review the social and economic impact. The energy transition requires a high level of investment and brings with it profound and visible changes, such as the significant expansion of renewable energy plants or a changed mobility. Citizens should, therefore, be more involved in shaping the energy transition. Their investments in the energy, building and transport sectors will be decisive in determining whether the climate targets can be achieved. Citizens are more than just the addressees of energy policies; they are also important partners and investors of the energy transition.

## Guarantee support for the energy transition

There is a broad social consensus in Germany about the need for global climate protection and the targets of the energy transition. Nevertheless, it is important to continually point out the significance of the energy transition for society as a whole. The long-term individual and societal benefits and the associated opportunities are great. A society that is aware of these advantages and opportunities will be able to tackle the upcoming transformation more decisively.

## Recommended course of action

- **Provide framework for reducing $CO_2$:** Policy-makers should provide a reliable regulatory foundation geared toward reducing $CO_2$-emissions, preferably at the European or global level.

- **Reorganise the system of fees, charges and levies:** Before the end of this legislative term, the Federal Government should redesign the system of fees, charges and levies in the context of an integrated energy transition. The goal must be a level playing field that eliminates distortions between energy sources and sectors and enables innovation. Related to this, grid and system-friendly behaviour on behalf of producers and consumers should be promoted.

- **Prevent market failures:** The Federal Government should introduce specific instruments in sectors where the overarching regulatory framework encompassing market orientation and openness to a range of technologies is insufficient to trigger the desired development. This applies, for example, to the use of energy-efficient technologies as well as timely research and the market introduction of the technologies necessary for the success of the energy transition in the long term.

- **Strengthen protection against carbon leakage:** German industry should not be at a disadvantage in global trade due to the energy transition. Therefore, the Federal Government should ensure sufficient room to manoeuvre at the national level in the planned revision of the EU's state aid legislation.

- **Enable financial participation for citizens:** There should be political incentives to increase the investment dynamic in industry and from private households. The Federal Government should examine how citizens can invest even more in the energy transition and benefit from it.

[6] ewi Expert Report (2018), p. 248.

# 2.2 How and when do the transformation paths diverge from each other as well as with regard to the 80 and 95 per cent climate targets?

The transformation paths modelled in the dena study vary significantly by 2030. Not only do the paths differ depending on whether a scenario is based on a mix of technologies or electrification, in the following years, it is particularly decisive whether an 80 or 95 per cent reduction of greenhouse gas emissions is sought.

However, both targets require immediate action. Therefore, it should be decided which greenhouse gas reduction target is to be pursued before the end of this legislative term.

## All political climate targets require considerable effort and commitment

A future projection of current developments on the basis of the existing regulatory framework and political decisions already made only yields a 62 per cent reduction of greenhouse gases[7] by 2050. Both the 80 per cent target and the 95 per cent target can, in principle, be achieved. However, this is only possible with more far-reaching measures in every sector, an intensification of the commitment of all participants and an appropriate policy framework. This requires further investigation.

There is currently no consensus on whether an 80 or 95 per cent reduction of greenhouse gases should be achieved as a binding climate target – the convictions of various stakeholders from industry and civil society are as diverse as those held by stakeholders within the Federal Government.

From today's perspective, achieving the upper climate target corridor is associated with significantly greater efforts and higher economic costs than the 80 per cent target. For instance, the 95 per cent target requires that the energy, building and transport sectors become completely carbon neutral by using renewable energy carriers and improving potential for efficiency. Compared to the 80 per cent target, even more renewable energy sources, greater efficiency efforts and significantly higher quantities of synthetic renewable energy carriers are needed. Taking into account foreseeable technical innovations in emission-intensive processes, carbon emissions in the industrial sector will still total 16 million tonnes in 2050[8]. From today's perspective, these emissions can only be avoided by implementing Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU). At the same time, the climate target set in Paris probably requires a national target closer to the top of the described corridor.

Thus, the study results show that a transformation path towards the 95 per cent target cannot simply be an extension of the path to the 80 per cent target. It requires quite different approach strategies and technologies starting today, in addition to the measures to reach the 80 per cent target. Long-term planning security is necessary, especially for long-term investment decisions, for example for large industrial plants with several decades of service lifetime. Companies must be able to assess whether investment in current technologies will still lead to achieving the climate targets, or whether it will impede or hinder future necessary adjustments to achieve the upper range of the target corridor (lock-in).

[7] ewi Expert Report (2018), p. 183.
[8] ewi Expert Report (2018), p. 187.

In the current climate protection debate, the focus is primarily on the issue of coal-fired power generation. Coal-fired power generation continuously decreases up to 2050 in all the climate target scenarios in the dena study, although a coal phase-out was not explicitly assumed in the scenarios.

## Broad mix of technologies offers advantages

The decision on a 2050 climate target will create major differences, as will the orientation of the transformation paths. Depending on whether final energy applications are largely based on electricity or a broader mix of technologies, developments in the individual sectors will already differ greatly as early as 2030.

As a result, scenarios with a broader mix of technologies by 2050 cost significantly less and are more robust in the face of implementation challenges, such as acceptance. However, it was not possible to take into account further macroeconomic effects of the paths, such as employment effects or domestic added value, in the dena study. It is not possible to predetermine a detailed optimal transformation path of the energy system. Therefore, the regulatory framework should be designed in an open way so that various technologies and energy sources can join the competition for achieving the energy and climate policy targets as efficiently as possible.

All the scenarios have one thing in common: The far-reaching or complete phase-out of fossil fuels as primary energy carriers is indispensable. Competition between systems is needed to find the best technological innovations to achieve the energy policy targets.

## Intermediate targets are important to respect the overall budget of greenhouse gas emissions

The Paris Agreement not only defines a reduction target for greenhouse gas emissions in 2050 compared to 1990, but also a total amount of greenhouse gas emissions that may be emitted by 2050. It is important that the technologies and infrastructures required in the future be initiated at an early stage. This will make it possible to develop know-how, benefit from economies of scale and prevent any ‘kinks’ or ‘jumps’ in the transformation paths, i.e. particularly significant changes in technologies or applications within a short time. Nevertheless, it is important not to lose sight of additional innovations.

Achieving the climate targets in 2050 is important, but so are the savings along the way. For instance, the Federal Government’s climate targets include reducing greenhouse gas emissions by 55 per cent in all sectors by 2030 and by 70 per cent by 2040. In order to respect the overall budget, it is necessary to closely control the achievement of the intermediate targets via constant monitoring.

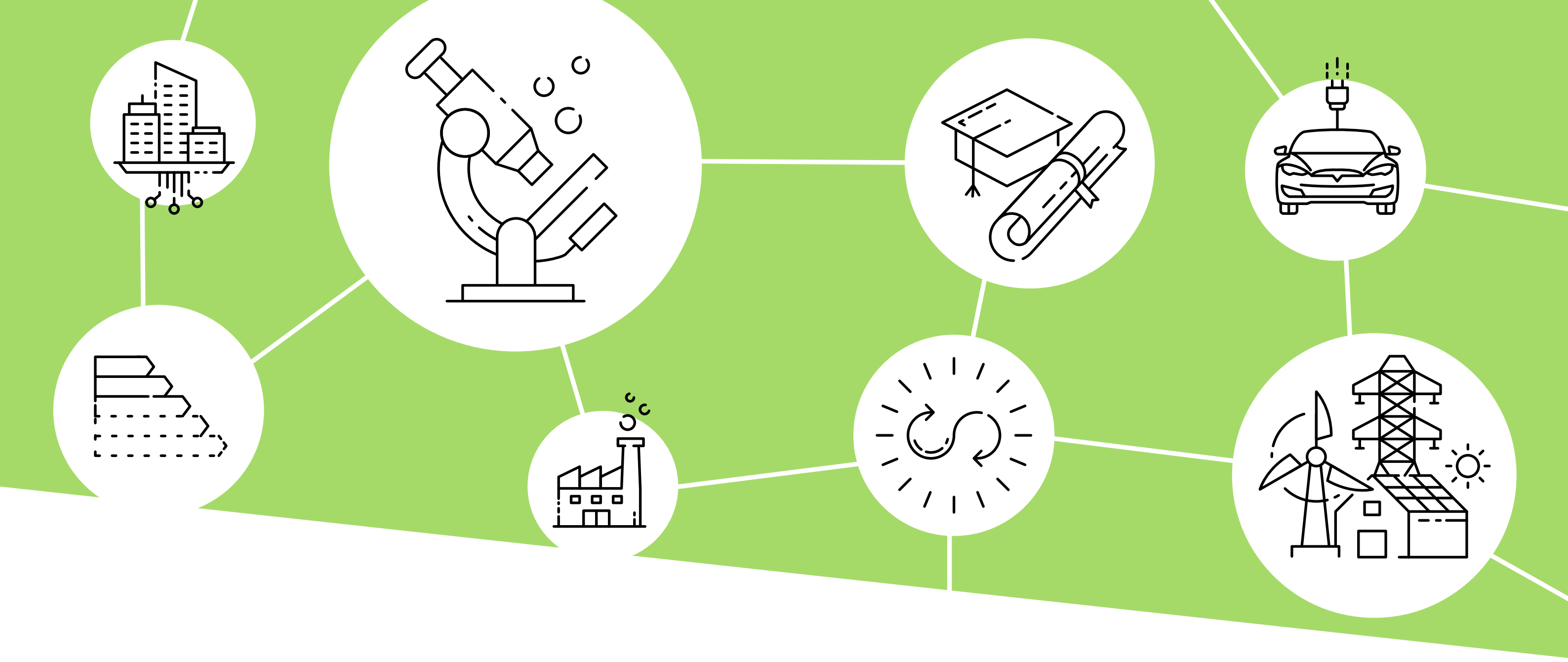
In order to reach the upper corridor of the climate targets, a higher intermediate target would have to be set for 2040 so the necessary emission reductions are distributed more evenly over the years, avoiding unrealistic jumps. In the dena study, an intermediate target of 75 per cent in 2040 was therefore introduced for the transformation path to reach the 95 per cent target.

## Recommended course of action

- **Make a decision about the target corridor:** Based on an intensive dialogue with industry and society, the Federal Government should make a political decision before the end of this legislative term on the basis of a broad consensus as to which end of the (too broad) target corridor, ranging from an 80 to a 95 per cent reduction of emissions, should be pursued. Based on this decision, the transformation paths will differ significantly.

- **Research and develop climate protection technologies:** The Federal and State Governments should encourage stakeholders from companies and science to research, develop, and launch climate protection technologies on the market in a timely and sufficient manner. Innovation cycles take two to three decades in some industries. Innovative technologies are the prerequisite for achieving ambitious climate targets. This will also allow Germany to create the basis for benefiting from the international implementation of climate protection.

- **Control the reduction of greenhouse gas emissions:** The Federal Government should use sector-specific guidelines and monitoring to evaluate how the reduction of greenhouse gases is progressing. This will make it possible to ensure that each sector fulfils its responsibilities. However, these guidelines should not be too rigid; they must provide room to manoeuvre and allow for optimisation possibilities, for example by including the reduction of emissions across all sectors. This is especially true for the 2030 targets for individual sectors.



# 2.3 What role does energy efficiency play in achieving the climate targets?

An ambitious energy efficiency strategy and a reduction in final energy consumption in Germany are absolutely necessary in order to achieve the energy transition targets and the economic policy targets to reduce dependence on imports and energy prices. For an integrated energy transition, the energy efficiency strategy must be designed so that, from a microeconomic perspective, there is sufficient freedom to enable a reduction of emissions and optimisations that transcend system boundaries and value chains.

## Energy efficiency is a prerequisite for climate protection and economic growth

Energy and resource efficiency, as well as strengthening the circular economy, can counteract trends to increase energy consumption through economic growth and increasing consumption. The investigations of the dena study assume an overall economic growth of 1.0 per cent per year. Depending on the scenario, this would result in the industrial sector consuming between 1,000 and 1,100 TWh/a in 2050. Depending on the scenario, it is assumed that energy efficiency in the industrial sector will increase by 0.85 to 1.12 per cent per year. It will be possible to limit energy consumption to between 670 and 840 TWh/a in 2050. This corresponds to a 26 to 33 per cent reduction.

In the building sector, energy consumption decreases by 47 to 64 per cent. The demand for energy in the transport sector can also be reduced by 43 to 52 per cent despite rising transport demand. This is partly due to the high degree of electrification, but also to the increased energy efficiency of vehicles.

Only a sufficient increase in energy efficiency will allow the energy transition to be implemented in the overall system as cost-effectively as possible. The targets for the renewable energy expansion in Germany will be even more accessible if absolute energy consumption is reduced. Energy production capacities and energy imports can be reduced. The security of supply is also increasing. After all, 'energy efficiency made in Germany' is a global future market for industry and offers advantages for the competitiveness and innovation of the German economy.

## So far the energy efficiency targets will not be reached

The previous increases in energy efficiency remain well behind the target values. The Federal Government's energy concept involves an annual increase of 2 per cent. However, it is actually only about 1 per cent. This trend is likely to continue, causing the efficiency gap to widen. Without a course correction, it will not be possible to achieve the other targets of the energy transition. Without doubt, the later the course correction is made, the more complex the implementation will be.

The technical potential for energy efficiency through technical progress and digitisation often amount to well over 50 per cent of energy consumption. The implementation of the most profitable energy efficiency measures would already reduce energy consumption in Germany by 10 to 20 per cent.

## Energy efficiency must be assessed more systemically

Energy efficiency must be considered more systemically. For instance, a directly electrical or electricity-based application may be more efficient on its own. However, it may lead to greater burdens because national land potential needs to be more fully exploited or more storage or reserve capacity must be developed so the necessary electricity is available at all times. A more systemic view can create the necessary balance between energy efficiency on the one hand and, on the other hand, aspects such as flexibility or resource efficiency. This must be reflected in policy instruments as well as in practice, such as in energy consultant training. There should also be a stronger focus on rebound effects. Otherwise, it's too likely that the desired savings will not be achieved despite energy efficiency measures.

## Recommended course of action

- **Control and adjust energy efficiency strategies:** Within the framework of the planned 'Energy Efficiency White Paper' process, the Federal Government should review the existing energy efficiency strategy and all its individual instruments. Important aspects include the achievement of targets, effectiveness, cost-benefit ratio (efficiency) and the promotion of the market and know-how. The development of energy efficiency should be continuously monitored and, if necessary, should be followed up with more powerful instruments. The following points are crucial:
    - Energy efficiency policy should be further developed to support and promote systemic optimisation across sectors, energy sources and value chains.
    - The system of taxes, charges and levies should be redesigned to make more efficient measures economically viable.
    - The instruments should cover the entire chain of activities from initial information and motivation to consulting and the development of measures to financing, implementation support and evaluation or follow-up.
    - Individual freedom of decision and action should remain unchanged with a balanced mix of regulatory law and incentive policy. For example, minimum requirements for providers and the strengthening of transparency and incentives are preferable to requiring an implementation from all end users.
    - The possibilities of digitisation and innovative solutions for unlocking the potential for energy efficiency should be more systematically used.
    - Framework conditions must be created that steer market-oriented investment decisions toward energy efficiency.
- **Strengthen energy efficiency research:** In the context of designing the future energy research programme, the Federal Government should continue to study and demonstrate high-efficiency technologies, especially for system interfaces.
- **Improve training and professional development:** National and federal education ministries should develop a strategy to anchor the needs of a more far-reaching systemic perspective and integrated energy transition in training and professional development.
- **Create information services for providers:** An attractive and easily accessible central information offering and broad communication should motivate and enable all energy users to invest more in energy efficiency. These information and communication offerings should be assisted and supported by all relevant experts and multipliers.
- **Support ambitious EU standards and implement them faster:** Many energy efficiency regulations are designed and decided at the EU level, for example minimum energy efficiency standards for more and more products (EU eco-design). Germany should support the European Union in developing ambitious standards and accelerate the national implementation of these standards.

# 2.4 What can and must be the contribution of renewable energy expansion in Germany?

Alongside energy efficiency, renewable energy are the second element crucial to achieving the climate targets. In addition to the direct use of renewable energy sources in the heating sector, for example by means of solar thermal energy, the electricity in all scenarios must in particular be generated using renewable energy sources by 2050. Demand for electricity is increasing in every sector despite efficiency efforts as different processes become increasingly electrified, for example in industry or with the expansion of electromobility and electricity heat pumps.

## Onshore wind and photovoltaics must be expanded more than planned

The dena study assumes that hydroelectric power and the energetic use of biomass have no relevant expansion potential in Germany. With biomass, the debate about 'food or fuel' is currently an important factor in the societal discussion. The potential for imports is also limited[9]. At the same time, discussions with stakeholders show that it will be possible to use bioenergy more efficiently in the future. Instead of today's on-site conversion into electricity, it should be a priority to stimulate the feeding-in of biomethane into the gas grid in the future. This will allow bioenergy to be used in every sector independent of the season and the place.

The largest expansion in renewable energy plants must be in more cost-effective onshore wind farms and photovoltaic power compared to other options. The dena study anticipates the average net expansion of onshore wind will be 3.7 to 4.0 GW per year between 2015 and 2050, and of photovoltaics between 2.2 and 3.6 GW. This corresponds to a threefold increase in the 80 per cent scenarios and a fourfold increase of today's renewable electricity generation capacity in the 95 per cent scenarios[10]. The expansion of onshore wind calculated in the scenarios currently exceeds the targeted annual gross expansion of 2.5 GW/a required by law. In most scenarios, the technology will be extended to its potential limit by 2050. It is important to distinguish between gross and net expansion. Net expansion does not take into account replacement investments; it is therefore much more ambitious than the legally prescribed gross expansion.

## Expansion obstacles for onshore wind increase the importance of offshore wind in the medium term

For cost reasons, the dena study only modelled a 15 GW expansion of offshore wind farms by 2030, in accordance with current policy targets. The comparison of the different scenarios and sensitivities shows that in the years after 2030, expansion should go beyond the policy target of 15 GW if the possibility to

[9] The possibility of feeding bioenergy into the natural gas grid was already taken into account in the scenarios. Other studies – including other dena studies – assume bioenergy has more potential in Germany. It can be assumed that bioenergy can then be used at higher potentials up to its limit.
[10] ewi Expert Report (2018), p. 200.

import electricity and synthetic renewable energy carriers from abroad is reduced[11] and/or onshore wind in Germany cannot be expanded as much as is required. This could happen if expansion of onshore wind does not gain the necessary acceptance or fewer wind energy areas are available[12]. The dena study foresees an installed capacity of up to 34 GW for offshore wind for 2050, depending on the scenario[13]. Higher economies of scale with offshore wind may also increase competitiveness and lead to the greater expansion of offshore wind capacity.

## The expansion of renewables requires acceptance, space and electricity grids ...

The required high net expansion of renewable energy capacities is the same as the average level of the past five years and therefore seems feasible in principle. However, the actual implementation is a challenge. Resistance to new wind farm projects is increasing and some federal states have significantly reduced the space available for wind turbines. Existing regulations, which stipulate that the distance between a wind turbine and the nearest residential building must be at least ten times the height of the turbine, were not taken into account in the dena study. Such regulations place additional limits on the potential land available for wind energy.

The necessary continuously significant expansion of renewable energy capacities requires that the expansion of the electricity grid be significantly accelerated and that electricity grid capacity be optimally utilised. Furthermore, the various energy infrastructures and markets must be more optimally integrated from an overall system perspective.

## ... but also a regulatory framework for an intelligent system integration

Especially at the regional level and in urban areas, there is potential for the energy optimisation of the various energy infrastructures for electricity, gas and heat and for consumption-related generation, for example with roof-mounted photovoltaics. The use of decentralised flexibility such as demand side management (DSM) or an intelligent combination with storage facilities and controlled charging options for electric cars can have a positive effect on system stability and efficiency. There is also a high level of innovation and willingness to invest through local value creation networks as well as opportunities for citizens to actively participate. The right configuration could get other social strata involved, for example through tenants' electricity or district models. Market design and grid regulation must make it possible for the large-scale energy markets in Germany and Europe to use this local potential in conjunction with the economic opportunities in the best possible way.

