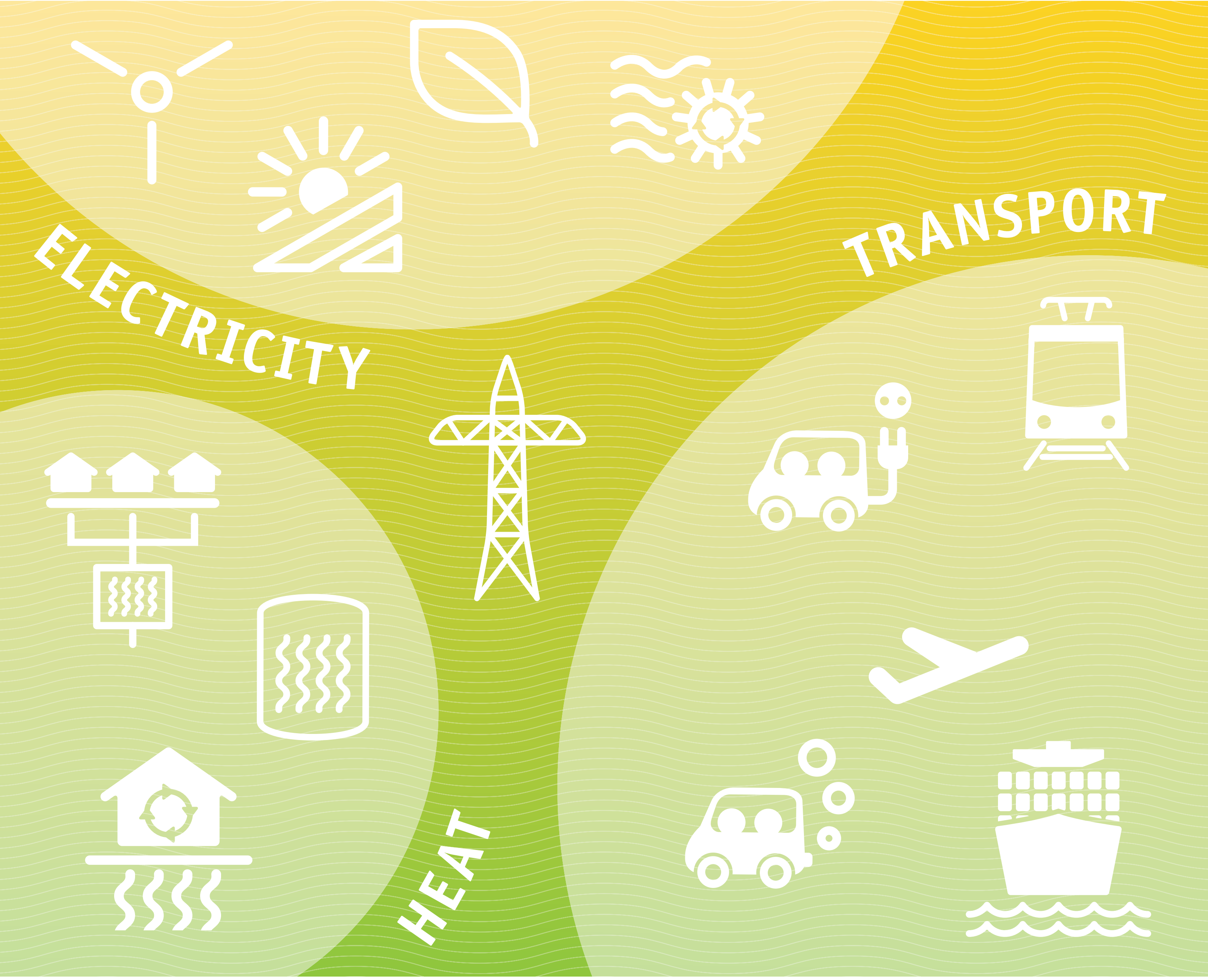

Sector coupling

Using electricity for heating and transport to protect the climate

Background paper | Version date: 16.03.2017

Summary

This background paper discusses the benefits to the climate offered by various options for the use of electricity in heat generation and electricity in transportation, with the following findings:

- In view of the climate targets set for 2050, it is anticipated that the complete replacement of fossil fuels in these sectors will only be achieved through the additional use of electricity generated from renewable energy sources (RES).