## Recommended course of action

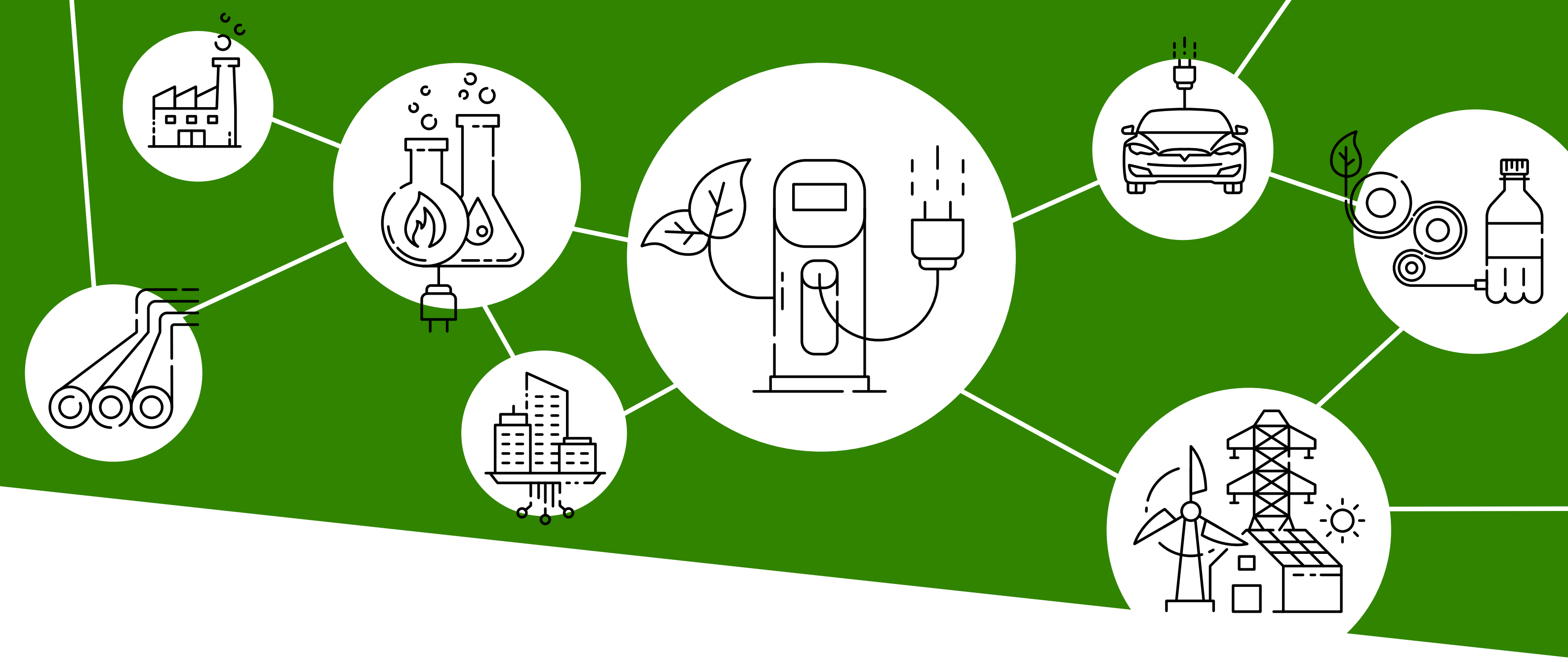
- **Extend expansion corridors:** In the course of the next amendment to the 'Renewable Energy Sources Act – Erneuerbare-Energien-Gesetz (EEG)', the Federal Government is expected to adapt the statutory expansion corridors for onshore wind and photovoltaics so the targets for 2030 and 2050 can be achieved. The targets for expanding renewable energy will differ depending on whether the 80 or 95 per cent greenhouse gas reduction target is chosen for 2050.

- **Improve spatial coordination:** In addition, to the measures to optimise the electricity grid expansion and utilisation – by examining the benefits of a more integrated analysis between electricity and gas grid infrastructure – the Federal Government should examine instruments that will make it possible to better allocate space and coordinate the expansion of renewable energy plants with the expansion of the electricity grid.

- **Provide sufficient land in the Federal States:** The Federal and State Governments should work together to ensure that there is sufficient land potential for all medium-term, long-term and statutory expansion paths for renewables in all the federal states. In doing so, they should take into account the distance regulations and designated priority areas.

- **Prepare the expansion of offshore wind:** The Federal Government should design and determine the more far-reaching strategy for the expansion of offshore wind from 2030 at least ten years in advance.

[11] ewi Expert Report (2018), p. 279.
[12] ewi Expert Report (2018), p. 278 et seq.
[13] In the case of the sensitivity analysis, with less available offshore wind potential, also up to 80 GW; see ewi Expert Report (2018), p. 279.



# 2.5
# What is the significance of synthetic renewable energy carriers and raw materials?

Energy efficiency, renewable energy sources and electrification make a decisive contribution to the energy transition in all the examined scenarios. Another key driver for achieving ambitious climate targets is synthetic renewable energy carriers (known as 'Green Power Fuels').

### Synthetic renewable energy carriers and raw materials close gaps for a successful energy transition

Synthetic renewable energy carriers (Power Fuels) can be generated via electrolysis – using renewable electricity to split water into hydrogen and oxygen. The gaseous hydrogen can be further processed in additional synthesis steps to the gaseous energy carrier methane or to liquid fuels such as liquefied natural gas (LNG) and synthetic gasoline, diesel and kerosene.

In addition to its use as an energy carrier, the synthesised substances will also be required as non-fossil raw materials for the chemical industry.

It is impossible to precisely predetermine the optimum transformation path for the energy system over the next 30 years since there are too many uncertain factors along the way. But regardless of whether we can count on increased electrification or a broader mix of technologies, the results of the dena study show that synthetic renewable energy carriers play an important role in achieving the climate targets. Demand in 2050 may reach up to 908 TWh[14]. By using the appropriate infrastructures, Power Fuels can store renewable electricity seasonally. This makes renewable energy widely available in international trade. Power Fuels will be used especially where electricity-based applications are not possible or not economical. The technologies needed for this are largely available, but require a rapid market boost, so that practical experience in the real grids, further innovations and economies of scale can be achieved.

Sensitivity calculations that examine more significant challenges and acceptance issues with regard to the implementation of the energy transition will require Power Fuels more comprehensively and earlier, even if only the lower end of the 80 per cent green house gas reduction target corridor is to be achieved by 2050.

[14] ewi Expert Report (2018), p. 237.

## Synthetic renewable energy carriers will be produced and traded internationally

According to current estimates, the bulk of the demand for synthetic renewable energy carriers in Germany in 2050 will be imported from regions such as North Africa, where production costs including transport are lower and there is more space potential compared to Germany.

Even if heavily used, the import volumes of Power Fuels in 2050 are significantly lower than the current import volumes of fossil fuels. Complete energy self-sufficiency in Germany or Europe, however, should not be sought for reasons of economic efficiency and security of supply.

Nationally, between 130 and 164 TWh/a[15] of Power Fuels will be generated in 2050 with optimised use of renewable energy feed-in peaks. In view of the assumed electrolysis capacities in the report for 2030 of 15 GW in Germany, the corresponding expansion must begin soon, especially for the generation of hydrogen for new, climate-friendly applications in the industrial and transport sectors. Because of the anticipated economy of scale with the technologies used, the market development should not be linear but, as with other technological innovations, should increase exponentially.

## Power Fuels are used in all sectors and applications

To significantly reduce greenhouse gases, Power Fuels are required in every sector. The importance of Power Fuels increases significantly in all scenarios, especially in order to achieve the 95 per cent target. The high-level use of Power Fuels requires ambitious international climate protection efforts for the successful broad international penetration of the technologies and the required imports of energy to Germany in 2050 to be realistic.

In principle, the technologies required to produce Power Fuels have existed for many decades. At up to 10 MW, the production facilities that already exist or are planned for generating Power Fuels from electricity can still be regarded as rather small. Scaling in terms of the size and number of installations is expected to lead to further technical innovations and economies of scale.

Since the use of Power Fuels has a significant influence on the design of the energy system, sensitivity calculations were used to investigate the effects of changing assumptions concerning the economies of scale in the required electrolysis and synthesis processes[16]. As a result, the scenarios open to a range of technologies remain more advantageous, even when significantly lower cost reductions for the technologies they require are assumed, as opposed to scenarios with a high proportion of electricity-based end-use applications and the necessary adjustments and investments in the consumption sectors[17].

The sensitivity study also shows that if it is not possible to import the assumed quantity of Power Fuels from outside Europe, the required Power Fuels could also be sourced from other European countries. However, it would be necessary to further investigate which potential would arise if other EU countries undertook climate protection efforts similar to the ones made in Germany.

## Liquid and gaseous synthetic renewable energy carriers are relevant

It is not possible to conclusively assess the ratio of the various synthetic energy carriers (hydrogen, methane or liquid fuels) in the various application areas on the basis of the results of the investigation. This ratio is very sensitive to changes in many unforeseeable unknowns (for example, sector-specific $CO_2$ regulations, willingness to pay, consumer preferences).

What is decisive in the results of the dena study is that as the energy transition progresses, Power Fuels are becoming more competitive compared to conventional fossil alternatives (oil and natural gas, hydrogen from natural gas steam reformation). The question of which solutions will actually prevail for which areas of application will ultimately be answered by the market.

[15] ewi Expert Report (2018), p. 240.
[16] ewi Expert Report (2018), p. 240.
[17] ewi Expert Report (2018), p. 290; The cumulative total costs increase in the power-to-x sensitivity for EL95 by €194 billion and TM95 by €460 billion. Nevertheless, the overall sensitivity for the TM95 scenario remains more favourable than the EL95 scenario, despite the higher power-to-x cost.

## Recommended course of action

- **Build international markets:** The Federal Government should consistently promote the development of global markets for synthetic fuels, co-initiate and support them (for example, in the context of energy partnerships and at the G20 level) and strive for technology leadership.

- **Develop market boost strategies for synthetic renewable energy carriers:** In this legislative term, the Federal Government should develop an active strategy to boost the market boost for synthetic energy carriers in Germany and support it via the following measures, among others:

    - Prioritise the use of carbon free generated hydrogen as new hydrogen applications are introduced to create a development market for the scaling of power-to-gas/power-to-liquid technologies. At the European level, the Federal Government should aim for an appropriate creditability of the use of Power Fuels, including in preliminary processes on quotas and targets specific to the application sector. This concerns, for example, the greenhouse gas reduction quota as well as the fleet emission targets of vehicle manufacturers. This may, for example, create an incentive to use green hydrogen for current hydrogen applications in refineries.

    - The further development of the energy research programme should focus on economies of scale for the technologies required for Power Fuels.

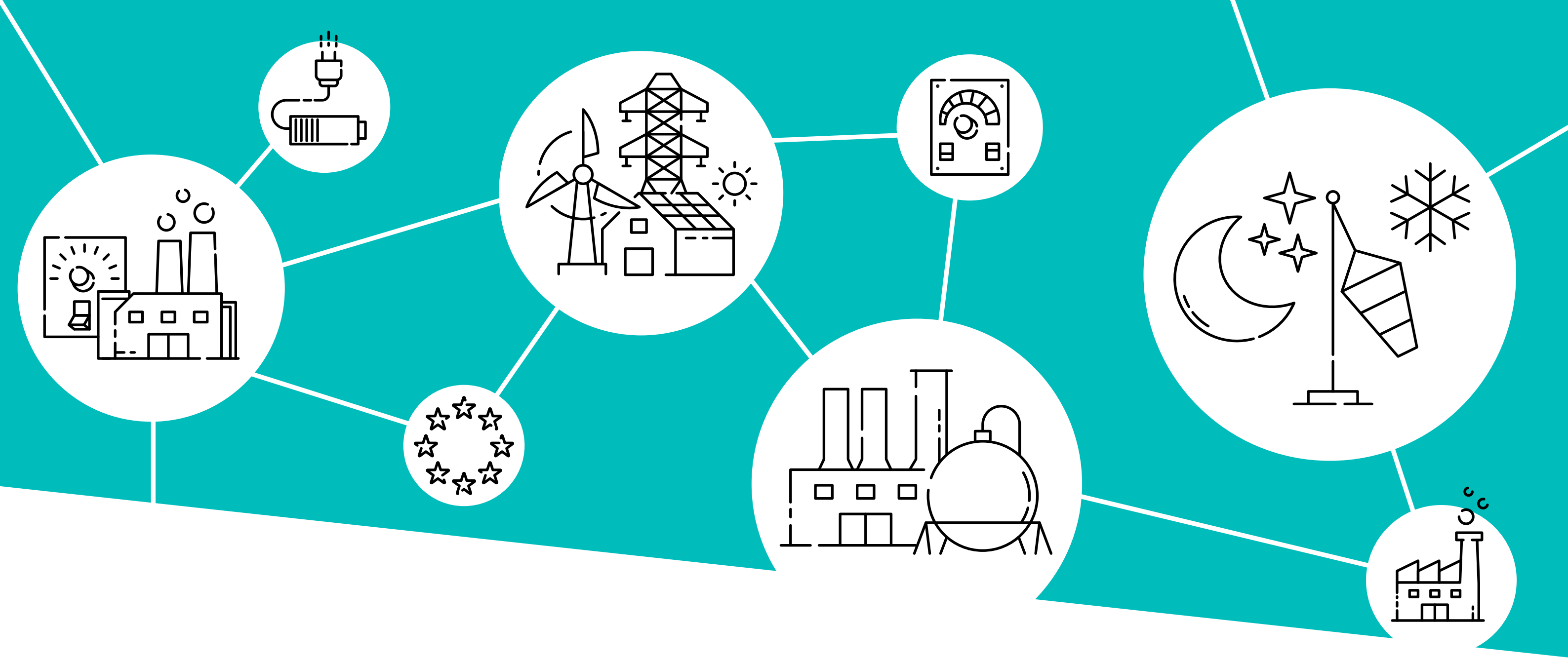
    - The Federal Government should examine the introduction of time-limited instruments for the market introduction of power-to-gas/power-to-liquid facilities.

    - In the short term, the Federal Government should revise the existing regulations for flexible electricity loads with a view to facilitate openness to a range of technologies in order to create opportunities for the use of renewable electricity volumes that could not otherwise be integrated, including for use in power-to-gas/power-to-liquid facilities.

- **Further develop infrastructures for gaseous and liquid energy carriers:** In addition, the Federal Government should plan the further development of infrastructures for gaseous and liquid fuels.

    - The Federal Government and gas grid operators should work together to promote the addition of hydrogen to natural gas and, in the medium term, create the technical prerequisites for increasing the amount of hydrogen in the gas grid. The results of the integrated infrastructure planning laid out in the coalition agreement must be taken into account.

    - The Federal Government and the operators of infrastructures for liquid energy carriers should work together to develop a roadmap for the use of liquid synthetic fuels in Germany.



# 2.6
# How do we ensure security of supply and meet demand, even during the ‘dark doldrums’?

Due to economic growth and steady electrification, demand for electricity and the annual peak load increase significantly[18]: up to 840 TWh/a with an annual peak load of 100 GW in the technology mix scenario and up to 1,160 TWh/a at a peak load of 160 GW in the electrification scenario[19] despite energy efficiency.

### The 2050 energy system must guarantee coverage of the increasing demand for electricity and annual peak load

It will also not be possible to cover the demand for electricity at any point in time directly via renewable energy sources, as such sources are highly weather-dependent and can provide electricity only in accordance with the supply.

Factors that have a significant influence on the demand for the secured and controllable generation of capacity include:

- price elasticity or demand side management including decentralised storage systems,
- simultaneous residual peak loads and potential contributions from other countries,
- the probability of weather events that need to be covered (‘dark doldrums’ over longer periods of time),
- the need to cover specific weather events or accept restrictions or the prioritisation of supply during less common extreme weather events,
- the degree of electrification across all sectors, such as in industrial processes, and the increased use of heat pumps and electric vehicles.

Various methods to assess security of supply and the demand for secured capacity must be further explored and discussed in light of the aforementioned factors.

The European climate targets will cause the production of renewable electricity to increase in other European countries, as well as the demand for electricity due to increasing electrification. However, the simultaneity of power generation from renewable energy sources in Europe remains comparatively high. When little renewable electricity is available in Germany, it is highly likely the same will apply to neighbouring countries as well.

[18] For comparison: The demand for electricity in 2015 amounted to 567 TWh, the annual peak load was 84 GW; see ewi Expert Report (2018), pp. 195 and 205.
[19] ewi Expert Report (2018), pp. 195 and 205.

### Storage, demand side management and gas-fired power plants provide secured capacity

Today, as in 2050, the annual peak load will be covered in particular by secured, controllable power plant capacity, demand side management, storage and electricity imports. Above all, gas-fired power plants as well as larger and smaller combined heat and power plants, which are increasingly being powered by Power Fuels, are used to secure power plant capacity. Together with the nuclear phase-out and the reduction of coal-fired power plants, the increasing demand for secured capacity due to the rise in use of electricity-based applications will require the construction of a significant number of new gas-fired power plants between 2020 and 2030, which will continue to increase until 2050. Due to the growing proportion of renewable energy in the electricity market, the power plants are only in operation for comparatively few hours per year.

The investment required to provide the secured capacity, as well as the operating and maintenance costs in the energy sector, vary significantly from €140 to €170 billion in the technology mix scenarios compared to €310 to €320 billion in the electrification scenarios[20]. These costs are included in the additional costs reported in this study.

The energy-only market merely compensates for electricity volumes, not the provision of power plant capacity. Free pricing can lead to high scarcity prices. Frequency and intensity are difficult to predict or to include in the economic analysis. It should be closely monitored whether the energy-only market can provide sufficient incentives to invest in secured capacity and to activate demand flexibility. This applies to the expected shortage on the electricity market due to the nuclear phase-out by 2022 and the reduction of coal-fired power plants. In the long term, this question is all the more pertinent due to the increasing demand for electricity and further decreasing full-load hours of power plants.

## Recommended course of action

- **Set up stakeholder process for security of supply:** In addition, to the planned commission of growth, structural change and employment, the Federal Government should initiate a stakeholder process to address the issues concerning the development of security of supply. The focus should be on investigating the need for secured electricity capacity in Germany and how it can be covered, as well as sufficient security of supply for heating. The aim is, in view of new issues relating to the integrated energy transition, to achieve a better common understanding among experts and policy-makers (demand side price elasticity, contribution of secured controllable capacity through demand side management, storage facilities or electric vehicles, as well as correlations with developments in other European countries and dealing with extreme weather events).
- **Further develop monitoring systems:** Building on this, the Federal Government should continue to develop the capacity balance estimation method used in Germany[21] and the monitoring system of the security of supply report. Furthermore, it should set up close monitoring of scarcity prices and situations on the electricity market as well as the development of the power plant fleet and the supply of storage systems and demand flexibility.
- **Verify reserve mechanisms:** In the medium term, the Federal Government should investigate the extent to which there is a need to further develop the current set of reserve mechanism instruments.

[20] ewi Expert Report (2018), p. 247 et seq.
[21] German transmission system operators already use so-called probabilistic processes, for example in the context of the Pentalateralen Energy Forum (PLEF) – see "Discourse: Security of supply and the 'dark doldrums'".

# Discourse: Security of supply and the 'dark doldrums'

Ensuring **security of supply is one of the key requirements** for the energy system. An increasing proportion of fluctuating power generation from renewable energy sources is expected in the development of the energy system between now and 2050. At the same time, the demand for electrical power is growing due to the increasing electrification of the building, transport and industrial sectors. The term 'long, cold dark doldrums' is understood to refer to a longer period of time during which little electricity is generated from fluctuating renewable energy sources such as photovoltaic and wind farms while the demand for electricity for electrical heating technologies due to low outside temperatures simultaneously increases. This requires a relatively high load to be largely covered by secured power plant capacities and electricity imports over a longer period of time.

After the publication of the interim conclusion of the dena study in October 2017 and in the subsequent discussion among the circle of partners as well as with relevant stakeholders from science and politics, it quickly became clear that the results and findings, as well as the expectations and the parameterisations of the scenarios, led to **very controversial discussions with regard to the 'dark doldrums'.** The key questions are what impact the energy transition will have on the development of security of supply, especially with regard to the annual peak load and its coverage, and whether it is necessary to make additional adjustments for the so-called 'dark doldrums' at all.

From the discussions that have taken place, it has become very clear that it is necessary for society as a whole to discuss the requirements of the energy system of the future to maintain the security of supply and **the corresponding policy decisions to be made.**

Four questions stand out:

1. How much **electricity is in demand and how high is the peak load** during a cold phase? To what extent are the electrical applications simultaneous and is there any potential for load shifting?

2. How low is the least expected **contribution of renewable electricity generation** during the 'dark doldrums' and how long does this period with weak generation from photovoltaic and wind farms last?

3. To what extent can Germany rely on **other European countries** with regard to:

   - assumptions on stochastic balancing effects for simultaneous high load and low renewable power generation in the European electricity market,
   - technically available options for the international exchange of electricity in bottleneck situations,
   - sufficient political agreements on the possibility of still meeting these in order to obtain adequate support for generating capacity in other countries in bottleneck situations.

4. To what extent is Germany prepared to no longer secure capacity during seldom and extreme weather events for reasons of efficiency, but to accept **supply failures to a manageable extent**, as necessary?

Designing the electricity supply system in response to the above questions will provide the required demand for secured capacity. This can be used as a controllable generating capacity regardless of the supply of wind or solar energy to meet the demand for electricity.

## Methodology to assess the security of supply in the dena study

In order to determine the power plant capacities required for security of supply in Germany, the dena study examined two extreme events: the annual peak load that must be covered by sufficient capacity over the course of the year and the cumulative energetic coverage of cold 'dark doldrums' lasting two weeks.

- **Annual peak load:** This refers to the point in time of the year's highest electricity load, resulting from the maximum demand for electricity of all the individual applications in the overall system and usually in the late afternoon on a cold winter weekday. In addition to the maximum load of the individual demand profiles, the simultaneous use of the various applications is significant. As the energy system becomes increasingly electrified, the annual peak load increases over the years studied. The annual peak load will be covered by consumer-side influence and the shifting of energy demand (demand side management), storage systems and secured power plant capacities (including decentralised power generation units and combined heat and power generation). For the non-controllable power generating plants using renewable energy sources, 1 per cent of the installed capacity of onshore wind and 10 per cent of offshore wind is taken into account to contribute to covering the annual peak load. There is no contribution from photovoltaics. Furthermore, after discussions with the partners on the module steering group, it was assumed energy imports from other European countries would amount to 5 GW.

- **'Dark doldrums':** For the study of the cold 'dark doldrums', the contribution of wind and photovoltaics during a two-week phase with low feed-in values was considered on the basis of historical feeding-in profiles. During this time, wind farms (onshore and offshore) each provide 10 per cent of their capacity on average, and photovoltaic systems average 3 per cent. At the same time, due to the low temperatures, averaging minus 3°C, there is a comparably high demand for heating and electricity. Electricity imports, electricity storage and demand side management contribute to evenly distributing the load and covering power peaks, but they do not completely cover the amount of energy required on the basis of the assumptions made.

In the dena study scenarios, the power generation mix must always be sufficient to cover both critical situations. Storage system availability can further reduce the reported demand for secured capacity from power plants. This includes storage facilities that respond independently to implicit signals (such as electricity price fluctuations) or offer controlled demand side management.

The average **peak power during the two-week cold 'dark doldrums'** in 2050 will correspond to about 90 GW in the technology mix scenarios and 150 GW in the electrification scenarios. The demand for capacity is predominantly conditioned by the building and industrial sectors. The output requirement during the cold 'dark doldrums' is covered in particular by gas-fired power plants (65 or 120 GW in 2050). Such power plants are a relatively low-cost and emission-free – when using Power Fuels – option for providing the necessary capacity when other options, such as electricity imports, are limited.

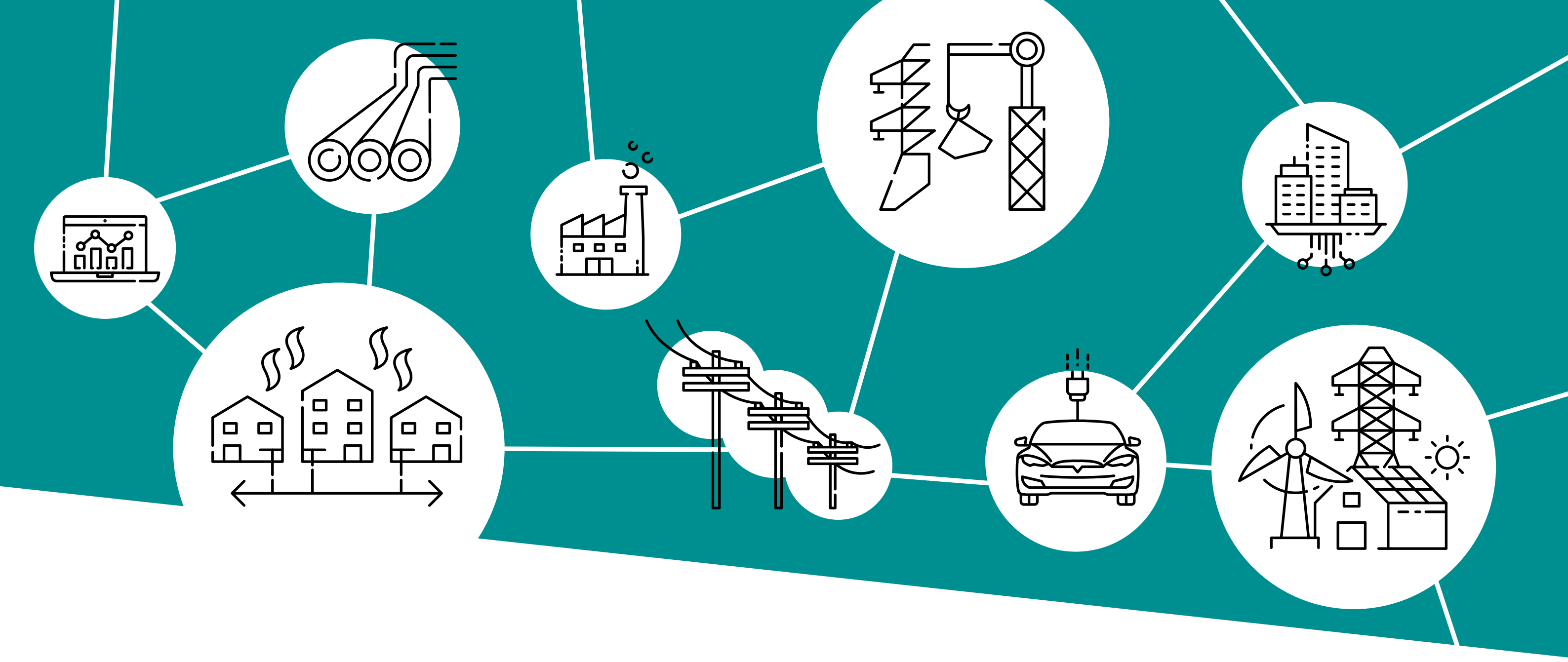
A relevant parameter in the calculation of the necessary secured capacity is to what extent **electricity imports from other European countries** can be counted on. While some studies do not take into account, or only to a limited extent, import capa-cities to ensure security of supply, other studies also assume that electricity imports from the European electricity grid will be available to a large extent during the 'dark doldrums' in Germany. For instance, the electricity output imported in the long-term and climate scenarios commissioned by the Federal Ministry for Economic Affairs peaks at about 50 GW, even during the 'dark doldrums'. The dena study defines a rather restrictive assumption that a maximum of 5 GW of power can be imported to cover the output requirement.

An important precondition for security of supply is the further convergence of the European electricity market. This will make it possible for the countries to support each other in the event of shortages, provide services across borders, and thus reduce power plant utilisation within the EU for the individual member states. The challenge is the high degree of simultaneity of 'dark doldrums' throughout the EU and high demand, for example due to increasing electrification.

## Methodology to study the security of supply at the European level

An alternative approach to assessing the security of supply is to use probability-based procedures, such as those used by the European Network of Transmission System Operators for Electricity (ENTSO-E) and the Pentalateral Energy Forum since 2017. In paragraph 51 of the 'German Energy Industry Act (EnWG)' on monitoring the security of supply by the Federal Ministry for Economic Affairs and Energy (BMWi), the use of probabilistic approaches is also required by law. It is assumed that limited, short electricity shortages with low probability of occurrence can be accepted in context. Furthermore, security of supply is provided jointly at the European level. Due to the balancing effects regarding demand for electricity and power generation from renewable energy sources, smaller power plant capacities must be maintained for the individual member states than for a purely national consideration.

A further study should investigate what contribution is required to secure capacity for a long, cold 'dark doldrums' period and whether electricity imports can achieve this.



# 2.7
# How will the energy infrastructure change?

The energy system of the future will continue to use a variety of energy carriers, such as electricity, various liquid and gaseous energy carriers, as well as local and district heating. The existing transport and distribution infrastructures will therefore continue to be needed in the future. In order to optimise costs when designing the energy transition, it is necessary to utilise and develop these infrastructures in the best possible way. As demand increases, they should be expanded as needed.

## Expand and develop electricity grids

Electricity transmission grids must be significantly strengthened and developed beyond current grid development plans in order to integrate the ever-increasing volumes of renewable electricity and to allow for the extension of the EU electricity market. Depending on the scenario, the infrastructure costs at the transmission grid level, in excess of current plans, vary between €79 and €107 billion[22]. The distribution grids must also be expanded so they can accommodate higher loads due to new electricity applications such as electromobility and heat pumps, in addition to the increasing proportions of renewable energy. Depending on the scenario, the additional costs at the distribution grid level amount to between €146 and €253 billion[23].

To improve utilisation and intelligently use flexibility at the various grid levels, successive innovative operational management concepts must be developed and implemented. Such concepts include the active use of decentralised energy producers and storage facilities by grid operators as well as regulations for the integration of potentially large volumes of electric cars and heat pumps. These new approaches require a higher degree of system management automation and more coordination between the participants. Especially at the distribution grid level, significantly more intelligent measurement and control technology is needed than is currently the case. Innovative concepts and the increased use of flexibility capacities are also required to limit expansion costs.

## Use existing infrastructures for gas, heating and liquid energy carriers efficiently

The advantages of a transformation path with a broader mix of technologies can only be harnessed if there are sufficient energy infrastructures for electricity, gas, district heating and liquid energy carriers, and if existing infrastructures are optimally utilised and deployed. This is a prerequisite for a cost-efficient and robust energy transition.

[22] ewi Expert Report (2018), p. 215.
[23] ewi Expert Report (2018), p. 219.

The transition to the medium- and long-term climate-friendly energy system will take place by increasing the use of Power Fuels. For the gas grid, this will initially be achieved by further integrating hydrogen through admixture and, at least in part, transferring to a hydrogen infrastructure and converting filling stations for the new energy carrier. Depending on how the propulsion mix develops in the transport sector, a relevant proportion of the demand for mobility will continue to be based on the infrastructure for liquid fuels. Today's infrastructures for liquid energy carriers can accommodate liquid renewable synthetic fuels without any need for conversion.

For gas grids, the challenge is that demand for gas will decrease in the electrification scenarios by 2050, even if the use of hydrogen and synthetic methane increases. There are several causes for this, including the future lower generation of electricity from gas-fired power plants as well as the reduced energy demand in the building sector due to refurbishments and heating modernisation with the conversion to electricity/gas hybrid heating or heat pumps. While demand for gas in the electrification scenarios decreases from around 790 TWh/a in 2015 to 500 or 680 TWh/a in 2050, demand for gas in the technology mix scenarios examined remains constant or even increases to 877 TWh/a[24]. As gas grid utilisation decreases, infrastructure costs for the remaining grid users increase.

As for the district heating networks, refurbishments and energy efficiency improvements result in lower heating needs, but this is associated with an increasing number of service connections across all the scenarios. Therefore, in the future, it cannot be assumed that the district heating networks will be dismantled[25]. Through the transition from coal to, initially, natural gas and then renewably produced gas in the future, district heating will emit less and less carbon. Even today, district heating networks should be modified for lower useful temperatures and also absorb more and more industrial waste heat.

## Recommended course of action

- **Promote understanding of electricity grid expansion, accelerate procedures:** The Federal and State Governments should continuously and decisively promote the necessity of expanding the electricity grid among the population. Approval procedures should be further accelerated.

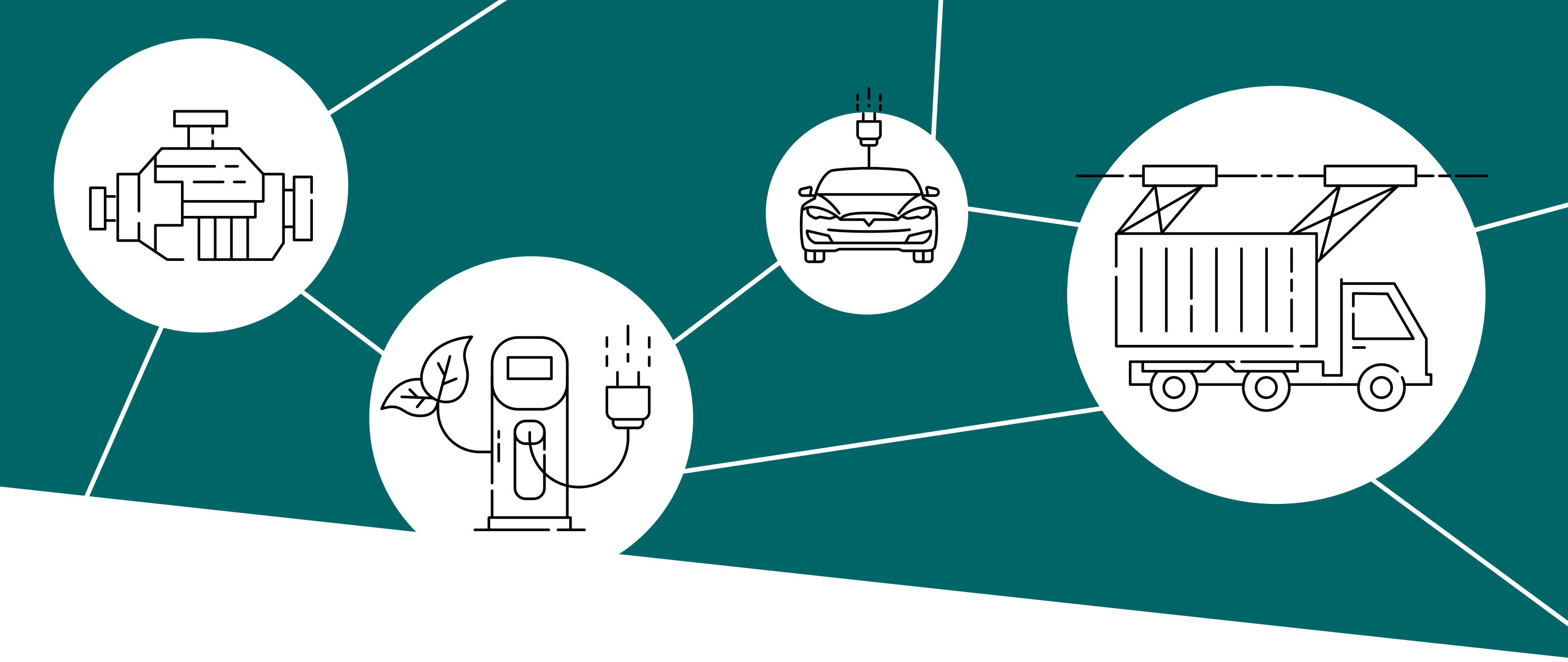
- **Advance automation and intelligent operating equipment:** At the transmission grid level, it is important to examine what additional potential could be exploited to optimise grid utilisation, such as increasing the degree of automation in system management, using more intelligent operating equipment such as phase shifters or static compensators via new concepts like grid boosters.

- **Interlock planning of electricity and gas grids:** The Federal Government should examine how the planning of energy infrastructures can be further developed in the medium term with a view to an integrated energy transition. For instance, the operators of electricity transmission grids and gas transmission grids should interlock their previously separate plans in cooperation with the Federal Network Agency in the medium term. The first step could be the development of a joint scenario for the electricity and gas grids. At the European level, this was first implemented in the current 'TYNDP Gas and Electricity Joint Scenarios' in 2018. Furthermore, the Federal Government should examine the possibilities for a more integrated grid planning of the electricity and gas distribution network operators.

- **Further develop grid regulation:** The Federal Government, in cooperation with the Federal Network Agency, should further develop the incentive regulations in preparation for the next regulatory term (2023 to 2027). These should provide a more balanced incentive for CAPEX/OPEX-intensive solutions to increase intelligence in the distribution grid and provide a framework for grid operators to access flexibilities beneficial to the grid such as demand side management, storage systems or electric vehicles.

  Incentive regulation for gas grids should support and facilitate the conversion of gas infrastructure to accommodate higher proportions of hydrogen.

[24] ewi Expert Report (2018), p. 220.
[25] ewi Expert Report (2018), p. 220 et seq.



# 2.8 Which parameters influence the energy transition in transport?

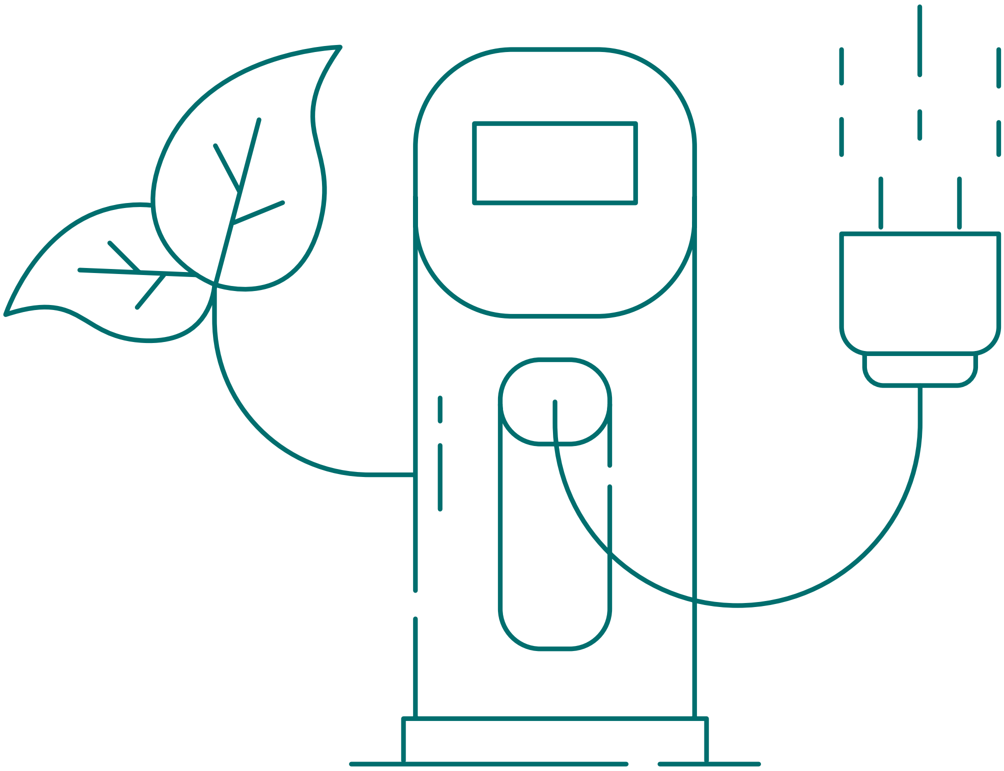
So far, the energy transition in the transport sector has not been particularly successful in Germany. If the transport sector is to make a significant contribution to reducing greenhouse gas emissions by 2030, as envisaged by the Federal Government's climate action plan, effective measures must be taken immediately with regard to sustainable mobility, renewable fuels and alternative forms of propulsion.

Increasing propulsion efficiency is the key to the specific reduction of emissions. Nevertheless, the climate targets can only be achieved by significantly increasing the proportion of low-carbon renewable fuels. In the short and medium term, sustainable biofuels will continue to play an important role, but they are gradually becoming less important compared to other renewable fuels. Most of the energy needs of liquid and gaseous fuels must be met by Power Fuels. Traffic volume should be limited and, at best, reduced thanks to innovative mobility services, adapted production systems, as well as sustainable urban and regional planning.

### Efficiency is the key to achieving the targets in all the scenarios

The importance of propulsion efficiency is clear in all the scenarios. Even in the reference scenario, where 69 per cent of passenger cars are purely combustion vehicles, greenhouse gas emissions in the transport sector can decrease to 39 per cent by 2050 compared to 1990[26]. This is possible because the specific energy consumption of gasoline, diesel and CNG passenger cars is expected to drop by 25 per cent by 2050, according to study assumptions. Depending on the driver's profile, semi-electric propulsions save another 30 to 50 per cent compared to conventional combustion engines. The potential of purely battery electric and hydrogen-powered propulsion technologies is evident in the final energy reduction in the scenarios that achieve the climatic targets. The final energy demand will decrease by 20 to 28 per cent in these scenarios by 2030, compared to 12 per cent in the reference scenario. As a result of energy savings, the transport sector will need around 90 to 160 TWh less final energy in 2050 in the scenarios that achieve the climate targets than the reference scenario[27].

[26] ewi Expert Report (2018), p. 137.
[27] ewi Expert Report (2018), p. 129.



## Climate targets cannot be achieved in heavy freight transport without Power Fuels

More and more alternative forms of propulsion are currently being marketed in the light commercial vehicle sector. LNG trucks are the only marketable alternative for transporting heavy goods by road and over long distances. In regional transport, gas-powered vehicles as well as battery electric vehicles and, in future, fuel cell electric vehicles are possible options.

Replacing fossil fuels in road transport can be achieved by using Power Fuels. In the medium term, predominantly biofuels will be available. If greenhouse gas emissions are to decrease significantly, there is no way around Power Fuels in heavy freight transport. In the scenarios that meet the climate targets, up to 84 TWh in heavy freight transport would have to be covered via Power Fuels[28]. They will also be needed if hybrid trolley trucks and fuel cell electric trucks are to achieve high market penetration (see 'Discourse: Hybrid trolley trucks').

However, the scenario results show that the use of Power Fuels without high propulsion efficiency can lead to cost disadvantages. Thus, the costs of the scenario with a broad mix of technologies and energy sources will increase compared to the scenario with a high degree of all-electric propulsion systems in the years 2040–2050 due to the higher demand for Power Fuels.

In addition to road freight transport, demand for Power Fuels will increase, especially in shipping and aviation. Without their widespread use, the 95 per cent climate target cannot be achieved.

## The propulsion development for trucks requires fundamental policy decisions

When looking at overall energy consumption, the proportion of final energy heavy commercial vehicles consumption will increase as a result of further increases in traffic. In the reference scenario, high-efficiency diesel and gas-powered vehicles could reduce the energy consumption of heavy goods vehicles (greater than 12 t) by 10 per cent by 2030 and by 23 per cent by 2050. The scenarios that achieve the climate targets reduce final energy by 29 to 38 per cent by 2050. If there is a market boost in hybrid trolley trucks, final energy consumption could even decrease by 49 per cent by 2050 compared to 2015.

[28] ewi calculations for the ewi Expert Report (2018).