- In the heating and transport sectors, measures to reduce final energy consumption by increasing efficiency and avoiding consumption are necessary to achieve the climate targets. They have a high greenhouse gas (GHG) abatement potential, even in the short-to-medium term.

- Assumptions vary widely regarding the amount of additional power from renewables required to support a heating and transport sector run largely on electricity. Because electricity from RES is not in infinite supply, it is expected that sector coupling ("Sektorenkopplung") would only be able to make a contribution to climate protection if the final energy demand of the sectors were to fall by 40 to 60 per cent overall.

- A significant reduction in CO_2 emissions from the electricity used will be necessary if electricity-based applications are to replace fossil fuels gradually between 2030 and 2050. To achieve this, the growth trajectory for RES must be raised significantly and coal-fired generation reduced.

- The use of electricity from RES in the heating and transport sectors only makes sense from a climate protection perspective if this prevents more CO_2 being produced than is emitted in the electricity mix (in 2015 this was 565 grams CO_2/kWh). As a result, only a few applications currently benefit the climate:

  » In the **buildings sector**, electrically powered **heat pumps** – including those in heating networks supplied by renewables – achieve efficiency levels of about 300–500 per cent. Even with RES comprising just under one-third of today's electricity mix, the replacement of oil-fired heating systems with heat pumps could already save around 14 Mt of CO_2. Exchanging existing gas boilers for heat pumps could save a further 14 Mt. Potential savings will also increase as the share of RES in the electricity mix grows.

  » With the current electricity mix, the direct use of electricity to generate heat in **electrode boilers** is not yet expedient. In this case, supplying one kilowatt-hour of electricity emits twice as much CO_2 as supplying the same amount of energy from fossil fuels. Only electricity from RES that would otherwise be curtailed and which has a very low CO_2 emission factor can be used for this purpose.

  » In the **transport sector**, **battery-electric vehicles** in the passenger car segment can achieve a carbon footprint that is comparable with that of efficient petrol and diesel engines. Within the parameters of today's electricity mix, battery-electric transport is, however, still not able to make a significant contribution towards reducing emissions from transportation. The balance may improve in favour of electric drives as the CO_2 load of the electricity supply decreases.

  » In the transport sector, the use of electricity is particularly effective in **rail transport**. Moving elements of motorised passenger and goods transport over to rail offers significant potential in terms of GHG abatement. For example, increasing the share of the goods transport load carried by rail to 25 per cent could theoretically allow for savings in CO_2 emissions amounting to approx. 8.6 Mt. For this to succeed, however, the competitive conditions would need to be improved through regulatory adjustments, and investments in infrastructure development would be required.

  » Due to the high energy input required in their production and their lower efficiency compared with the direct use of electricity, the use of synthetic fuels produced by means of processes such as **power-to-gas (PtG)** and **power-to-liquid (PtL)** is only ecologically worthwhile when the share of RES within the power supply reaches almost 100 per cent. However, as an option for providing flexibility or storage, PtG and PtL may be significant in a power system where the share of RES is only 60 to 80 per cent. With the use of electricity-based fuels, the necessary amount of electricity generated from renewables increases disproportionately. Given the limited availability of electricity generated from RES, these fuels should therefore only be used when the direct use of renewable energies or renewable electricity is not possible. However, since electricity-based fuels could play a key role in the decarbonisation of the heating and transport sectors in the future, it would be advisable to continue to develop the technology and begin its use from 2030.

Introduction

In the light of the resolutions agreed at the United Nations Climate Change Conference held in Paris in December 2015, GHG emissions in Germany must be reduced by 95 per cent by 2050. Consequently, in addition to the electricity sector, the energy consumption sectors heating and transport must also become greenhouse gas-neutral by 2050. To achieve this, efficiency measures must first be taken to significantly reduce the existing energy consumption in all three sectors. The remaining energy demand will need to be met for the most part through renewables. Alongside energies like solar thermal energy and biomass, which can be used directly, renewable electricity particularly from sun and wind is also necessary.

To this end, the heating and transport sectors must be "coupled" with the electricity sector. Sector coupling ("Sektorenkopplung") is also proposed as a flexibility option to stabilise power systems comprising large proportions of fluctuating electricity generation.

This background paper describes the requirements and opportunities for coupling heating and transport with the electricity sector.