## Recommended course of action

- **Follow a consistent strategy:** In order to achieve the climate targets in the transport sector, a bundle of measures must be implemented. A single measure will not lead to success. The aim must be to reduce traffic, shift it wherever possible to climate-friendly transport modes and improve propulsion systems and fuels.

- **Advance the market for energy-efficient engines:** It is especially important to increase the efficiency of all propulsion systems. The Federal Government should support ambitious $CO_2$ fleet targets at the EU level while simultaneously stimulating the development of the necessary public infrastructure. It could be an option to include the use of Power Fuels in the $CO_2$ fleet targets of vehicle manufacturers to encourage early market development of these energy carriers via the sector most willing to invest. In addition to the demand in the greenhouse gas quota market, an additional customer base could develop for the producers of Power Fuels. However, double funding would have to be avoided; for example, revenue from the greenhouse gas reduction quota would have to be coordinated with a reliable statistical classification of the greenhouse gas emissions to be avoided per vehicle over its entire service lifetime.

- **Create incentives for company cars:** In Germany in particular, propulsion efficiency improvements can be supported by a differentiated taxation of company cars. This should be geared toward the specific carbon emission of the vehicle and should be revenue-neutral for the federal budget. The public sector should act as a role model in the procurement of low carbon company cars.

- **Harmonise tax rates and align them with carbon emissions:** In the short and medium term, different energy tax rates for different fossil fuels should be eliminated and the carbon emissions intensity of fuels given more importance in the taxation system. The price per unit of $CO_2$ should gradual-ly increase over the next few years. The revenue can be used to support the development and market penetration of alternative forms of propulsion and fuels.

- **Introduce ambitious quotas for renewable fuels:** Since renewable fuels are more expensive than fossil fuels in the medium term, but at the same time contribute significantly to the reduction of greenhouse gases, the Federal Government should call for a more ambitious quota for advanced and synthetic renewable fuels (including Power Fuels) at the EU level during the negotiations for the further development of the 'Renewable Energy Directive'. At the same time, it should consider tenders for the development of large power-to-x plants. Tenders could reduce the uncertainty of plant operators and help to bring Power Fuels gradually to market.

- **Reduce tolls on low-emission trucks:** For heavy freight transport, tolls are a decisive cost factor. The use of low-emission trucks with alternative forms of propulsion should be made more attractive by significantly differentiating the toll compared to diesel trucks.

- **Set standards for system-friendly charging, simplify billing:** In the short term, standards and services should be created that make the system-friendly charging of electric vehicles possible so the grids are not overwhelmed and to reduce the secured capacity during peak load periods. To promote electromobility, it is necessary to simplify calibration regulations. It is currently difficult to bill charging per kWh. To this end, hardware and software requirements should be simplified and clarified.

- **Analyse Europe-wide potential of hybrid trolley trucks:** In addition to initial funding for LNG commercial vehicles, the effect and acceptance of hybrid trolley trucks should be tested in practical projects in the next few years. In an EU-wide analysis, areas of use and transport corridors should be investigated, which can add value to the cost-effective reduction of emissions.

# Discourse: Electrified highways with hybrid trolley trucks

The opportunities and challenges of hybrid trolley trucks are currently the subject of intense discussions. As part of the modelling, the steering committee of the mobility module in the dena study therefore decided to have the **effects of a market boost, including the associated infrastructure development,** studied with a sensitivity calculation for the scenarios achieving the 95 per cent target[29]. This discourse covers discussions among the study partners as well as with external stakeholders on the subject of hybrid trolley trucks.

Hybrid trolley trucks **may be a suitable technology** to electrify heavy freight transport. In this procedure, the vehicles have an electrical propulsion system with a buffer memory that is electrically powered via a pantograph and an infrastructure of overhead lines. Furthermore, the vehicles have a secondary propulsion system, such as a battery or fuel cell electric system, or a gas or diesel internal combustion engine, for driving outside the overhead line system. From today's perspective, diesel hybrid propulsion systems could be the most attractive combination, as they have the lowest investment costs and a high degree of flexibility. Hybrid trolley trucks are interesting for high-mileage logistic areas on busy roads such as highways. They are expected to achieve lower energy consumption due to the higher efficiency of the electric powertrain and the increased direct use of renewable electricity without conversion losses.

Currently, the **first test stretches on German highways** are under construction, for example on the A1 between Lübeck and Reinfeld and on the A5 between Frankfurt Airport and Darmstadt. Their use is also being tested internationally, for example in California and Sweden. The technology may be introduced gradually using a polycentric approach. As a first step, overhead lines will be built in regions with high traffic density and suitable back-and-forth regional heavy freight transport. For supra-regional coverage, the individual focal areas will then be continuously connected.

### Advantages in terms of energy end-use efficiency, system costs and climate and environmental protection

The use of hybrid trolley trucks will displace other propulsion technologies in heavy freight transport and lead to a **reduction in final energy consumption in the transport sector.** In the sensitivity study carried out as part of the dena study, the demand for electricity from the transport sector in the scenarios studied increases by 18 to 33 TWh by 2050. At the same time, the demand for hydrogen, methane and diesel decreases by 31 to 46 TWh. The total final energy demand from the transport sector is lower[30].

Despite additional infrastructure costs and increased electricity imports, the sensitivity calculation with hybrid trolley trucks has a **lower total cost of ownership** than the underlying baseline scenarios. Compared to the electrification scenario, the savings by 2050 will amount to about €21 billion. This can be attributed to the replacement of fuel cell electric trucks by less capital-intensive diesel hybrid trolley trucks in the transport sector, as well as lower capital costs in the energy sector due to lower capacities of **electrolysers** and electricity generation due to lower demand for hydrogen. Compared to the technology mix scenario, total costs will decrease by about €23 billion by 2050, especially as a result of reduced imports of Power Fuels[31].

In the two baseline scenarios underlying the sensitivity study, the transport sector must already fully reduce its greenhouse gas emissions. This technology introduction has no effect on the climate change impact of the transport sector in the scenarios, but it could also make a contribution like the currently modelled alternatives. Regardless of this, however, hybrid trolley trucks can bring about significant **reductions in local environmental emissions:** The use of an electric drive train completely eliminates particulate matter and nitrogen oxide emissions (NOX) from engine exhaust, and the noise emissions at slow speeds are very low. If the secondary propulsion system is not electric, however, these benefits do not work for journeys away from the overhead lines, such as inner-city deliveries.

[29] ewi Expert Report (2018), p. 302 et seq.
[30] ewi Expert Report (2018), p. 305.
[31] ewi Expert Report (2018), p. 308.

## Concerns about operational profitability, practicability and feasibility

The scenario results reveal advantages of hybrid trolley trucks in terms of energy end-use efficiency, system costs, as well as climate and environmental protection. At the same time, discussions within the dena study have highlighted some fundamental concerns. In particular, the operational practicability, the actual economic advantages, as well as the costs and feasibility of the necessary overhead line infrastructure are in question.

The **'chicken and the egg problem' is often considered the biggest challenge.** This refers to the fact that the capital-intensive construction of the overhead line infrastructure is only economical if many vehicles use it. But these vehicles only exist if there is a **minimum of overhead lines on public roads**. There must be enough overhead lines to create the necessary flexibility in the operational disposition and for a sufficiently large proportion of the journeys to be performed on electrified routes, regardless of the day's individual route profile. On the other hand, from an operational point of view, LNG or fuel cell electric trucks can already be used at a small number of filling stations if the vehicles have sufficiently long ranges.

The elimination of border controls, the availability of international labour and the high degree of cabotage freedom within the EU means that **road freight transport is increasingly being carried out by international stakeholders**. In Germany, vehicles registered outside Germany account for half of the freight transport. An overhead line system can therefore only be successful if its use is not limited to German truck operators. Its construction must be addressed and coordinated internationally.

For the economic feasibility study, the **total cost of a truck over its entire service lifetime** is relevant. This cost includes the purchasing costs, the ongoing costs for its operation, mainte-nance and upkeep, as well as the costs at the end of its use from selling or scrapping it. According to current estimates, the investment costs of a hybrid diesel truck in 2030 are about 18 per cent higher than those of a pure diesel truck, but lower than a gas-powered truck (−4.6%) and significantly lower than a battery electric truck (−21%) and a fuel cell electric truck (−36%)[32]. For the operation, maintenance and upkeep of hybrid trolley trucks, the overall cost of using the electric drive train is expected to be slightly more economical. The end of use costs depend on whether it is possible to resell it. The resale value largely depends on the presence and size of an international secondary market. Since such a secondary market for hybrid trolley trucks is lacking, the vehicles would have to be retrofitted before being resold; after disassembly of the pantograph, they would revert to 'normal' hybrid trucks. This could have a negative impact on competitiveness in an early market development phase.

The **impact of hybrid trolley trucks on the energy system** can currently only be estimated on the basis of studies and assumptions. So far, there is no empirical data on the temporal effects of hybrid trolley trucks on the regional electricity system, and its security of supply differentiates in practice. Initial studies assume that the load profiles correspond well to the temporal feeding-in profile of photovoltaic systems. Especially at the regional level, the additional electricity and peak demand can diverge significantly as a result of the use of hybrid trolley trucks; this demand would therefore have to be considered in the expansion planning phase. Overall, the effects on the energy system remain to be investigated.

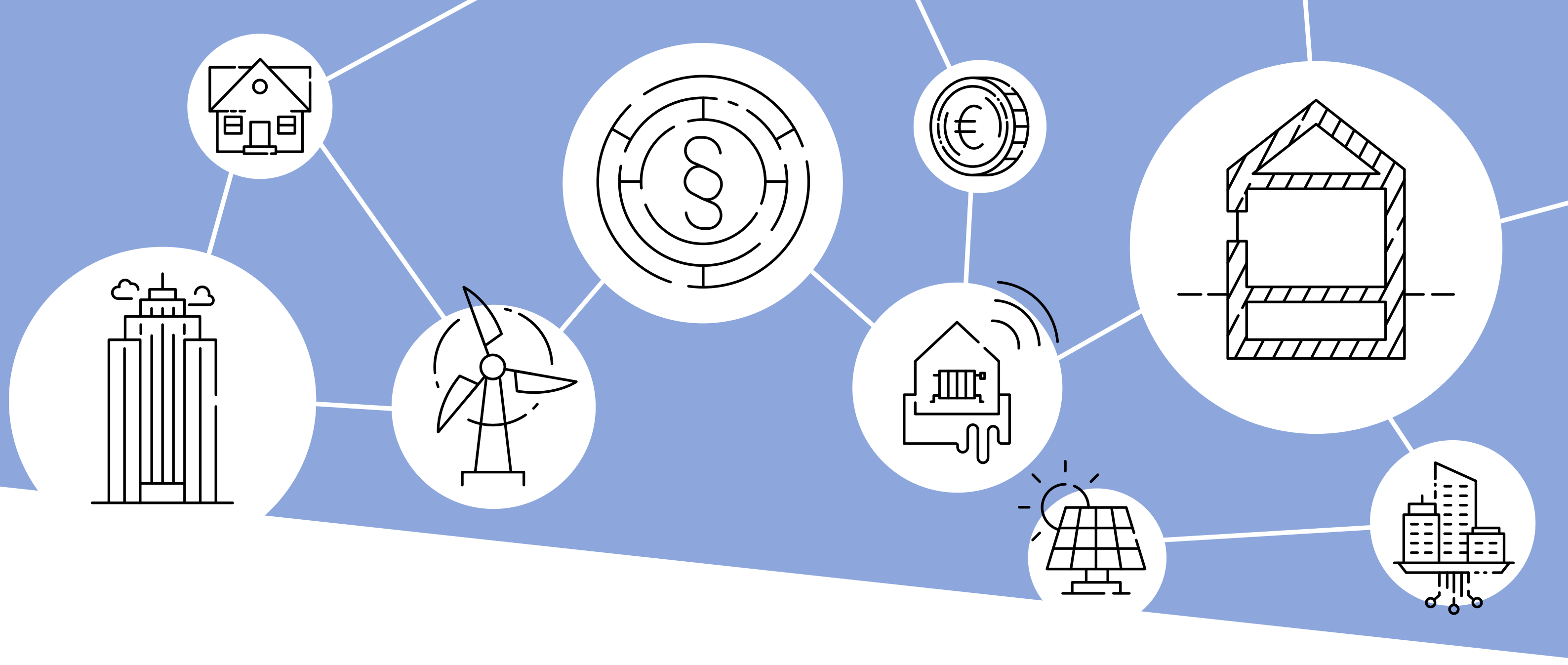
## Societal discourse and international collaboration as prerequisites

From today's point of view, it is difficult to predict whether hybrid trolley trucks will be sufficiently accepted to enable the desired **positive climate and environmental protection effects**.

As with other technologies and infrastructures, the development of a successful alternative to today's diesel-powered road freight transport must be based on **policy choices** and the integration of the European member states most involved in transport through **international cooperative agreements**. If the system is to be fully effective, it must be built across borders on Europe's busiest roads. Only sufficiently international coverage can lead to foreign transporters also buying the new vehicles and contributing to the utilisation of the system.

It would have to be further investigated to what extent such an EU-wide overhead line system would contribute to reducing energy consumption and emissions due to road freight transport in Germany and the EU. The new system could also have an **industrial and climate policy potential** for other regions of the world characterised by high transport demand coupled with significant environmental emission problems.

[32] ewi Expert Report (2018), p. 304.



# 2.9
# How can buildings become more energy-efficient and climate-friendly?

The building sector offers great technical potential for increasing energy efficiency and the use of renewable energy. This applies primarily to the building stock. In all the scenarios, the current rate of refurbishment of around 1 per cent for the building envelope would have to increase significantly in order to achieve the energy and climate policy targets by 2050. At the same time, the building sector is highly diversified in terms of its ownership and user structures, the various building types, the energy-efficiency status of the buildings, as well as the technologies and energy sources used. Due to long investment cycles, there are special requirements in the building sector with regard to the 2050 climate target. In order to make the building sector more energy-efficient and significantly more climate-friendly, a differentiated consideration of energy measures is required. This is the only way to find the best solution for the properties or urban districts from an energetic, social and economic perspective.

### A cost-effective energy transition in the building sector requires openness to a range of technologies

Under the assumptions of the study, an approach open to a range of technologies offers economic cost advantages compared to a path that relies on the almost complete electrification of the building sector. In any event, an integrated approach from the building envelope and technology to a building-integrated energy production system, such as rooftop photovoltaics or combined heat and power generation, is important. It is only possible to effectively reduce heating and cooling demand if unrenovated building envelopes are refurbished to improve energy efficiency and a higher efficiency of the construction technology is ensured, combined with the use of renewable energy sources, all at the same time. With district heating networks, conversion to a general reduction in temperature and the integration of renewable heat generation should receive support. These aspects apply both to new buildings and, with particular urgency, to existing buildings.

The technology mix scenario is based on lower refurbishment rates[33] (full refurbishment equivalents for the building envelope) than the electrification scenario (1.4 compared with about 2 per cent). However, even an increase to 1.4 per cent clearly requires higher efforts compared to today. Equally important is the replacement rate of plant engineering, which the study estimates to be 3.5 per cent per year.

The energy use in the building sector must be further decarbonised by adding renewable energy sources, in particular in the 95 per cent target path and in the in-depth investigations on obstacles[34]. There is a wider range of energy carriers in the technology mix scenarios, while electricity plays the dominant role in the electrification scenarios. All four scenarios, renewable energy is increasingly utilised, especially through the use of heat pumps and Power Fuels. The technology mix scenario requires at least 6.5 million heat pumps in 2050, and at least 16

[33] ewi Expert Report (2018), p. 61.
[34] ewi Expert Report (2018), p. 266 et seq.

million are required in the electrification scenario. For comparative purposes, there are currently about 800,000. In any event, renewable energy sources are an essential element of the future supply of heating and cooling.

The study also shows that Power Fuels must become increasingly important. In particular for the 95 per cent target paths, this goes hand in hand with significant imports of Power Fuels. The successive admixture of liquid or gaseous Power Fuels into exist-ing infrastructures will allow the continued use of existing technical facilities (including in hybrid systems). Specific advantages of the existing infrastructures for solid and liquid fuels enable a particularly highly flexible supply for demand variations.

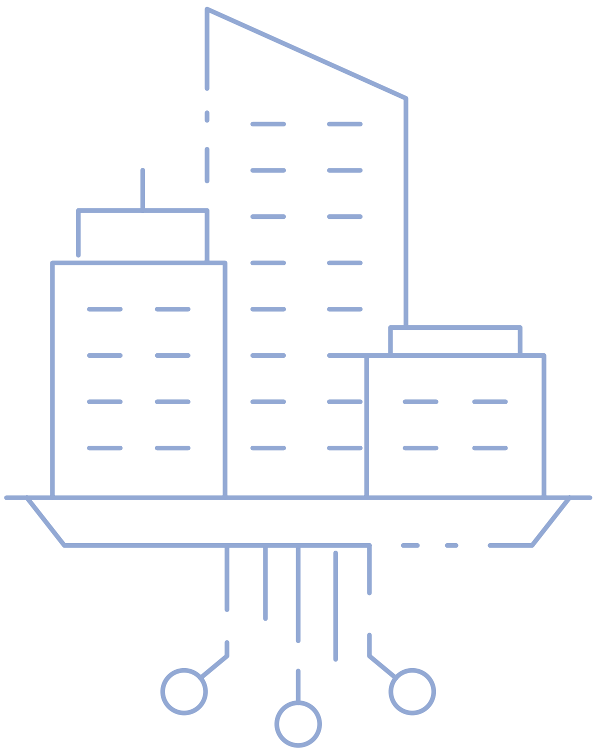
## Recognise the key significance of the building sector and stimulate investments

At €442 to €450 billion, the additional investments in building envelope and technology are lower in the scenarios open to a range of technologies than in the electrical scenarios where they total €890 to €1,026 billion[35] A key driver for this are the different annual refurbishment rates used in the scenarios –1.4 per cent in the technology mix scenarios compared to around 2 per cent in the electrification scenarios – and the associated higher capital costs. The net extra macroeconomic costs do not yet tell us anything about actual capacities and cost-effectiveness with regard to building owners and tenants, or any other economic effects. This study did not throw any light on questions of distribution and cost-efficiency from the perspective of individual players, nor on employment and growth effects. Fair distribution of these extra costs plays a vital role in the acceptance of the energy transition in the building sector, as this is where a large part of the economic investment costs are incurred.

In the interplay between the building sector and the integrated energy system, digitalised control opens up new possibilities for making a more extensive contribution towards efficient use of technologically impartial heating supply systems. Additional options for flexibility are provided by the capacity for long-term storage of gaseous and liquid energy carriers.

A differentiated consideration of heating supplies in relation to base and peak loads would be worthwhile. Technologically impartial hybrid systems as well as decentralised production and storage systems will play an ever greater role in integrating various energy sources – increasingly renewables – into the heating system. Here the most important issues to be considered are security of supply and the impact of particular weather conditions (e.g. cold, becalmed periods known as the ‘dark doldrums’).

Ultimately, the great potential and heterogeneity of non-residential buildings must also be incorporated in further considerations and development.



[35] ewi Expert Report (2018), p. 248.

## Recommended course of action

- **Stay on the path to achieve the goal of openness to a range of technologies:** There is a need for broad innovation paths as well as more research and development to promote innovation in key areas of heating supply, such as power-to-heat, power-to-gas, power-to-liquid, electrical and thermal storage systems, waste heat recovery, fuel cells or heat pumps. This includes control (smart building, integration of on-site generation), the building envelope (innovative construction and insulation materials), the provision of energy, as well as new business models and services. It is necessary to create regulatory framework conditions that encourage a cost-effective reduction of carbon emissions, such as under the new 'Building Energy Act'.

- **Keep the regulatory framework simple and efficient:** In order to ensure a high-quality implementation in the broadest sense, the necessary regulations and the law of order must be clear and as unbureaucratic as possible. This includes the further development of the regulatory framework for electricity consumption or the summary of the 'Renewable Energy Heating Act', the 'Energy Savings Ordinance' and the 'Energy Saving Act on the Building Energy Act'.

- **Expand subsidisation:** In order to initiate a significant intensification of the energy-efficient refurbishment of buildings, a subsidy mix of grants, loans and tax incentives is necessary. In the context of average annual additional investments of approx. €13 to €29 billion[36] compared to the reference scenario, a significantly higher total subsidy amount is necessary as an incentive. The planned tax refurbishment subsidy must be introduced quickly in order to provide the necessary refurbishment stimulus. With a view to the 2030 climate target, the subsidy strategy should be further developed following an approach open to a wide range of technologies, taking into account all technologies that contribute to improving energy efficiency and use renewable energy sources more in order to achieve an effective investment and refurbishment effect.

- **Strengthen information and supportive market instruments:** These measures must be accompanied by broad communication, specific building energy consulting and a better incentive system for individual refurbishment schedules to ensure sufficient transparency and acceptance.