The following issues are examined:

- What CO_2 reduction potential can be realised through the sector coupling of power to heat and power to transport?

- What sector coupling technologies can be deployed to achieve reductions in CO_2 emissions, and when?

- What significance does this have for the expansion of renewable energies?

- What contribution can sector coupling make as a flexibility option?

The objective is to create a basis for discussion and to provide guidance on how sector coupling can be useful from a climate protection perspective. At the end of each section, the paper formulates policy recommendations for the advancement of sector coupling.

The climate-protection potential of sector coupling in the heating sector

Current situation and targets in the heating sector

The heating sector (industry, households, trade, commerce and services) makes up about 50 per cent of Germany's final energy consumption and about 32 per cent of its energy-related GHG emissions. As the largest of the three consumption sectors (power, heating, transport), the heating sector has a key role to play in achieving Germany's climate protection goals.

Policy makers have not set any specific targets for the heating sector as a whole either in terms of the reduction of final energy consumption or the share of renewable energies. The Federal Government has only set clear objectives for the buildings sector[1], in which it is striving for an almost carbon-neutral building stock by 2050. Consequently, this evaluation and the recommendations derived from it are focused on the buildings sector.[2]

With a combination of energy saving and the utilisation of renewable energies, it is intended that the primary energy demand of buildings will be reduced by 80 per cent by 2050 in comparison with 2008 values.[3] With the 1.5-degree limit in mind, which was set at the Paris United Nations Climate Change Conference and which necessitates a GHG reduction of 95 per cent by 2050 (compared to 1990) across all sectors, the objective for the buildings sector will need to be even more ambitious.[4] If technologies such as carbon capture and storage (CCS), which are subject to risks and trade-offs, or a possible reduction of emissions from land use, land-use change and forestry (LULUCF) are excluded from the calculation of future emissions budgets, then a 100 per cent reduction in primary energy demand by 2050 would actually be required. In absolute figures, this corresponds to a reduction in the non-renewable primary energy consumption in the buildings sector from approx. 1,200 TWh (640 TWh for residential buildings, 560 TWh for non-residential buildings) in 2008 to 0 TWh (for residential and non-residential buildings) by 2050.[5]

This goal can be achieved only by implementing very ambitious energy efficiency measures and establishing a heating supply based exclusively on renewables.

Although progress has been made with regard to increases in energy efficiency and thus a reduction in final energy consumption since 1990, the values have stagnated in recent years and the annual rate of building renovation is below one per cent. Renewable energies currently only represent a share of about 13 per cent in the heating sector. The remainder is still provided by fossil energy sources. These figures clearly show that there is still significant potential for GHG reduction in the heating sector.

Energy efficiency as a basis for sector coupling

Improvements in energy efficiency are absolutely key to achieving the climate goals and the coupling of the electricity and heating sectors. Firstly, a 100 per cent reduction in the primary energy demand in the buildings sector cannot be accomplished without efficiency gains. Secondly, efficiency gains limit the additional demand for renewable power (electricity from RES for the decarbonisation of the heating sector) to a necessary minimum. Otherwise, the additional electricity demand would increase dramatically and would exceed achievable capacity owing to problems of space and acceptance.

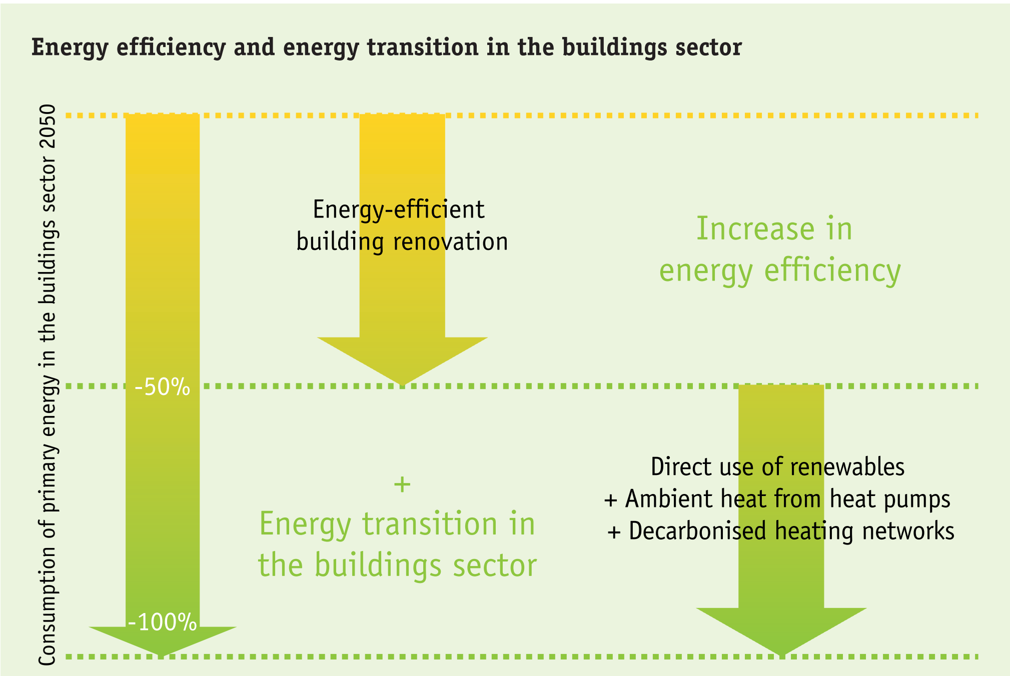

Figure 1: Reduction of primary energy consumption through energy efficiency and energy transition in the buildings sector. Source: own illustration

Depending on the efficiency and renewable energy priorities set to achieve the goal of greenhouse gas-neutrality, the installed electrical capacity will vary up to 2050.[6] Once again, it is clear that the most climate-friendly kilowatt-hour is the one that is not consumed.

This should also be reflected in political priorities when it comes to the ongoing development of the energy transition: according to the principle of "efficiency first", investigating ways of saving energy should be the first concern. When these options have been fully exploited, attention should move to the direct use of renewable energies followed, only as a last resort, by the use of renewable electricity to generate heat by means of sector coupling (see Figure 1).[7]

When it comes to the energy efficiency potential, various scenarios in terms of trends and targets demonstrate savings in final energy consumption for space heating and hot water ranging from 40 to 60 per cent by 2050 (compared with 2008). Greater savings are not possible for various reasons. Preservation orders as well as architectural and technical constraints on insulation in the building stock (relating to construction, building physics, geometry) are a hindrance.[8] Since existing buildings represent a much higher proportion of the total building stock than new buildings, greater emphasis should be placed on them with regard to energy savings.[9] In practical terms, an ambitious efficiency scenario would require a building renovation rate of an average of two per cent – i.e. double the current rate of renovation. Based on final energy consumption for space heating and hot water of 889 TWh in 2008, this would result in a reduction to 445 TWh.

What is certain is that the greater the level of energy efficiency, the more realistic it is that the remaining heating requirement can be met with renewables. However, it is also clear that the primary-energy savings obtainable through efficiency measures are limited and a greenhouse gas-neutral building stock cannot be achieved solely by reducing final energy consumption.

Direct use of renewable energies (biomass, solar thermal energy, geothermal energy)

Due to the limited energy-saving potential of efficiency measures in primary energy, the next step must be to make direct use of renewable energies to supply heat in the buildings sector.

On-site, direct use of renewables

According to projections, the potential contribution of on-site solar thermal energy to the heating demand of buildings in 2050 is between 53 and 69 TWh per year[10]. There are constraints placed on the technology through the orientation and load-bearing capacity of roof surfaces, seasonal supply and limited solar fraction.

The potential of biomass in decentralised applications is expected to be between 69 and 139 TWh per year by 2050.[11] The amount of waste materials is limited and there are also concerns from a sustainability perspective when it comes to the cultivation of biomass. Moreover, there is competition for resources with other applications that are difficult to convert to electricity, as well as the exploitation for industrial process heat at high temperatures. Consequently, biomass must be used as efficiently as possible in cogeneration units, which simultaneously provide electricity and heat at a high temperature. The use of biomass is thus increasingly shifting from decentralised local heating to a networked supply or industrial biomass plants.[12] The potential from the direct, on-site use of renewable energies is accordingly between 122 TWh and 208 TWh. That leaves a further 237 to 323 TWh of final energy consumption still to be decarbonised.