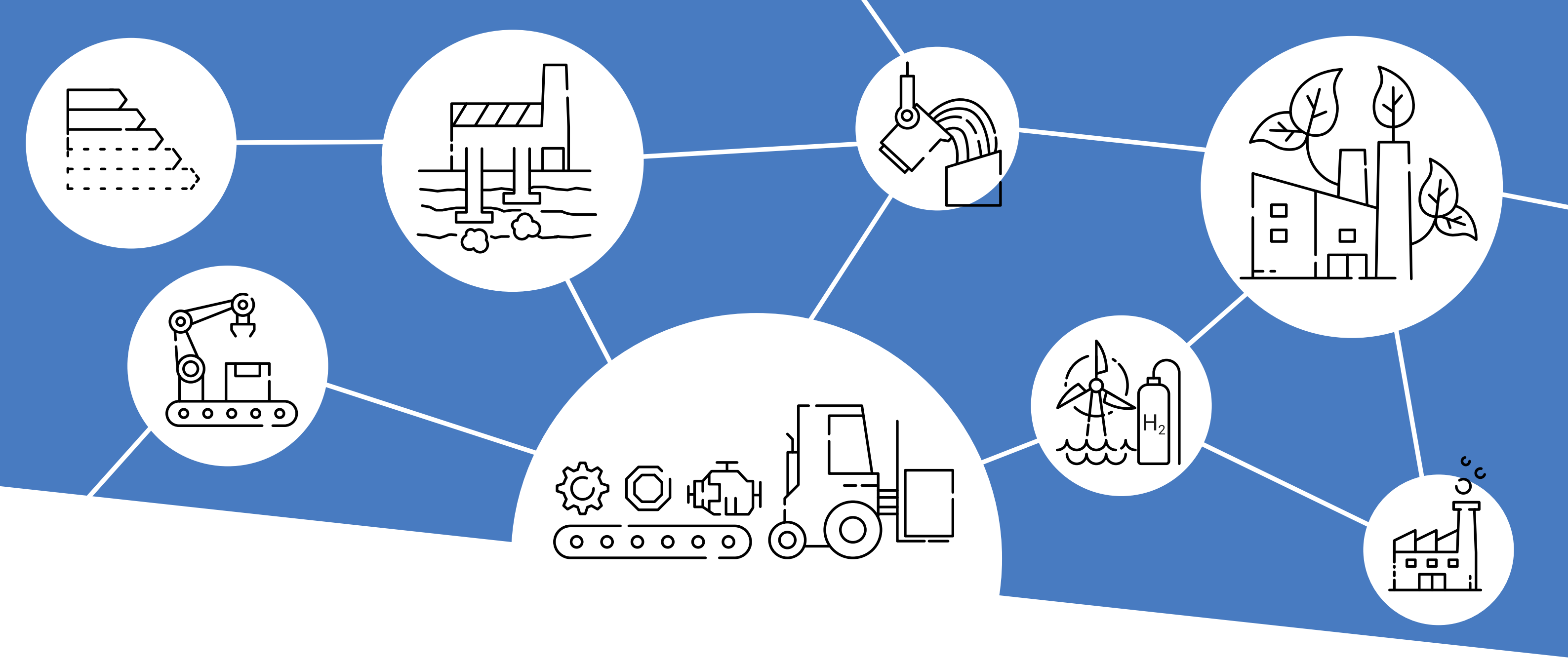
- **Improve qualifications:** A qualified consultation as well as professional planning and execution requires that those involved be suitably qualified. Incentives should therefore be provided so job descriptions and training regulations meet the requirements of the energy transition.

- **Ensure the energy-efficient operation of installed building technology:** Efficient building technology must also exploit its technical potential during operation. There are considerable deficiencies here which lead to increased energy consumption. In this context, it would be crucial to monitor the facilities. System operators and installation companies should be motivated and given suitable measures to enable them to detect and optimise unnecessarily high energy consumption.

- **Increase the energy efficiency of non-residential buildings:** Unutilised energy efficiency potential in non-residential buildings should be exploited. This requires targeted funding, the continuous further development of proper regulatory framework as well as appropriate informative and advisory measures.

- **Improve the database:** In addition to increasing energy efficiency, the available database must also be substantially and rapidly improved, especially for non-residential buildings. In both the residential and non-residential building sectors, effective market-based monitoring should also be implemented to better assess the effectiveness of energy efficiency measures and to derive specific measures.

[36] dena (2017), Building Study, p. 46.




# 2.10
# What changes can be expected in the industry sector?

With the technologies available today, Germany can at best achieve a greenhouse gas reduction of 62 per cent across all sectors by 2050, despite the ambitious developments in energy efficiency and the use of alternative technologies in industry already assumed in this reference scenario.

Achieving the climate target of 80 per cent will require greater efforts to introduce new production processes and increase energy efficiency. In part, new climate-friendly production processes lead to an increased demand for energy, such as the high demand for electricity for hydrogen electrolysis for the production of ammonia. On the whole, however, energy efficiency improvements mean that demand for energy across the entire industrial sector can be reduced by 26 to 32 per cent by the year 2050. In addition to the positive impact on carbon emissions, the increases in energy efficiency will counteract the effect of rising energy prices on production costs.

High energy efficiency can be a competitive advantage and protection against carbon leakage[37].

In order to achieve the 95 per cent target, new technologies and production processes must, as a matter of principle, be developed as quickly as possible and successively implemented. It may also be necessary to use the controversial CCS technology to a limited extent in order to eliminate industrial process emissions that could not otherwise be reduced in today's context.

Furthermore, carbon prices for industrial companies are expected to increase. Increasing carbon prices can act as a driver for the quicker adoption of alternative technologies. However, care must be taken to ensure the competitiveness of German industry and to ensure effective carbon leakage protection.

### Start developing new processes now due to long innovation and investment cycles

In order to ensure the availability of the technologies, research and development must be accelerated at an early stage. The dena study shows that many alternative technologies, such as the use of hydrogen instead of coal in steel production, will be widely used from 2040 onwards. This is due to the very long investment and innovation cycles of industrial processes that can take up to 30 years in the steel and chemical industries – 15 years for development, 15 years for market penetration. Tools must therefore be developed to ensure the timely development and market introduction of the technologies over decades, while guaranteeing planning security for companies.

[37] dena (2017), Building Study; This term refers to the transfer of production capacity to countries where products are manufactured at a lower cost due to lower climate protection requirements, but emit more $CO_2$. From a macroeconomic point of view, the associated reduction in domestic economic output should be avoided, and from a climate policy point of view, the associated increase in total emissions.

At the same time, industry should be closely involved in the integrated energy transition – for instance through demand side management or feeding waste heat into a district heating network.

### Value networks are facing structural change

The energy transition will lead to a significant structural change by 2050, especially in highly integrated value-added industry processes. For example, the lower processing of fossil fuels is affecting the availability of certain raw materials because refineries typically produce a wide range of products including fuels and raw materials. As electricity, rather than oil and gas, is increasingly used as energy carrier in 2050, the chemical industry must be provided with the important raw material naphtha by other means. This can be imported, or investments can be made in refineries specialising in naphtha extraction in Germany. In the examined scenarios, even the 95 per cent path foresees crude oil imports amounting to around 100 to 120 TWh/a. These will be used exclusively for material uses in industry, mainly for the chemical industry. Alternative supply channels and manufacturing processes of synthetic raw materials are conceivable, but would further increase the demand for renewable electricity for electrolysis. Furthermore, it would also be necessary to answer the question of how other major refinery products for non-energy use, such as bitumen, lubricants or petroleum coke, could be made available such as for aluminium production or the construction industry. This structural change must be taken into account in the context of designing the future energy transition and also in the development of technology.

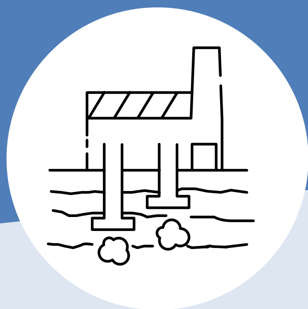
### Hydrogen applications become increasingly important

Hydrogen applications are becoming increasingly important in industry, especially in the steel and chemical industries. The proportion of hydrogen in its pure form or as an admixture to synthetic methane in the 2050 energy demand is up to 20 per cent for the steel industry, 8.5 per cent in the chemical industry, and 28 per cent in the industrial rocks and minerals sector. In view of its limited transportability, hydrogen will be produced regionally in Germany. The required hydrogen infrastructure can be largely provided by converting the existing natural gas infrastructure. Over the next decades, the natural gas infrastructure will require regular replacement investments in preparation for assessing the development of regional and supra-regional hydrogen infrastructures.

## Recommended course of action

- **Accelerate research and development:** When designing research funding programmes, the Federal and State Governments should ensure that research and development of the long-term climate-friendly technologies is already sufficiently possible and that there are sufficient incentives for their gradual implementation in companies. Policymakers must establish a stable regulatory framework as soon as possible and set priorities to increase the willingness of industry to invest in new processes and make investments more calculable in the long term (planning security).
- **Clarify the handling of remaining $CO_2$ quantities:** In the medium term, a renewed political discussion and classification of CCS is needed, especially if it is decided to pursue the 95 per cent target.
- **Introduce hydrogen applications:** Industry provides a good entry-level market for hydrogen applications. The Federal and State Governments should initiate and promote further pilot projects for the use of hydrogen in industry. With a view to an integrated energy transition, the implementation should consider renewable energy sources, infrastructures and industrial customers holistically.
- **Examine the consequences of the energy transition for industry:** the Federal Government should initiate short-term follow-up studies on the precise structural effects of the energy transition on industry and the available raw materials in the various sectors in order to be able to address opportunities and risks in a timely and appropriate manner.
- **Expand corporate networks:** The Federal Government and the German economy should open and expand their successful instrument of voluntary energy efficiency networks for further matters relating to the energy transition. Already more than 1,600 companies (status of April 2018) are participating in this multi-annual, systematic and target-oriented exchange of experience, thereby increasing their energy efficiency twice as fast as the average rate.

# Discourse: Carbon Capture and Storage (CCS)



Another issue that has been the subject of intense and controversial debate in recent years is the use of carbon capture and storage (CCS) methods. CCS refers to the separation of carbon dioxide ($CO_2$) in power plants or industrial plants and its subsequent permanent storage in deep geological strata on land or in the seabed to avoid the release of climate-damaging emissions.

The technical feasibility of carbon capture is fundamentally beyond doubt. The process has been used for years in certain industrial processes, such as the production of ammonia. However, **the general population has reservations about the technology**, especially regarding carbon storage. Even if no negative effects on human health were to be expected from normal operation, there is concern that accidents or a gradual release from storage may result in health risks. Since $CO_2$ is heavier than air, it is possible that a $CO_2$ layer forms around a large leak, unnoticeably displacing the oxygen and causing humans and animals to suffocate. Advocates of CCS consider this risk manageable through continuous monitoring of transport pipelines and reservoirs. Another concern are the risks leakage poses to groundwater and soil. Freed $CO_2$ can release pollutants into the subsurface or displace salty groundwater from deep aquifers, thereby causing damage (salinisation) to groundwater, soil and surface water.

All the **steps required for CCS are legally regulated in Germany**: the separation of $CO_2$ in the 'Federal Emission Control Act (BImSchG)' and its transport and storage in the 'Carbon Dioxide Storage Act (KSpG)' of 2012. Furthermore, capture facilities, transportation pipelines and storage facilities for the underground storage of $CO_2$ are subject to the monitoring requirements of the 'Greenhouse Gas Emissions Trading Act'. Thereafter, two-stage monitoring is required whereby a storage system must first and foremost be continually checked for leaks. If a leakage occurs, then advanced monitoring must be used to determine the amount of leaked carbon. However, it is currently **not legally possible to further expand carbon** transport or storage capacities in Germany, as article 2 parapgraph 2 of KSpG stipulates that an application for carbon storage must have been submitted before the end of 2016. Furthermore, with the 'States Clause', the Federal States have extensive powers to decide on the demonstration of CCS technology within their territory, and several Federal States have used this clause to prohibit or severely restrict carbon storage by State laws.

In the recently published **studies on the achievement of the 2050 climate targets**, it is often stated that achieving the 95 per cent target is not possible without CCS. For instance, CCS is included in the 'Long-term scenarios for the transformation of the energy system in Germany' commissioned by the Federal Ministry for Economic Affairs and Energy (in 2050, around 35 million t $CO_2$ in six emission-intensive industrial processes[38]) as well as in the study entitled 'Climate paths for Germany' commissioned by the Federation of German Industry (BDI e.V.) (in 2050 about 73 million t $CO_2$ for process and energy-related emissions from steel, ammonia and cement production as well as another 20 million t $CO_2$ in the energy/conversion sector[39]).

[38] Fraunhofer ISI et al. (2017), Long-term scenarios for the transformation of the energy system in Germany, module 3: Reference scenario and basic scenario, chapter 2.4 (p. 44).
[39] BCG/prognos (2018), Climate paths for Germany, chapter 5.1.4 (p. 153).

CCS does not completely eliminate the greenhouse gases from the treated processes. The goal is usually to capture more than 90 per cent of the emissions. In reality, according to the German Environment Agency (UBA), often only about 60 to 80 per cent are actually captured. In the long-term scenarios of the Federal Ministry for Economic Affairs and Energy, separation rates average about 60 per cent when certain industries are taken into consideration (e.g. steel: 36 per cent, chemical processes: 95 per cent). The use of **CCS is associated with a considerable energy consumption**. "Depending on the particular process and the chosen CCS pro-cedure, the specific energy requirement is about 1 MWh per tonne of separated $CO_2$"[40]. This reduces the economic viability of the primary processes where CCS is used.

As part of the dena study, this subject was discussed intensively among the circle of partners. For phase 1 of the processing, the consideration of CCS as an option to reduce carbon emissions was unanimously excluded. While the transformation paths developed in phase 1 met the 80 per cent target, they missed the 95 per cent target by about four percentage points due to remaining process emissions from the industrial sector. It should be noted that a wide range of processes have already been converted to climate-friendly, electricity or hydrogen-based innovative production processes. For phase 2, in close discussion with the study partners as well as with the scientific experts, the transformation paths adopted in the individual emission-intensive industrial sectors were individually reviewed and – where possible – foreseeable technical innovations to reduce $CO_2$ were introduced. Furthermore, **CCS was allowed to reach the 95 per cent target** to eliminate the remaining residual emissions up to 95 per cent. After implementation of all the energy efficiency and climate protection measures, the residual emissions of the industrial sector in 2050 will amount to 42 million t $CO_2$. **CCS can reduce this by an additional 16 million t**, leaving a total of 27 million t $CO_2$.

In relation to total greenhouse gas emissions in 2050, CCS makes a significant contribution to achieving the climate targets. CCS will reduce residual emissions from the industrial sector by 38 per cent from 42 to 27 million t $CO_2$ in 2050. This reduction accounts for a quarter of the remaining greenhouse gas budget of 62.4 million t $CO_2$ for all of Germany in 2050.

These carbon quantities can also be put into another context. The greenhouse gas emissions, equivalent to 16 million t $CO_2$, balanced out by CCS in the dena study correspond to **1.2 per cent of the 1,248 million t $CO_2$ in the base year, 1990**. Thus, it is conceivable that by 2050, technologies will be available in time to offer economically viable climate-friendly process alternatives or materials for the remaining carbon intensive processes, making CCS unneccessary.

[40] Fraunhofer ISI et al. (2017), Long-term scenarios for the transformation of the energy system in Germany, module 3: Reference scenario and basic scenario, chapter 2.4 (p. 44).

# 2.11
# How must the development in Germany be embedded in the international energy transition?

With its 2050 climate targets, Germany is contributing to the achievement of the targets of the Paris Agreement. At the same time, the reduction of German greenhouse gas emissions alone is far from sufficient to halt climate change. In this context, it is important that the German ambitions be approached within the framework of European and global efforts and that Germany actively participates in the necessary coordination at the European and international level. This will create export opportunities for German companies and secure sustainable jobs.

## The energy transition needs renewable energy imports and the European market

The assumptions of the investigated transformation paths lead to the conclusion that Germany will continue to rely on energy imports even if the energy transition is successfully implemented, albeit to a lesser extent than previously. The dependency ratio drops from nearly 90 per cent today to less than 50 per cent in all of the scenarios that achieve the targets[41].

All the scenarios show an intensive exchange of electricity with neighbouring European countries (up to 136 TWh/a net electricity imports in 2050[42]) in order to make use of the balancing effects on the load, the generation of renewable energy and the provision of secured capacity. Furthermore, from today's point of view, there is a clear need for imports of synthetic fuels (up to 744 TWh/a in 2050[43]) from European and non-European countries, while the import of fossil fuels for energy use is almost completely eliminated.

A successful management of the energy transition in Germany must therefore be closely coordinated with the climate and energy policy of the EU member states, in order to be able to make a realistic assessment of the extent to which import and balancing options for electricity are available, for instance. This balance is also important in the light of global developments in the supply of, and demand for, Power Fuels.

[41] ewi Expert Report (2018), p. 232.
[42] ewi Expert Report (2018), p. 211.
[43] ewi Expert Report (2018), p. 240.

## Ensure the availability of technologies and economic viability

The implementation of the energy transition in all sectors relies on the use of a wide range of technologies, some of which are still young. Their availability and price development, as well as further innovations, are ultimately determined by global market developments. It is therefore important to follow the path and the structure of the energy transition worldwide in order to determine emerging international trends at an early stage. This may result in important implications for shaping the energy transition in Germany. At the same time, German companies have the opportunity to develop these future technologies and market them worldwide.

Germany must remain an attractive business location for industry in the future. The results of the dena study show that the implementation of the energy transition and a strong industrial base need not be at odds with each other. The practical implementation of the energy transition should also adhere to this maxim. Germany's strong industrial sector is the primary reason why the implementation of the energy transition is being followed with such interest internationally. This increased attention offers the opportunity to shape the energy transition as a role model. At the same time, its profitability is strongly linked to the international regulatory framework. It should therefore be ensured that the international and national playing field is as level as possible in order to avoid economic disadvantages for individual companies. If this is not possible, appropriate measures must be taken to relieve pressure where necessary.

## Adapt the energy transition to international framework

The development of international agreements and the determination of regulations at the European level as well as national laws have a major impact on the implementation of the energy transition in Germany and how it is integrated into international trade and trade relations. Therefore, the objectives and instruments should be as compatible as possible at the various levels mentioned, but also for different sub-targets of the energy transition (for example, targets and instruments for reducing energy consumption compared with those for reducing emissions). With regard to the EU level and legal framework, it is clear that the failure to reach targets can also lead to corresponding sanctions. Achieving the climate targets is therefore not only a question of credibility at the national level, but also essential for the common achievement of targets at the European level.

## Recommended course of action

- **Substantiate international agreements:** The Federal Government should work for the implementation of more extensive international agreements at the G20 level in order to involve national regimes in the reduction of carbon emissions. This can reduce distortions in global trade. Firstly, it could seek international agreements for specific emission-intensive sectors in order to protect German industry and lessen the societal burden.

- **Analyse progress, recognise conflicting goals:** The Federal Government should review and harmonise the target system and mix of instruments across the various stakeholders and policy makers involved (sectors, State Governments, Federal Government, EU). In addition it should set up an overarching position for continuous monitoring and reconciliation in the event of conflicting targets for the energy transition, for example in the Federal Chancellery.

- **Monitor global trends:** The Federal Government and industry should monitor global, energy-relevant trends more closely in order to detect cost developments and position future technologies in the global market.

- **Avoid disadvantages for the German economy:** The Federal Government should further strengthen protection against carbon leakage. This requires the use of the planned revision of the EU's state aid legislation in order to ensure sufficient room for the German economy to manoeuvre at the national level and to sufficiently protect it from disadvantages in global trade caused by the energy transition.

# 3. Structure and partner group of the dena Study Integrated Energy Transition

The goals of German energy and climate policy are widely known: by 2050, the aim is to reduce greenhouse gas emissions by 80 to 95 per cent in comparison with 1990. In addition, the resolutions of the Paris Climate Conference, according to which global warming must be limited to significantly less than 2 degrees or, better still, to 1.5 degrees.

To this end, in February 2017, along with 60 partners from various sectors, the German Energy Agency (dena) – launched the dena Study Integrated Energy Transition. The aim of the study was to identify solutions and a suitable regulatory framework for an optimised, sustainable energy system by 2050, and analyse realistic implementation options in four sectors with numerous subsectors. The project was initiated and managed by dena. It was responsible for the conception and implementation of the working process and for communications.

## Structure of the contents

The dena Study Integrated Energy Transition is divided into four study modules: 'energy production and distribution', 'buildings', 'industry' and 'mobility'. In the three modules buildings, industry and mobility, the most realistic development of technologies, processes and materials as well as the resulting energy requirements were discussed from the point of view of the final energy consumption sectors. Likewise, the potential of the sectors to participate in the energy system through consumption-side energy production, conversion or storage as well as flexibility potentials were discussed. The coverage of the final energy demand of the consumption sectors – across sectors, taking into account the short and long-term provision costs of all energy sources in the overall European system, under consideration of mutual interdependencies and given political, regulatory and technological conditions – were then discussed in the study module energy. This study module also considered the further development of the necessary energy infrastructures, i.e. the electricity, gas and heating networks, as well as the infrastructures for liquid energy carriers.

Four target scenarios and a reference scenario were defined for the modelling. The reference scenario describes an already ambitious technological development until 2050 and corresponds to a continuation of the current energy policy in Germany at the policy level. The target scenarios describe possible paths for a transformation of the energy system that make it possible to achieve the cross-sectoral greenhouse gas emission reduction targets of 80 or 95 per cent by 2050 compared to 1990.