Direct use of renewables in heating networks

The limited capacity of on-site, direct use of renewables must be supplemented with decarbonised (local and district) heating networks. Possible options for the direct use of renewable energies in heating networks include (deep) geothermal energy, large-scale solar thermal installations, biomass and waste heat from industry. Unfortunately, the technical and economic potential of heating networks has not yet been examined in sufficient detail. Estimates suggest a heating network potential of between 100 and 140 TWh. In 2013, only approx. 15 TWh of district heat consumed was sourced from renewables. Accordingly, the proportion of RES (biomass, deep geothermal energy, etc.) in heating networks would have to be increased by seven to ten times to allow for decarbonisation.[13]

However, a more comprehensive assessment of the potential of large-scale solar thermal installations and deep geothermal energy is needed. For deep geothermal energy in particular, favourable geological conditions are required, which are present in only a few places in Germany. In addition to other factors, such as cost-effectiveness and acceptance, the development potential of this energy source therefore appears to be limited. Solar thermal energy's potential for expansion has also been classed as limited by the scientific community.[14]

Overall, the potential of the on-site and networked direct use of renewable energies in combination with efficiency measures is not sufficient to achieve decarbonisation of the buildings sector. **The gap to be filled amounts to between 212 TWh and 308 TWh (of which approx. 85 to 125 TWh in heating networks)**.

Use of electricity from renewables in the heating sector

To decarbonise the remaining energy demand, when it comes to a low-temperature supply, electric heat pumps are deemed to be the key technology for the integration of renewable electricity into the heating sector.[15] They can be used both locally in the buildings themselves and centrally to supply heating networks. In almost all existing scenarios, heat pumps will become one of the most important sources of heat for individual buildings by 2050. The technology is already relatively mature and technological progress is expected to lead to further efficiency gains.[16] With the advancing transformation of the energy system, projections and studies predict a necessary proportion of heat pumps in all heating installations of over 80 per cent.[17]

Heat pumps can make use of various sources of ambient heat: air, ground water or the ground itself. There are differences in their levels of efficiency. The efficiency of heat pumps is dependent on their seasonal performance factor (SPF). This describes the ratio of the electrical energy used for useful energy in the form of heat for over a year. The SPF depends on the type of heat pump, the quality standards observed, the configuration, the area of application and the temperature of the heat source. Brine-to-water heat pumps normally achieve higher efficiency values than air-to-water heat pumps. Forecasts for future SPFs range from 2.9 to 4 for air-to-water heat pumps and from 3.1 to 4.9 for brine-to-water heat pumps.[20]

High-capacity heat pumps can be used to supply heating networks. This requires the transformation of existing heating networks – high-temperature networks must be adjusted to suit the low temperature.[21] To develop a comprehensive heating supply based on renewables, the consolidation of existing heating networks and the construction of new networks in places where they are needed to harness renewable heat sources must be driven forward.

Use of high-capacity heat pumps and power-to-gas for process heat

With regard to process heat, energy savings must be obtained through the consistent exploitation of waste heat and by optimising processes. For a temperature level of below 100 degrees Celsius, the use of high-capacity heat pumps is worth considering when it comes to decarbonisation. This technology would also contribute toward an efficient use of waste heat. Most notably, cogeneration systems with integrated electrode boilers have a role to play for temperatures up to 500 degrees Celsius. For temperatures higher than this, power-to-heat (PtH) and – in the long term also – PtG technologies must be deployed in order to replace fossil energy sources. These schemes are, however, still not seen as economically viable. Due to high conversion losses, PtG is only economically and environmentally worthwhile once the share of renewables has reached almost 100 per cent.[18] Nevertheless, it is vital that this technology is tested and further developed today. Forecasts indicate that no technology should be excluded, especially given the ambitious climate goal, and that in the long term PtG will play an important role in the generation of renewable process heat as fossil energy sources are increasingly squeezed out.[19]

CO_2 mitigation potentials

The heating sector can only be fully decarbonised by integrating renewable electricity. Unlike PtG technologies, heat pumps are already able to make an important contribution to reducing CO_2 emissions with the current share of renewables in the electricity mix (see Figure 2). In terms of time and with regard to the content of CO_2 in the electricity mix, which is currently still high, the use of heat pumps is more efficient than PtG as things stand at present.

Current scenarios suggest that the share of RES in the heating supply for buildings must undergo a five- or sixfold increase if the buildings sector is to be largely decarbonised and if the 2050 targets are not to be jeopardised.[22] This means that the time factor plays an important role when developing CO_2 mitigation potentials. The current sales figures of just under 60,000 heat pumps per year[23] are not sufficient. To be on target for 2050, four to eight million heat pumps would need to be installed by 2030,[24] but there were only around 600,000 in total by the end of 2015.[25] At the same time, at least 3.7 million oil-fired boilers and 2.8 million gas boilers in the building stock are more than 25 years old and, in accordance with the Energy Saving Ordinance (EnEV)[26], boilers must be replaced after a maximum of 30 years. Consequently, a large-scale replacement of heat generators lies in store for 2020. This convenient opportunity must be capitalised upon as a matter of urgency to avoid bad investments and lock-in effects.

The precise, technical emissions mitigation potential of the various types of heat pumps has been studied in field tests over several years. With an SPF of 2.3 and over, brine-to-water heat pumps are already saving GHG emissions compared with fossil-based systems. And with an SPF of 3.2, the CO_2 savings of a heat pump (with the current electricity mix[27]) equate to approx. 30 per cent compared with a gas boiler.[28] In new constructions, heat pumps can achieve an SPF of 5 (in some cases, even higher). This results in potential savings of approx. 50 per cent. This shows that heat pumps are generally also suitable for the existing building stock. Further development of the technology will lead to even better results. As the share of RES in the electricity mix rises, the decarbonisation effect and thus the potential for CO_2 savings also stand to grow. The details are illustrated in Figure 2.

CO_2 mitigation potentials of various heating technologies

Heating technology	CO_2eq. [g/kWh]	Efficiency factor	CO_2 eq. [g/kWh$_{th}$]	CO_2 eq. [T./a] Ø Single-family home	CO_2 eq. Saving in %
Oil-fired boiler	319	1	319	8,9	Reference
Gas-fired boiler	250	1	250	7	22%
Heat pump (SPF 3)	565	3	188	4,2	53%
Heat pump (SPF 5)	565	5	113	2,5	72%
Power-to-gas electrolyser	565	0,8	706	15,8	*77% additional consumption*

Figure 2: Assumption: Average single-family house with annual heating requirement of 22,400 kWh p.a. (160 kWh p.a. per m2; 140 m2 living space). Own calculations on the basis of TU Munich (2013). Electricity (German energy mix), CO_2 eq. (g/kWh): 565 g. Source: GEMIS database version 4.95, 11/2016

Despite this, the theoretical potential of heat pumps in achieving the climate goals has limits in real practice. Heat pumps cannot be deployed in every building due to constraints resulting from building density, hydrological conditions and existing subterranean infrastructure. Therefore, the maximum percentage of heat pumps for the entire building stock is currently estimated to be around 60 per cent.[29] Taking these limitations into account, the potential for the expansion of heat pumps remains at approx. 116 TWh in 2050.[30] Other forecasts assume a maximum potential for the exploitation of ambient heat through heat pumps of only 58 to 100 TWh.[31]

Figure 3 shows the amount of CO_2 saved by using heat pumps instead of conventional heating technology. It indicates that total savings of 28 Mt CO_2 can already be made through sector coupling.

Existing barriers

The current low price of heating oil is a bar to the introduction of heat pumps. Sales of oil-fired heating systems have risen in the last year.[32] Because oil-fired heating systems are also still being subsidised, there is a danger that the opportunity to act in

CO_2-savings potential of heat pumps compared with fossil-based heating technologies