On the basis of the scenarios and the specified transformation paths, the principle scientific expert body of the dena study, ewi Energy Research & Scenarios gGmbH, together with other experts, calculated the required energy volumes, the electricity grid and electricity generation infrastructures, as well as the cost distributions. The reference scenario, as well as the electrification and technology mix scenarios, involves increased costs for maintaining the current energy systems. The social distribution of these costs was not explored.

The dena study was prepared in two phases. An interim conclusion was published in October 2017. This included preliminary results and findings from the dialogue processes with various stakeholders. In this first phase, a transformation path was developed for each scenario and modelled towards achieving the 80 or 95 per cent reduction targets.

For phase 2, the scenarios and transformation paths were further refined on the basis of the findings and the broad discussions following the publication of the interim conclusion, and it was decided that additional detailed analyses and sensitivity analyses needed to be performed in order to answer important individual questions. This included, for example, investigating the effects of shortages or more expensive availability of Power Fuels and their effects on the energy mix and overall system costs. Other issues included the use of flexibilities beneficial to the grid and their repercussions on the electricity grids, the impact of the use of hybrid trolley trucks on the energy system and the impact of the shortage of available onshore wind land combined with the increased ground cabling of new power grids.

## Organisational structure

The chief scientific expert of the dena study was Dr. Harald Hecking (ewi Energy Research & Scenarios GmbH), supported by technical experts Prof. Dr.-Ing. Christian Rehtanz (ef.Ruhr GmbH), Prof. Dr.-Ing. Bert Oschatz (ITG Dresden), Prof. Dr.-Ing. Andreas Holm (FIW Munich), Prof. Dr. Peter Radgen and Dr. Frank May.

Within the project, study partners in the steering group gave advice and made decisions on the basic orientation of the study and cross-modular issues. In the module steering groups, the participating partners discussed specific transformation paths and parameters of the study modules. An advisory committee, comprising noted figures from science, politics and civil society, supported dena with its advice. Additionally, public dialogue events were held to enable questions and findings to be discussed with a broad group of stakeholders extending beyond the circle of partners.

On the basis of the scenarios, superordinate assumptions of the study (e.g. on population growth and interest rates) and framework parameters (e.g. on technological developments and costs, as well as energy prices) were discussed and determined in close consultation with the participating partners as well as with the experts, and module-specific transformation paths were developed for the buildings, industry and mobility consumption sectors, harmonised across the sectors, and predetermined exogenously for all further calculations.

**We would like to thank the partners of the dena Study Integrated Energy Transition:**

The advisory committee consisted of the following persons:

- **For science:** Prof. Dr. Dirk-Uwe Sauer (Acatech ESYS, chair of the dena study advisory commitee), Prof. Dr. Manfred Fischedick (Wuppertal Institute), Prof. Dr. Clemens Hoffmann (Fraunhofer IWES), Prof. Dr. Karsten Lemmer (DLR), Prof. Dr. Ortwin Renn (IASS Potsdam), Prof. Dr.-Ing. Ulrich Wagner (TU Munich)

- **For civil society:** Stefan Körzell (DGB), Holger Lösch (BDI), Klaus Müller (VZBV), Sabine Nallinger (Stiftung 2°), Michael Schäfer (WWF), Harriet Wirth (KfW), Dr. Christoph Wolff (European Climate Foundation)

- **For politics:** Dr. Axel Bree (Federal Ministry for Economic Affairs and Energy), Dr. Karl Eugen Huthmacher (Federal Ministry for Education and Research), Dr. Karsten Sach (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Dr. Volker Oschmann (Federal Ministry for Economic Affairs and Energy), Dr. Gerhard Schulz (Federal Ministry of Transport and Digital Infrastructure), Norbert Conrad (Ministry for Economic Affairs, Employment and Transport, Lower Saxony), Helmfried Meinel (Ministry for the Environment, Climate and Energy Industry, Baden-Württemberg), Ralph Lenkert (Member of the German Bundestag, 'Die Linke'), Dr. Joachim Pfeiffer (Member of the German Bundestag, 'CDU'), Dr. Julia Verlinden (Member of the German Bundestag, 'Bündnis 90/Die Grünen') and Bernd Westphal (Member of the German Bundestag, 'SPD')

# Part B:

## Executive Summary of the Expert Report

(ewi Energy Research & Scenarios gGmbH)

*Notice: The complete version of the Expert Report is available in German only.*

# Executive Summary of the Expert Report

The core findings of the scenario calculations in the expert report can be summarised in the following 19 core statements and are shown in the following TABLE 1 (page 64).

**1. Despite a high ambition level, the reference scenario only manages to reduce greenhouse gases by about 62 per cent in 2050 and misses the 2050 climate targets by 18 to 33 percentage points.**

The reference scenario already assumes a higher ambition level than is required by currently implemented climate protection measures. Although greenhouse gas emissions in the reference scenario are reduced by 62 per cent by 2050 compared to 1990 levels, the annual output of 470 million t $CO_2$ eq. results in the 80 per cent target being missed by 220 million t $CO_2$ eq. (18 percentage points) and the 95 per cent target being missed by 406 million t $CO_2$ eq. (33 percentage points). Nonetheless, Germany's current greenhouse gas emissions are nearly halved (2017: 905 million t $CO_2$ eq.), which corresponds to an average reduction in emissions of around 13 million t $CO_2$ eq. per year between 2017 and 2050.

Compared to 2015, the biggest reduction by far is achieved in the energy sector, where savings amount to more than 70 per cent by 2050. At 40 per cent by 2050, the reduction is much slower in the transport sector. The building sector reduces its emissions somewhat more, but at 51 per cent by 2050, it reaches significantly lower levels than the energy sector. The lowest reductions are in the industrial sector (including process emissions), amounting to 15 per cent by 2050.

The results clearly show that without substantial additional climate protection measures, Germany will fall short of its national climate targets.

**2. Both extensive electrification as well as a broad mix of energy sources in the demand sectors will allow the climate targets to be achieved.**

From now on, greenhouse gas emissions must decrease by about 19 million t $CO_2$ eq. per year in order to meet the 80 per cent climate target *(see figure 1.1)*. To meet the 95 per cent climate target, emissions must decrease by as much as 24 million t $CO_2$ eq. per year, which is about three times the level of the last 10 years *(see figure 1.2)*.

This ambitious reduction path can be achieved with an electrification strategy or a technology mix strategy. In the electrification scenario, the reduction pressure is focussed on the final energy consumption sectors of buildings, industry and transport. In a technology mix scenario, the energy sector needs to deliver greater contributions to reduction. Achieving the 95 per cent target requires extensive efforts in all sectors. In addition, important innovations and the use of CCS are necessary in the industry sector for achieving the 95 per cent target.

**Figure 1.1: Greenhouse gas emissions by sector**
80 % climate target

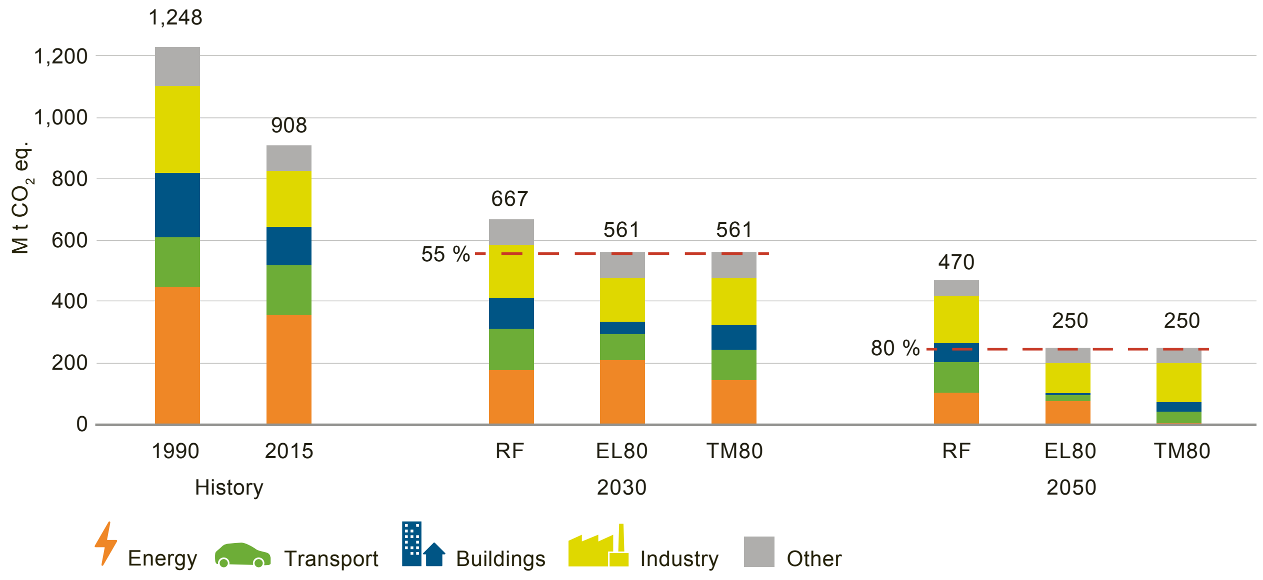
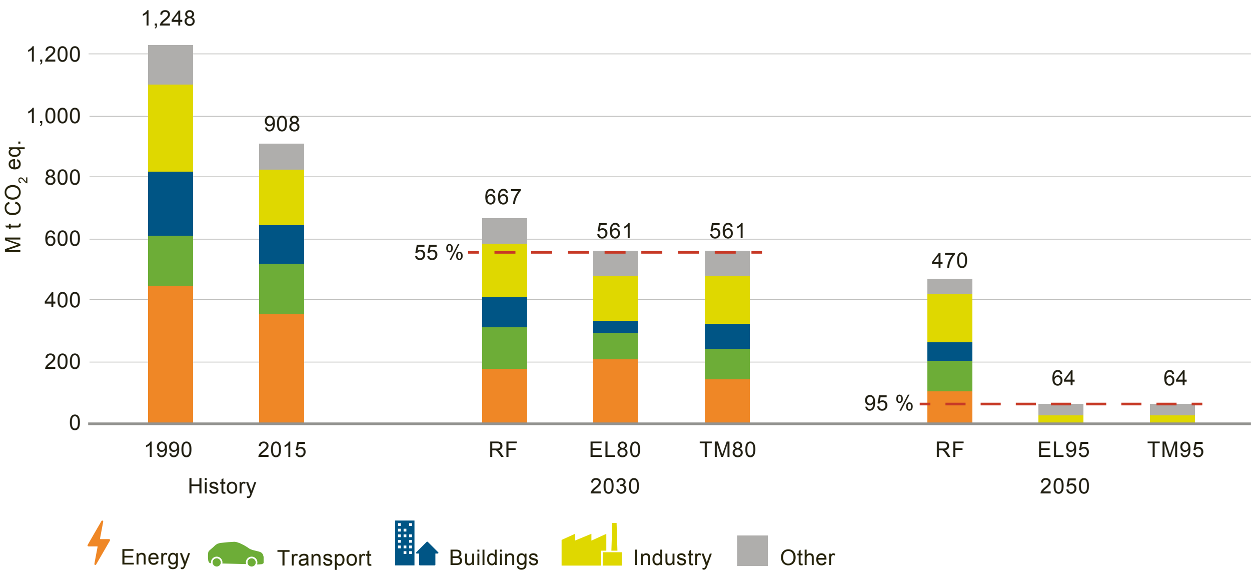


**Figure 1.2: Greenhouse gas emissions by sector**
95 % climate target




**3. To reduce greenhouse gases by 80 per cent by 2050, individual sectors must become completely carbon-neutral.**

For the 80 per cent target, either the building and transport sector (EL80) or the energy sector (TM80) must produce hardly any emissions in 2050. In EL80, the building sector reduces greenhouse gas emissions by 98 per cent compared to 1990, but only by 76 per cent in TM80. With an 88 per cent reduction, the transport sector also achieves almost complete climate neutrality in EL80. In TM80, however, only a 76 per cent reduction is possible, as the proportion of conventional engines is higher. Reductions in the industrial sector are comparatively small in both scenarios, as the remaining emissions are more difficult to eliminate.

In the building, industrial and transport sectors, the annual greenhouse gas emissions in 2050 amount to 123 million t $CO_2$ eq. in EL80 or 195 million t $CO_2$ eq. in TM80. Due to the higher emissions in the final energy consumption sectors, the energy sector must become almost climate-neutral in TM80, reducing its emissions by 99 per cent compared to 2015. Due to increasing electrification in the EL80 scenario, there is a significantly higher demand for electricity, lowering the reduction of greenhouse gases in the energy sector to 79 per cent by 2050 compared to 2015.

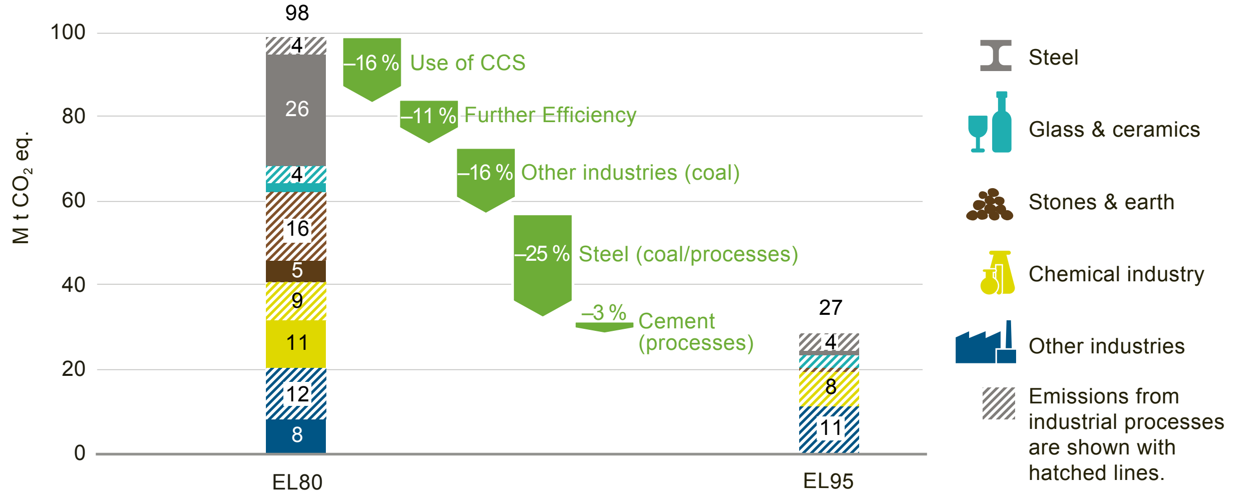
**4. With a 95 per cent reduction of greenhouse gases by 2050, the building, transport and energy sectors may no longer produce any emissions. The industrial sector requires major leaps in technology and the use of CCS.**

In EL95 and TM95, the energy, building and transport sectors will be completely carbon neutral, meaning that they no longer produce greenhouse gas emissions in 2050. After deducting emissions in the agriculture and waste industries, only 27 million t $CO_2$ eq. remain in 2050 – emitted by the industrial sector.

To take the reduction one step further, from 80 per cent to 95 per cent by 2050, the greatest efforts are required in the energy sector in EL95 (additional reduction of 76 million t $CO_2$ eq.). Compared to the 80 per cent target, industry also needs to reduce emissions significantly more (71 million t), which requires significant innovations and the use of CCS *(see figure 2)*. For the 80 per cent target, the building and transport sectors already reduce their emissions to a large extent by means of comprehensive electrification and provide an additional reduction of only 25 million t $CO_2$ eq. for the 95 per cent target.

In TM95, the additional burden is distributed differently. The largest contribution from 80 per cent to 95 per cent is made by an additional reduction of 99 million t $CO_2$ eq. in the industrial sector and the complete replacement of fossil fuels in the building and transport sectors (additional reduction of 69 million t $CO_2$ eq.). This is achieved by using significant quantities of Power Fuels. To reach the 95 per cent target in TM95, the energy sector only provides an additional reduction of 4 million t $CO_2$ eq., as it is nearly carbon-neutral for the 80 per cent target.

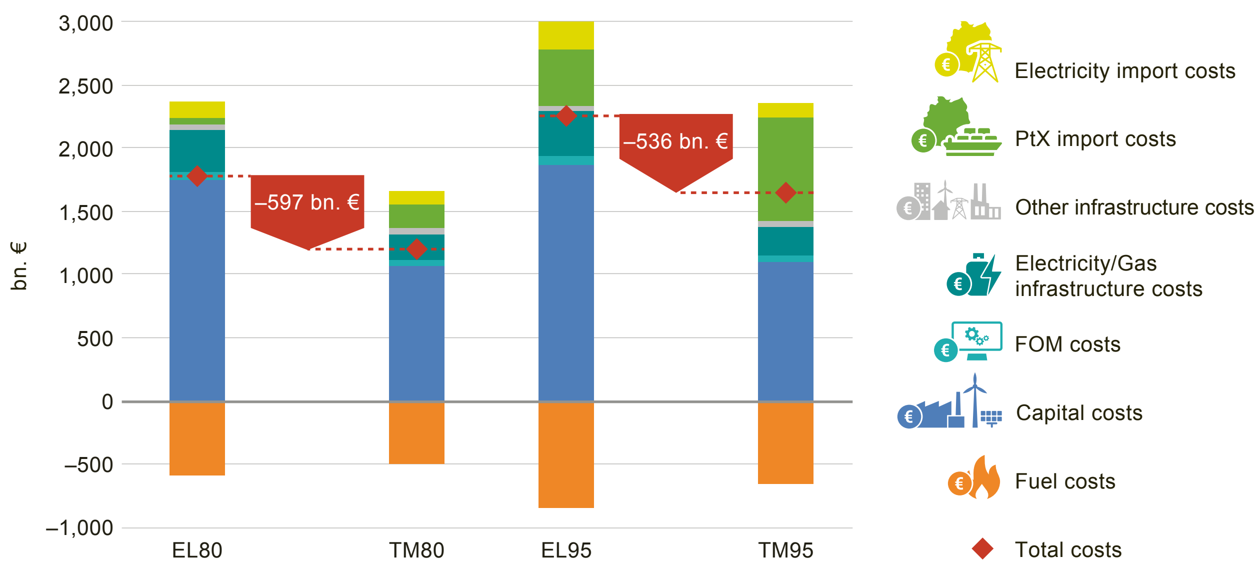
## Figure 2: Additional measures needed in the industry sector for reaching the 95 % climate target




**5. In order to meet the 80 per cent climate targets, additional costs of €1.18 to €1.77 trillion, depending on the scenario, are incurred by 2050 compared to the reference scenario. For the 95 per cent targets, this figure is €1.68 to €2.22 trillion. The climate targets are achieved at the lowest additional cost in the technology mix scenarios.**

Cumulative, undiscounted additional costs amounting to €1.77 trillion are incurred in the EL80 climate target scenario by 2050 compared to the reference scenario that does not achieve the targets. The TM80 scenario, with its additional costs of €1.18 trillion, is approximately €597 billion less expensive than EL80. The EL95 and TM95 scenarios cost €2.22 trillion and €1.68 trillion respectively compared to the reference trend. Thus, it is more economical to achieve the 95 per cent climate target with a technology mix strategy than with an electrification strategy *(see figure 3)*.

## Figure 3: Accumulated additional costs of the energy system 2018–2050 compared to reference



**6. In an electrification strategy, electric heat pumps become the dominant heating technology in the building sector. Furthermore, building refurbishment rates increase significantly. A technology mix strategy is characterised by a diverse range of technologies and energy sources with increasing building and plant efficiency.**

In the electrification scenarios, the building sector reduces its final energy consumption by 62 per cent (EL80) or 64 per cent (EL95) by 2050 compared to 2015. The final energy demand, especially of gas and oil, decreases so that in 2050 only smaller residual quantities of gas and oil are used.[1] In contrast, demand for electricity increases by 34 per cent / 72 TWh (EL80) or 31 per cent / 67 TWh (EL95) by 2050. This trend is characterised by significantly increasing refurbishment rates of 1.6 per cent to 2.8 per cent, depending on the type of building and scenario, which significantly decrease heating needs. The demonstrated decreases in final energy consumption are also due to the large-scale use of electric heat pumps. In 2050, 16 million (EL80) or 17 million (EL95) residential buildings will be heated by electric heat pumps, which corresponds to 77 per cent and 80 per cent of all residential buildings, respectively *(see figure 4)*.

By contrast, the technology mix scenarios are characterised by a greater variety of technologies and energy sources, as well as a less pronounced decrease in final energy consumption. In the TM80 scenario, the final energy consumption of the building sector decreases by 47 per cent by 2050 compared to 2015. Consumption of gas and oil in particular decreases, reaching 45 per cent and 24 per cent of their 2015 baseline levels in 2050. The reason for this decrease is, on the one hand, an increase in the refurbishment rate to 1.4 per cent and, on the other hand, the accelerated conversion to more energy-efficient technologies such as modern gas and oil heating or heat pumps. A look at the heating structure in residential buildings in 2050 illustrates this trend, as gas and oil heating remain the primary heating system in most residential buildings (49 per cent or 10.3 million). The number of electric heat pumps in residential buildings increases to 6.5 million, so they are used to heat 31 per cent of all residential buildings. The main difference between TM80 and TM95 is a slightly greater use of electricity to generate heat, bringing the number of residential buildings with heat pumps to 7.4 million in 2050, which is just over 1 million more than in the TM80 scenario.

**7. On an electrification path, electricity also covers a large part of the energy requirement in industry. In a technology mix strategy, however, gas and hydrogen become more important.**

In industrial production, the electrification scenarios utilise every potential to convert plants and processes to electricity. As a result, demand for electricity increases by 86 per cent / 246 TWh (EL80) or 88 per cent / 253 TWh (EL95) between 2015 and 2050. Electricity covers about two-thirds of the total final energy demand in the industrial sector (currently: 35 per cent). Other conventional energy carriers, notably coal and oil (down by 67 per cent in EL80 and 91 per cent in EL95 by 2050), become less important. Hydrogen and solar thermal energy supplement the energy mix in the industrial sector but play a minor role.

The technology mix scenarios rely less on electrification and more on the use of innovative processes and energy sources. Demand for electricity decreases by 13 per cent / 38 TWh (TM80) or 16 per cent / 46 TWh (TM95) due to the increased energy efficiency. The energy mix changes less than in the electrification scenarios, but coal and oil consumption are also reduced to a minimum of 61 per cent (TM80) or 87 per cent (TM95) by 2050. To offset this decrease, gas demand increases by about 25 per cent to 255 TWh (TM80) or 254 TWh (TM95) compared to 2015. The use of hydrogen in TM95 increases up to 64 TWh.

**Figure 4: Refurbishment rates needed in the different scenarios**

| | Family houses | Apartment buildings | Large apartment buildings |
|---|---|---|---|
| EL95 | 2.2 % | 1.8 % | 2.8 % |
| EL80 | 2.0 % | 1.6 % | 2.8 % |
| TM80/TM95 | 1.4 % | 1.4 % | 1.4 % |
| Current refurbishment rate | | ca. 1.0 % | |

[1] Note: Final energy demand in the building, industrial and transport sectors for gas, petroleum products and hydrogen can be covered by the energy sector in either a conventional or climate-neutral way via biogenic and synthetic energy carriers.

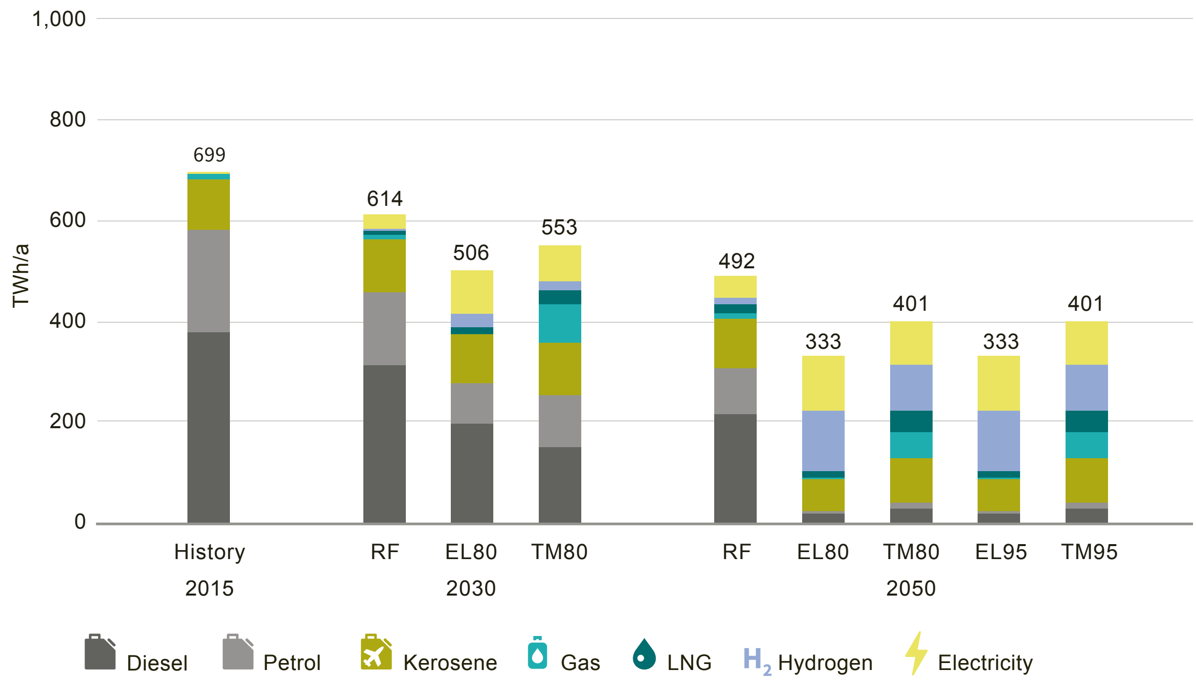
**8. In the electrification scenarios, battery and hydrogen propulsion systems become the dominant technologies in road transport. In addition, gas propulsion will be increasingly used in the technology mix scenarios.**

The transport sector undergoes major changes in both the electrification and technology mix scenarios *(see figure 5)*.

In the electrification scenarios, the transformation of road transport is characterised by a high market penetration of battery- and hydrogen-powered vehicles. By 2050, about 30 million BEV cars will be on the roads in the EL80 / 95 scenarios, thus achieving a car market share of 71 per cent. $H_2$-FCV cars will achieve a market share of just under 16 per cent. Petrol and diesel cars remaining in the market are used solely as plug-in hybrids. In road freight transport, hydrogen and electricity are the most significant energy carriers, displacing the diesel propulsion systems prevalent today. Market developments in rail, inland waterways and air traffic are also characterised by an increasing use of hydrogen propulsion systems. As a result, demand for electricity in the transport sector will increase to 110 TWh in EL80 / 95 by 2050 (compared to 11 TWh in 2015). At most, demand for hydrogen increases to 120 TWh in EL80 / 95 in 2050 (compared to 0 TWh in 2015). By contrast, demand for petrol and diesel – only 23 TWh in 2050 – is about 4 per cent of the level in 2015. Overall, the final energy demand of the transport sector decreases by 52 per cent to 401 TWh by 2050 compared to 2015 thanks to the use of innovative propulsion systems and the increased efficiency of conventional propulsion technologies.

In the technology mix scenarios, battery- and hydrogen-powered propulsion systems also play a major role in the future, especially in the car market, but gas propulsion systems will also be used to meet future mobility needs. In 2050, the car market will be comprised of BEV cars (12.1 million), $H_2$-FCV cars (12.1 million), methane cars (10.4 million, including 8.4 million plug-in hybrids) and petrol cars (7.9 million plugin hybrids). Diesel cars completely disappear from the market. In road freight transport, hydrogen and methane (LNG, CNG and their climate-neutral alternatives) are the most important energy carriers, displacing the diesel that dominates today. Gas, hydrogen and battery propulsion systems are also increasingly used in rail, inland waterway and air traffic. However, conventional propulsion systems remain in use. Accordingly, demand for gas in the transport sector increases most in the TM80 / 95 scenarios, amounting to 93 TWh in 2050 (compared to 4 TWh in 2015). Consumption levels of electricity (86 TWh) and hydrogen (92 TWh) will be similar in 2050. Demand for petrol and diesel is still 40 TWh in 2050 for the TM80 / 95 scenarios.

## Figure 5: The energy mix in the transport sector



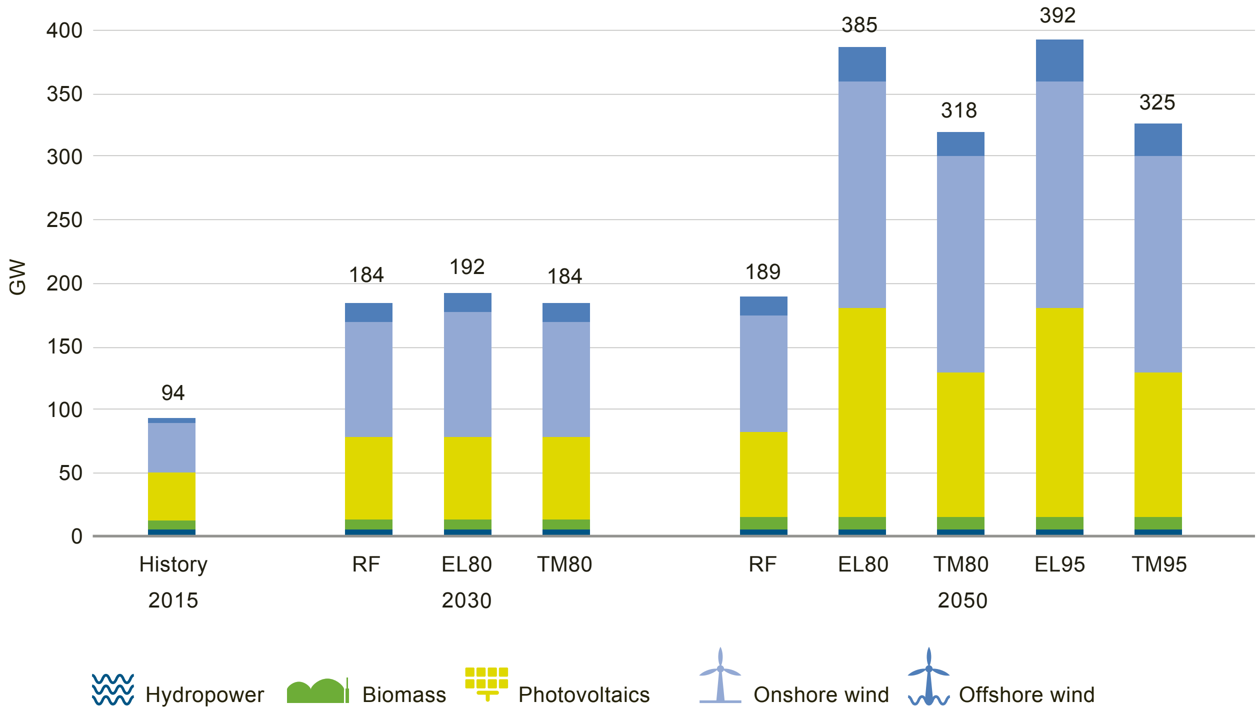
**9. Depending on the scenario, electricity generation from renewable energy sources will more than quadruple, reaching 740 to 879 TWh by 2050. This accounts for up to 91 per cent of total electricity generation. Around 60 per cent of this is generated by onshore wind turbines.**

In the EL80 and EL95 climate target scenarios, electricity generation from renewable energy sources increases by a factor of 4.1 to 4.7 between 2015 and 2050, reaching 851 TWh or 879 TWh, respectively. In the TM80 and TM95 target scenarios, electricity generation from renewable energy sources increases to 740 TWh or 769 TWh, respectively, by 2050. This is about 110 TWh less than in the electrification scenarios.

The increase in renewable electricity generation leads to a correspondingly increasing proportion of renewable energy in terms of net electricity generation. The proportion of electricity generated from renewable (primary) energy sources increases to at least 76 per cent (EL80) and up to 91 per cent (TM80 and TM95) by 2050.

In all the scenarios, onshore wind power accounts for the largest proportion of electricity generated from renewable sources – 493 TWh (EL80 / 95) or 471 TWh (TM80 / 95) – which corresponds to around 60 per cent of all renewable electricity generation. The second and third pillars of renewable electricity production are photovoltaics and offshore wind energy. Hydroelectric power as well as biomass and biogas power generation also contribute, but are limited by potential for expansion, which is already currently largely exhausted.

**Figure 6: Installed capacity of renewable energy sources in Germany**




**10. Gas-fired power plants are the dominant conventional electricity generation technology in all the climate target scenarios and are increasingly fuelled by Power Fuels and biomethane. Coal-fired power plants disappear from the market by 2050.**

Electricity generation from conventional power plants is subject to a drastic change in all the climate target scenarios. Lignite and hard coal electricity is halved by 2030 and no longer contributes a significant amount of electricity in 2050. This development is the result of national climate targets to reduce greenhouse gases by 55 per cent by 2030 and 80 per cent or 95 per cent by 2050.

At the same time, electricity generation shifts from coal to gas-fired power plants. While gas power generation increases in TM80 to about 69 TWh by 2050 (+15 per cent compared to 2015), it increases in EL80 to around 250 TWh by 2050 (+317 per cent compared to 2015). This difference is due to the much higher demand for electricity in EL80, as well as repercussions in the European electricity market, although there is less difference here between TM95 and EL95 due to greater efficiency gains in consumption. In all the climate target scenarios, gas-fired power plants will become the dominant conventional power generation technology.

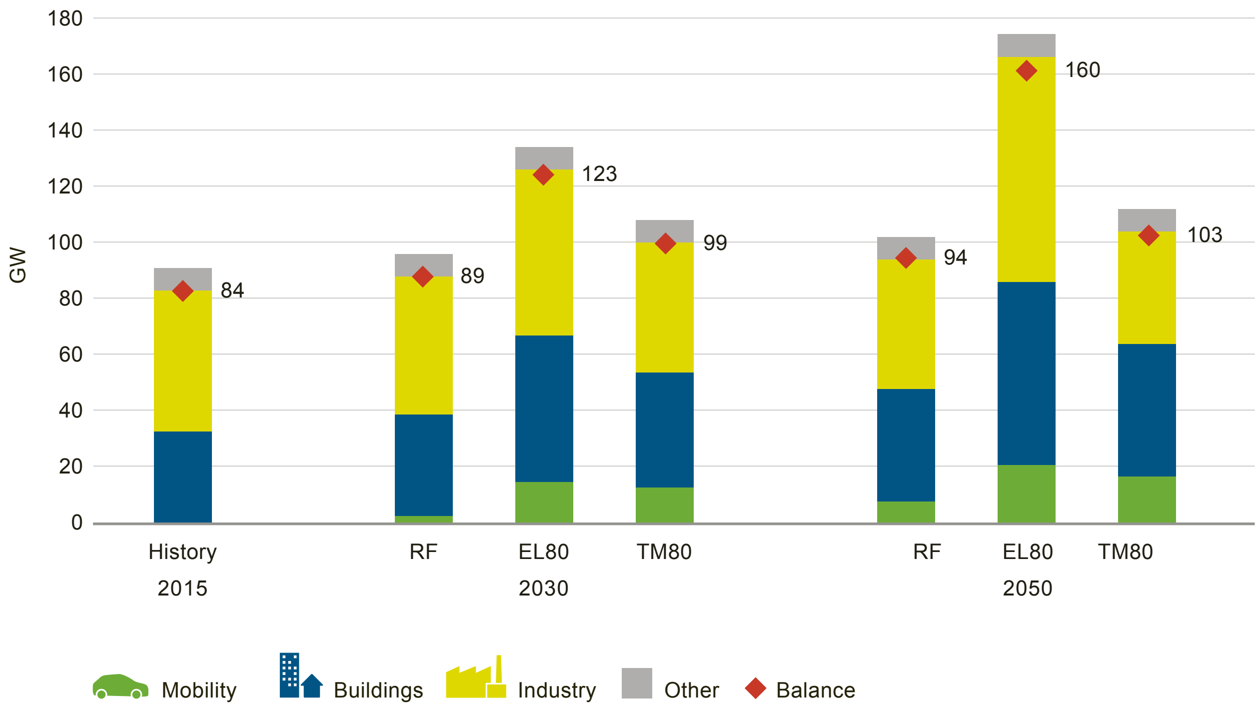
However, gas-fired power plants will not only burn natural gas in 2050, but also climate-neutral gases such as synthetic methane or biomethane. In 2050, exclusively climate-neutral gases are used in TM80, EL95 and TM95.

**11. The demand for secured electrical capacity doubles to 160 GW in the electrification scenarios by 2050, while it only increases slightly in the technology mix scenarios. Gas-fired power plants provide the majority of the demand for electrical power and are increasingly fuelled with climate-neutral gases.**

In the electrification scenarios, the demand for secured electrical capacity increases by 90 per cent to 160 GW by 2050 compared to 2015. This trend is attributable to the extensive electrification of the building and transport sectors. The electrical peak load increases significantly less, i.e. about +20 per cent by 2050 compared to 2015 in the technology mix scenarios, which have a lower degree of electrification. Easily storable energy carriers such as gas and oil, in increasingly climate-neutral forms, cover possible peaks in demand for energy which arise especially on cold days, e.g. for heating buildings *(see figure 7)*.

The increasing demand for electric power in all the scenarios is largely covered by gas-fired power plants. These include both large central plants as well as smaller decentralised plants, which leads to a decline in the utilisation of large-scale gas-fired power plants, especially in scenarios with high output requirements. These plants are increasingly fuelled with Power Fuels. In addition, increasing battery storage capacities and load control measures also contribute to load coverage.

**Figure 7: Demand for secured power generation capacities**




**12. In order to achieve the national climate targets, Germany imports large amounts of electricity from other EU countries, especially in 2030 and 2040.**

The phase-out of nuclear energy, the reduction in coal-fired power generation driven by the greenhouse gas reduction targets, and the simultaneous increase in demand for electricity all lead to clear import surpluses in all the target scenarios in 2030 and 2040, replacing today's electricity export surpluses. Depending on the scenario, these range between 92 TWh (TM80, 2030) and 155 TWh (EL95, 2040) and are lower in the TM80 / 95 scenarios than in the EL80 /

95 scenarios. With the exception of the EL95 scenario, import surpluses in the climate target scenarios decrease again until 2050, despite further increase in demand. In 2050, Germany is once again a net exporter of electricity in the in the technology mix scenarios but remains a net importer in the electrification scenarios.

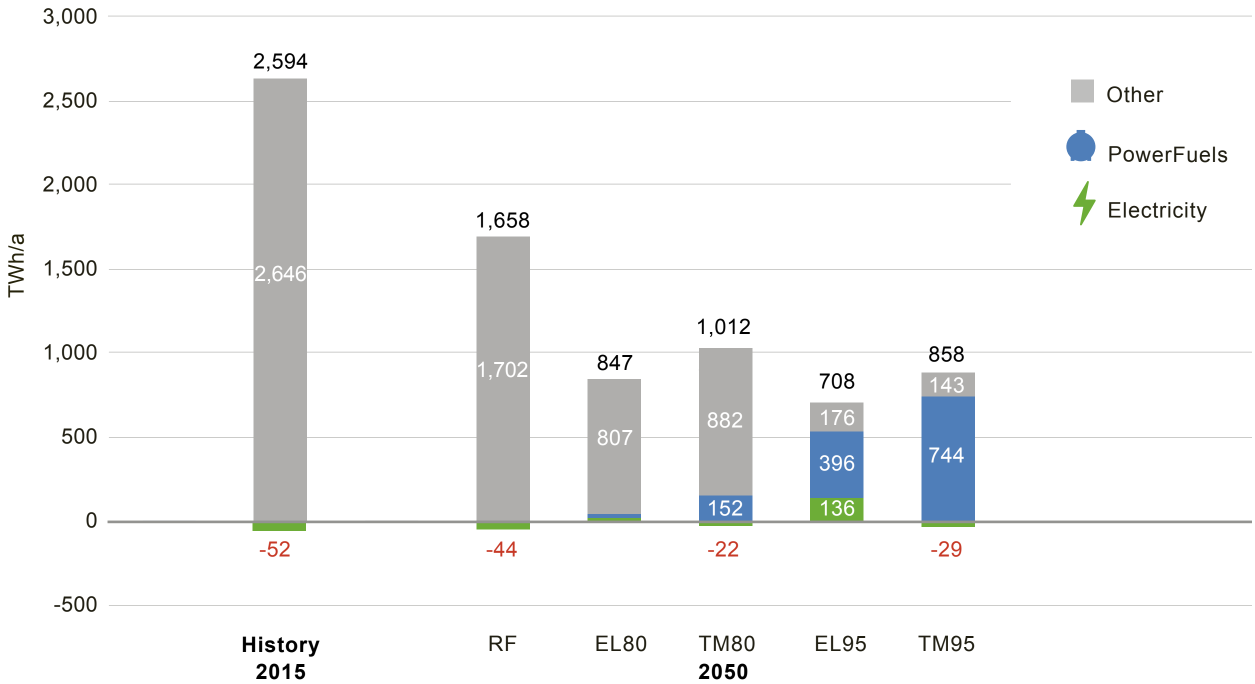
German electricity imports from other EU countries, however, have an increasingly lower greenhouse gas intensity in the climate target scenarios. This is due to the greenhouse gas reduction targets in the EU Emissions Trading System, which reduces the emissions of the electricity sector in other EU countries to as little as 61 million t $CO_2$ eq. by 2050. As a result of these reduction targets, the greenhouse gas emission factor of the energy mix in other EU countries decreases to less than 45 g/kWh in all the climate target scenarios.