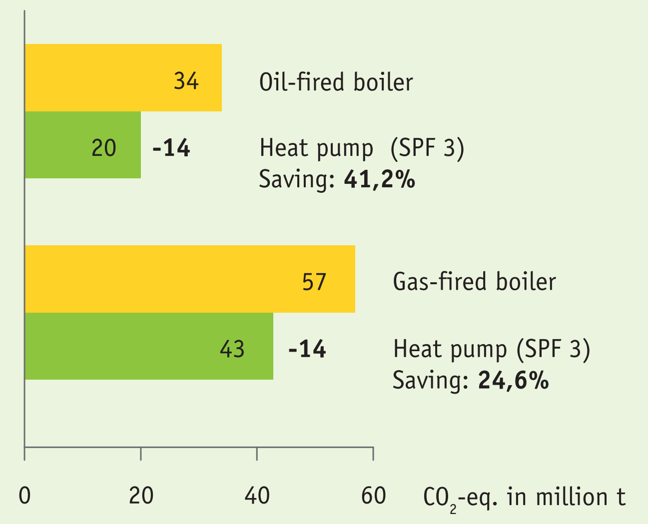

Figure 3: Assumption: Final energy consumption of oil (177 TWh) and gas (379 TWh) for space heating and hot water in 2014. Of this, 60% would be replaced by a heat pump (SPF 3) (maximum potential for heat pump installation). Electricity (German energy mix), CO_2 eq. (g/kWh): 565 g. Source: GEMIS database version 4.95, 11/2016. Consumption data from Quaschning (2016)

support of the climate will be lost when boilers are replaced due to perverse incentives.

In contrast, the electricity price is heavily weighed down by levies and taxes, which make up about 54 per cent of its cost to consumers.[33] The imbalance in taxation and the high price disparity between gas/oil and electricity represents the biggest obstacle to coupling the electricity and heating sectors.

In reality, the SPF of some heat pumps is relatively wide-ranging.[34] This indicates that the efficiency of heat pumps – which is actually good – is partially impaired by mistakes in their installation and configuration. Proper technical installation is an important requirement if GHG abatement potentials are to be unlocked.

Recommended actions

To eliminate the barriers described and fully exploit the potential of sector coupling in the heating sector, the following options are recommended for incorporation in the policy framework:

- Adjust energy taxes with CO_2 emissions as the basis for assessment: fossil energy sources must be made more expensive by realigning the tax rates to factor in the environmental follow-up costs, thus improving the competitiveness of energy-efficiency measures and renewable energies.
- Discontinue state support via the KfW development bank for oil and gas-fired condensing boiler systems: every investment decision in favour of a heating system run exclusively on fossil fuels means emissions for the next 20 to 30 years. Given the urgent need for action, investments in efficient fossil-based heating technology should not be state-funded either.
- Prohibition on the installation of oil-fired and gas heating systems from 2025: assuming a shortened decommissioning period of 25 years for old boilers, oil and gas-fired boilers should only be installed in exceptional cases after 2025. Failing this, a greenhouse gas-neutral heating supply in 2050 would not be possible.
- Continuing education campaign for craftsmen: in order to make the widespread, fault-free installation of heat pumps possible in practice, there must be training opportunities available for craftsmen. Specialist heating engineers will need to be trained to properly install and configure heat pumps so that the highest possible SPF can be obtained without repeated adjustments to the equipment being necessary.
- Promote municipal heat planning – investigations to see where heating networks need to be expanded and converted: for the heating requirement to be met in the most efficient way possible using renewable energies, planning must be adapted to the specific regional and local circumstances. The introduction of a compulsory municipal heating plan could help to develop appropriate concepts for the heating supply. In densely populated areas, heating networks could play an important role in the exploitation of renewable heat sources.
- Increase the rate at which buildings are renovated with a focus on energy efficiency by means of appropriate incentives: the potential for energy efficiency in the heating sector is still largely untapped.

The climate protection potential of sector coupling in the transport sector

Current situation and targets in the transport sector

In 2015, transport made up about 30 per cent of Germany's final energy consumption and 94 per cent of this was supplied by petroleum-based fuels. GHG emissions from transport have remained more or less stable since 1990. With direct emissions of approx. 164 Mt of CO_2 equivalents in 2015, transport is responsible for about 18 per cent of Germany's total GHG emissions. About 96 per cent of these issue from road transport. The German Federal Government's "Klimaschutzplan 2050" (Climate Action Plan 2050) envisages a 40–42 per cent reduction in GHG emissions in the transport sector by 2030 (compared with 1990 levels). However, the Federal Ministry of Transport anticipates a further increase in the volume of traffic by 2030 – approx. 13 per cent for motorised passenger transport and 38 per cent for goods transport.[35]

To achieve the GHG reduction target of 95 per cent across all sectors by 2050, it will be necessary to dispense with the use of fossil fuels in the transport sector almost entirely by 2050. This is in addition to measures – which urgently need defining – to reduce traffic volumes, promote a shift to other modes of transport and accelerate efficiency gains. Since biogenic fuels suitable for the replacement of fossil fuels are only available in very limited quantities, the energy demand will, for the most part, need to be met using other renewable energies.[36]

In the following text, the transition to alternative and electrically generated fuels is referred to as "energy transition in transport". Measures that contribute towards cutting the final energy demand of transportation – in the form of reducing and shifting the traffic load, as well as improvements to drive technology – will be understood as part of the necessary "mobility transition in transport".