**13. German primary energy consumption will decrease to around 2,000 TWh by 2050 in the climate target scenarios. Renewables and natural gas (80 per cent scenarios) or imported Power Fuels (95 per cent scenarios) form the new pillars of the German energy mix. With the 95 per cent climate target, fossil fuels are only used for material purposes.**

German primary energy consumption will decrease by 44 to 50 per cent to around 2,000 TWh in the climate target scenarios by 2050 compared to 2015. With an 80 per cent climate target, domestic renewable energy capacities will cover 55 per cent (EL80) and 48 per cent (TM80) of the remaining primary energy consumption in 2050. In both scenarios, around one-fourth is covered by natural gas, about 6 per cent (EL80) or 20 per cent (TM80) of which is for non-energy use. Due to the lower degree of electrified final energy consumption, imports of climate-neutral Power Fuels play a greater role in TM80 than in EL80 at 7 per cent compared with only 2 per cent. The proportion of fossil mineral oil (11 per cent in each) and coal (3 per cent in each) strongly decreases in both paths compared to today, where oil accounts for around half of the energy and material used *(see figure 8)*.

With a 95 per cent climate target, domestic renewable energy covers 61 per cent in EL95 and 51 per cent in TM95 of the remaining primary energy consumption in 2050. In TM95, the remaining consumption is almost completely covered by the import of Power Fuels. With a proportion of 21 per cent in 2050, these energy carriers are of far less importance in EL95 because the final energy consumption is far more electrified. With a proportion of 7 per cent, electricity imports play a greater role in EL95. Only the remaining 10 per cent of primary energy consumption is still covered by natural gas and oil fossil fuels. However, these are used exclusively for material uses in industry (mainly the chemical industry).

**Figure 8: Net energy imports in 2050**



**14. Synthetic climate-friendly energy carriers make a major contribution to reaching the climate targets. The 95 per cent targets cannot be achieved without these so-called Power Fuels. A large proportion of Power Fuels is imported from abroad.**

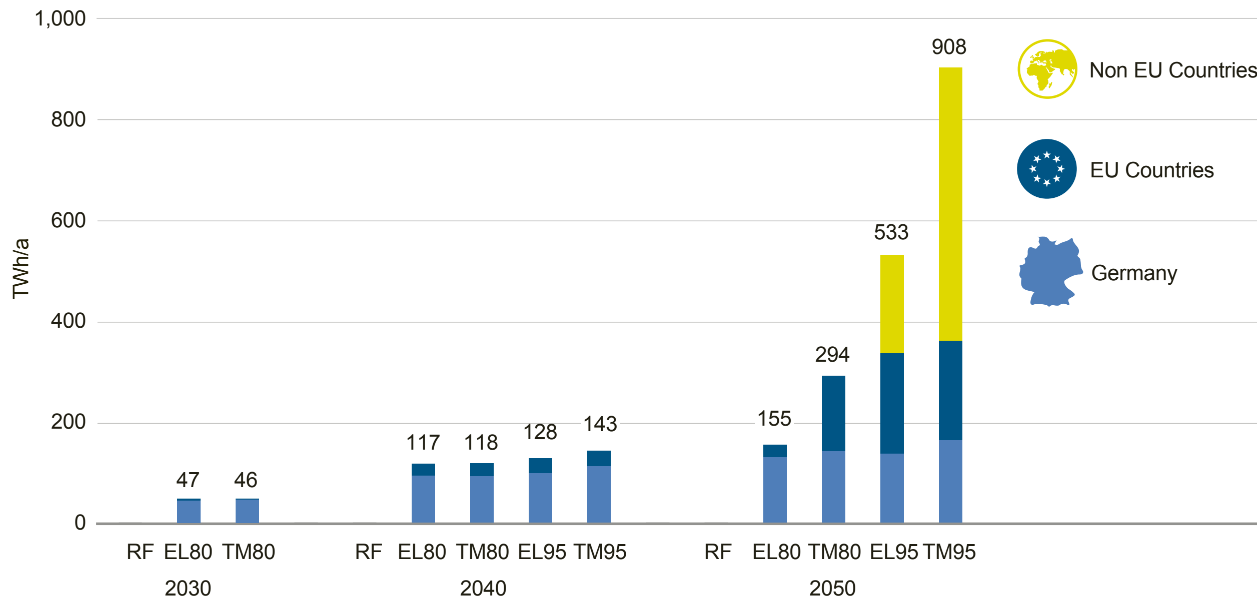
Starting in 2030, Power Fuels will increasingly be used to achieve the climate targets. Demand for Power Fuels will be around 47 TWh in 2030 and, depending on the scenario, 117 to 145 TWh in 2040. This results mainly from the assumptions that, first of all, hydrogen is increasingly used in industry and transport and, secondly, that this hydrogen must only be electrolysis-based, i.e. $CO_2$-neutral hydrogen. Accordingly, the demand is mainly for electrolysis hydrogen, which is mostly produced in Germany.

In 2050, the demand for Power Fuels is 155 TWh in EL80 and 294 TWh in TM80. With the 95 per cent climate target, the demand in 2050 is 533 TWh in EL95 and 908 TWh in TM95, which is more than three times higher than in the 80 per cent scenarios. Thus, in both the technology mix and electrification scenarios, the 95 per cent climate target can only be achieved by the large-scale utilisation of synthetic energy carriers *(see figure 9)*.

The demand in 2050 for Power Fuels is mostly hydrogen (151 TWh) in EL80 and about half hydrogen (147 TWh) and half methane (146 TWh) in TM80. The demand for Power Fuels in EL95 is largely covered by methane. But significant quantities of electrolysis hydrogen (169 TWh) and synthetic liquid fuels (43 TWh) are also used. In TM95, the largest proportion is also covered by synthetically produced methane (630 TWh), followed by similar amounts of hydrogen (169 TWh) and synthetic liquid fuels (108 TWh).

In the 80 per cent climate target scenario, most of the electrolysis hydrogen is produced in Germany, but synthetic methane is mainly imported from other EU countries. In the 95 per cent scenarios, the majority of the Power Fuels quantities will be imported from EU and non-EU countries in 2050. In the EL95 scenario, similar quantities are imported from non-EU countries as EU countries, amounting to 74 per cent. In TM95, an even larger proportion is imported, with 60 per cent imported from non-EU countries and 22 per cent from EU countries, for a total of 82 per cent. Due to the less favourable conditions for renewable electricity generation, only 26 per cent (EL95) or 18 per cent (TM95) of the total amount is produced in Germany, essentially hydrogen.

**Figure 9: Growing demand for renewable synthetic energy carriers**




**15. In the distribution grid, investments of around €150 billion in the technology mix scenarios and around €252 billion in the electrification scenarios are required to achieve the climate targets by 2050. Depending on the climate target, investment needs in the transmission grid amount to €79 to 91 billion by 2050 in the TM80 / 95 scenarios and €96 to 107 billion in the EL80 / 95 scenarios.**

While the lowest investment required in the distribution grid is expected to be around €48 billion in the reference scenario, it is much higher in the climate target scenarios. The highest investment need of around €252 billion is expected in the two electrification scenarios. For the technology mix scenarios, the expected need is around €142 billion (TM80) or €154 billion (TM95) *(see figure 10)*.

Overall, lower investment needs are expected in the transmission grid compared to the distribution grid. Depending on the climate target, this amounts to around €79 billion (TM80) or €91 billion (TM95) in the technology mix scenarios and around €96 billion (EL80) or €107 billion (EL95) in the electrification scenarios, compared to around €70 billion in the reference scenario. At about €53 to 58 billion, the investment required in the onshore sector in particular is similar in all the scenarios. Much of this (around €50 billion, of which 2/3 are HVDC measures and 1/3 overhead line technology) is accounted for by the measures already taken in the 2030 and 2035 Grid Development Plans.

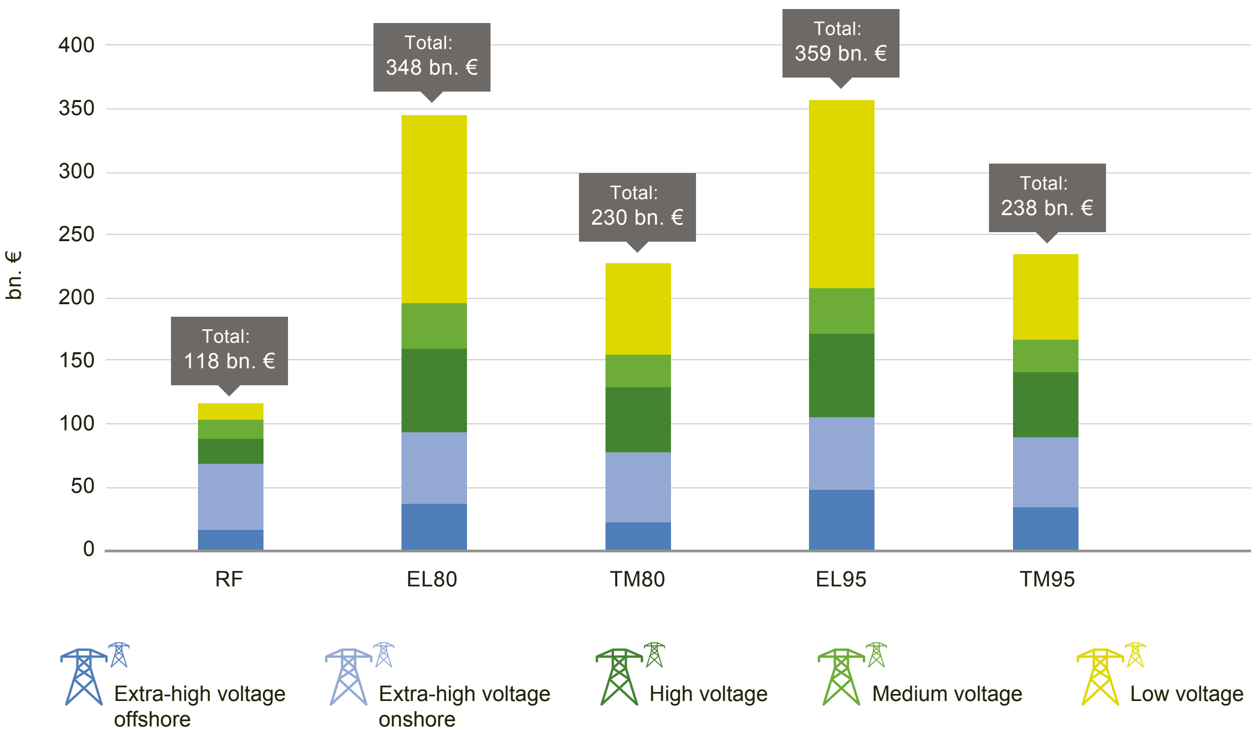
**16. The gas infrastructure continues to play a key role in the energy system in the future and is increasingly used to supply synthetic gas and biomethane as well as hydrogen.**

A significant decline in infrastructure-related demand for gas from building, industry, transport and energy conversion can only be observed in the electrification scenarios. While demand in EL80 and EL95 drops to 299 and 501 TWh by 2050, in TM80 and TM95 it remains roughly constant at 740 and 840 TWh compared to today. The existing gas infrastructure (long-distance grids, distribution grids and storage systems) can continue to meet the changing demand for gas, even if gas transit volumes to foreign countries are expected to increase. However, the location issue is increasingly relevant for the reliable operation of new gas-fired power plants since they must be close to both gas and electricity transmission grids.

Due to the high peak load in the electrification scenarios, parts of the gas infrastructure will continue to be of central importance for the energy system, despite the decreasing demand for gas. At the transmission level, only the utilisation of the grid is reduced, not the output. Depending on whether the secured electrical power capacity is provided from central gas-fired power plants or decentralised plants, the gas distribution grids may also experience a correspondingly high demand. Gas storage facilities also make an important contribution to providing temporal flexibility of gas demand and supply.

While today's gas grid infrastructure is used primarily for the transmission of natural gas, stricter climate targets are leading to the feeding-in of more and more synthetic gases and biomethane. Furthermore, admixed electrolysis hydrogen is increasing in importance.

**Figure 10: Accumulated investment costs in electricity grids 2018–2050**



**17. If important changes in the energy system do not occur fast enough due to societal acceptance problems, the 80 per cent climate target can only be achieved through the early use of synthetic energy carriers.**

A slower transformation of final energy consumption sectors as a result of societal acceptance problems leads to the more restrictive implementation of energy efficiency measures and the longer retention of conventional consumption technologies in the market. As a result, large amounts of final energy must be provided in the form of Power Fuels. Furthermore, the energy sector must compensate for this development by accelerating $CO_2$ reductions.

Moreover, if social resistance to the development of wind turbines onshore limits them to a maximum of 134 instead of 179 GW, the 80 per cent target can only be achieved if other technologies and energy sources compensate for this trend. This requires the early use of Power Fuels as well as increased generation of electricity from photovoltaics, wind energy at sea and (synthetic) gas. This requires 267 TWh of Power Fuels, for instance, by 2040. Demand is expected to increase to 493 TWh by 2050, which is about 200 TWh more than in the TM80 scenario.

**18. If Power Fuels imports from non-EU countries are more expensive than expected in the target scenarios, this will lead to a shift of production to other EU countries and additional costs of €195 to 461 billion.**

The sensitivity calculations, which assume that imports of Power Fuels from non-EU countries and production in the EU and Germany are generally more expensive than in the 95 per cent baseline scenarios, show the following: Firstly, Power Fuels production shifts from non-EU countries to other EU countries. Secondly, this creates additional costs. In this case, nearly the entire demand for Power Fuels will be produced in Europe. It becomes clear that large quantities of synthetic energy carriers can also be provided by the European electricity system in compliance with the greenhouse gas reduction targets set in the EU Emissions Trading System.

The more expensive Power Fuels production as well as the more expensive Power Fuels imports lead to additional costs €195 billion in the EL95 scenario and €461 billion in the TM95 scenario. Due to the lower use of Power Fuels in EL95, the additional costs compared to TM95 are significantly lower. Nevertheless, the TM95 scenario remains more economical than the EL95 scenario, even with higher prices for Power Fuels imports.

**19. The use of hybrid trolley trucks leads to the replacement of hydrogen-powered trucks in the electrification scenario and LNG trucks in the technology mix scenario. The demand for electricity in the transport sector increases while overall final energy demand decreases.**

Although the EL95 and TM95 scenarios vary with regard to the use of hybrid trolley trucks, this will lead to the replacement of other propulsion technologies in heavy freight transport and also change the final energy consumption of the transport sector. In EL95, hybrid trolley trucks mainly replace hydrogen-powered trucks, while in TM95 they mostly replace LNG trucks. Hybrid trolley trucks increase the electricity needs of the transport sector, while the final energy demand of traffic decreases due to the reduced demand for hydrogen, methane and diesel.

The integration of hybrid trolley trucks in both EL95 and TM95 leads to lower overall costs compared to the respective basic scenario. The increased costs for the expansion and operation of an overhead line infrastructure as well as for higher electricity imports are offset by savings to capital costs, fixed costs for operation and maintenance (FOM), Power Fuels import costs and energy system infrastructure costs, especially for the hydrogen infrastructure. The savings in TM95 are slightly higher than in EL95.

TABLE 1: Core findings of the scenario calculations

| Trends to 2050 (select) | Reference | 80 % climate target scenarios | | 95 % climate target scenarios | |
|---|---|---|---|---|---|
| | | Electrification (EL80) | Technology Mix (TM80) | Electrification (EL95) | Technology Mix (TM95) |
| **GHG emissions** | *Total* | | | | |
| | 470 M t $CO_2$ eq. (−62 % vs. 1990) | 250 M t $CO_2$ eq. (−80 % vs. 1990) | 250 M t $CO_2$ eq. (−80 % vs. 1990) | 64 M t $CO_2$ eq. (−95 % vs. 1990) | 64 M t $CO_2$ eq. (−95 % vs. 1990) |
| | *Average annual decrease from 2015* | | | | |
| | 13 M t $CO_2$ eq. | 19 M t $CO_2$ eq. | 19 M t $CO_2$ eq. | 24 M t $CO_2$ eq. | 24 M t $CO_2$ eq. |
| **Additional costs vs. reference (cumulative to 2050 and undiscounted)** | *Total* | | | | |
| | – | €1.77 T | €1.18 T | €2.22 T | €1.68 T |
| | *Electricity import costs* | | | | |
| | – | €131 B | €104 B | €231 B | €115 B |
| | *PtX import costs* | | | | |
| | – | €56 B | €187 B | €448 B | €813 B |
| | *Primary fuel costs* | | | | |
| | – | €−592 B | €−480 B | €−790 B | €−671 B |
| | *Infrastructure costs* | | | | |
| | – | €377 B | €253 B | €391 B | €272 B |
| | *FOM costs* | | | | |
| | – | €54 B | €47 B | €68 B | €52 B |
| | *Capital costs* | | | | |
| | – | €1,746 B | €1,064 B | €1,866 B | €1,098 B |
| **Final energy consumption** | *Final energy consumption in the building sector in 2050* | | | | |
| | 656 TWh (−34 % vs. 2015) | 383 TWh (−62 % vs. 2015) | 532 TWh (−47 % vs. 2015) | 362 TWh (−64 % vs. 2015) | 523 TWh (−48 % vs. 2015) |
| | *Final energy consumption in the industrial sector in 2050* | | | | |
| | 815 TWh (−1 % vs. 2015) | 837 TWh (+2 % vs. 2015) | 741 TWh (−10 % vs. 2015) | 781 TWh (−5 % vs. 2015) | 673 TWh (−18 % vs. 2015) |
| | *Final energy consumption in the transport sector in 2050* | | | | |
| | 470 TWh (−62 % vs. 2015) | 331 TWh (−52 % vs. 2015) | 401 TWh (−43 % vs. 2015) | 331 TWh (−52 % vs. 2015) | 401 TWh (−43 % vs. 2015) |
| **Final energy consumption of technologies** | *Average building envelope refurbishment rate 2015 to 2050* | | | | |
| | 1 % | 1.6–2.8 % | 1.4 % | 1.6–2.8 % | 1.4 % |
| | *Electric heat pumps in residential buildings to 2050 (2015: 0.5 M)* | | | | |
| | 3.2 M | 16 M | 6.5 M | 17 M | 7.4 M |
| | *Gas heating systems in residential buildings to 2050 (2015: 10.3 M)* | | | | |
| | 12 M | 1.6 M | 7.1 M | 1.2 M | 6.4 M |
| | *Oil heating systems in residential buildings to 2050 (2015: 6.2 M)* | | | | |
| | 2.8 M | 0.3 M | 3.2 M | 0.2 M | 2.9 M |

| Trends to 2050 (select) | Reference | 80 % climate target scenarios | | 95 % climate target scenarios | |
|---|---|---|---|---|---|
| | | Electrification (EL80) | Technology Mix (TM80) | Electrification (EL95) | Technology Mix (TM95) |
| **Final energy consumption of technologies** | *Efficiency gains in the industrial sector to 2050 vs. 2015* | | | | |
| | 23 % | 26 % | 28 % | 30 % | 33 % |
| | *Number of petrol / diesel cars in 2050 (2015: 44.3 M)* | | | | |
| | 29.1 M | 0.2 M | 0.0 M | 0.2 M | 0.0 M |
| | *Number of CNG / LNG / $H_2$ cars (2015: 0.3 M)* | | | | |
| | 2.1 M | 6.6 M | 14.5 M | 6.6 M | 14.5 M |
| | *Number of electric (BEV / PHEV) cars by 2050 (2015: 0.1 M)* | | | | |
| | 11.3 M | 35.7 M | 28.1 M | 35.7 M | 28.1 M |
| | *Number of petrol / diesel trucks / light commercial vehicles (2015: 2.7 M)* | | | | |
| | 1.6 M | 0.1 M | 0.1 M | 0.1 M | 0.1 M |
| | *Number of CNG / LNG / $H_2$ trucks / light commercial vehicles (2015: 0.0 M)* | | | | |
| | 0.8 M | 1.2 M | 1.7 M | 1.2 M | 1.7 M |
| | *Number of electric (BEV / PHEV) trucks / light commercial vehicles by 2050 (2015: 0.0 M)* | | | | |
| | 0.8 M | 2.0 M | 1.4 M | 2.0 M | 1.4 M |
| **Energy sector** | *Demand for electricity in 2050 (2015: 567 TWh)* | | | | |
| | 612 TWh (+8 % vs. 2015) | 1,150 TWh (+103 % vs. 2015) | 809 TWh (+43 % vs. 2015) | 1,156 TWh (+104 % vs. 2015) | 837 TWh (+48 % vs. 2015) |
| | *Proportion of net electricity generation from RES (2015: 30 %)* | | | | |
| | 72 % | 76 % | 91 % | 87 % | 91 % |
| | *Import balance (2015: −52 TWh)* | | | | |
| | −44 TWh | 15 TWh | −22 TWh | 136 TWh | −29 TWh |
| **Overall system** | *Primary energy consumption in 2050 (2015: 3,681 TWh)* | | | | |
| | 2,484 TWh (−33 % vs. 2015) | 2,007 TWh (−46 % vs. 2015) | 2,069 TWh (−44 % vs. 2015) | 1,861 TWh (−49 % vs. 2015) | 2,007 TWh (−46 % vs. 2015) |
| | *Proportion of primary energy consumption from renewable energy sources in 2050 (2015: 12 %)* | | | | |
| | 29 % | 55 % | 48 % | 61 % | 51 % |
| | *Imports of synthetic energy carriers (2015: 0 TWh)* | | | | |
| | 0 TWh | 25 TWh | 152 TWh | 396 TWh | 744 TWh |

For further information on the dena Study Integrated Energy Transition please visit:

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