Mobility transition as a basis for sector coupling

The reduction of final energy demand and the efficient use of energy are of paramount importance if the transport sector is to be decarbonised. For the climate goals to be achieved, a 50 to 60 per cent reduction in the final energy demand of transport by 2050 and a 30 per cent reduction by 2030 are absolutely essential.[37] Furthermore, measures that contribute towards traffic avoidance and efficiency gains in line with the mobility transition can be implemented quickly and using existing technologies.[38]

It is also particularly important that the final energy demand is reduced so that it will be possible to largely replace fossil fuels, which dominate the transport sector, with electricity from renewables.[39] After all, even renewable energies are in limited supply and cause competition for resources as a result of their land requirements, for example, the protection of species and nature conservation. Currently predominantly met by fossil fuels, the final energy demand for transport is 728 TWh (2015), of which over 600 TWh is consumed in road transport.[40] By contrast, however, the total gross domestic electricity output in 2015 was "only" 645 TWh.

The mobility transition will therefore be a key requirement for sector coupling with the aim of reducing CO_2 emissions.[41] Figure 4 illustrates the correlation.

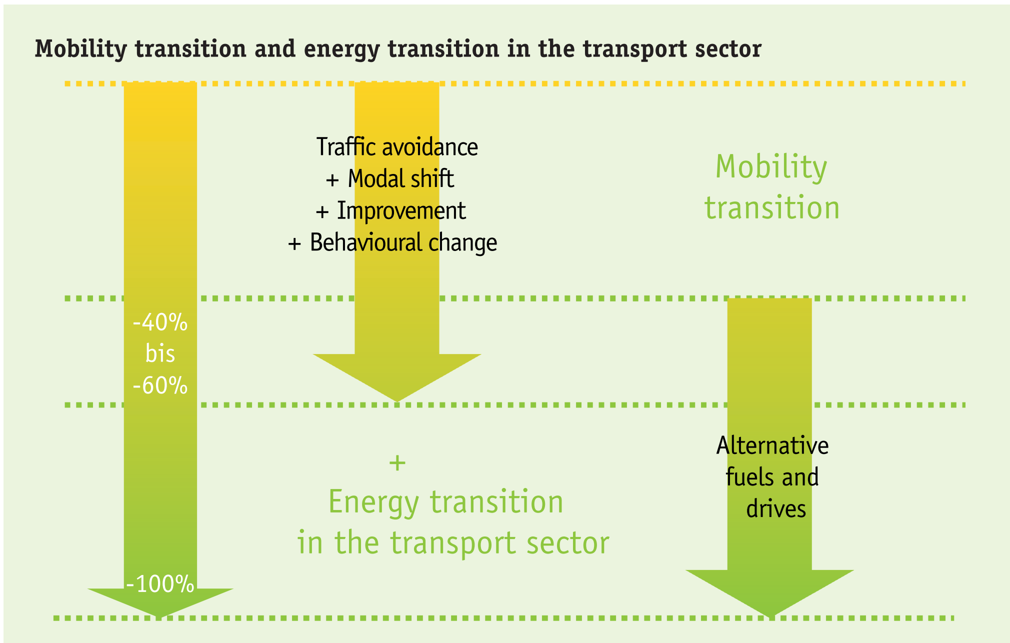

Figure 4: The mobility transition lowers the final energy demand of transport to a level at which it can be met using renewables. Source: Schmied 2016/Agora Verkehrswende

Energy transition in the transport sector

In scenarios based on a GHG reduction target of 95 per cent, it is generally assumed that both the direct use of electricity in the rail sector and in battery-electric drives, as well as its indirect use through the employment of electrically generated fuels in internal combustion engines will be needed to accomplish the energy transition in the transport sector.[42]

Direct use of electricity

Rail transport offers a highly energy-efficient way of electrifying passenger and goods transport. Therefore, there is a large CO_2 mitigation potential in shifting motorised transport onto the railways. Even if the amount of goods transported by rail were to grow by 160 per cent by 2050, it is expected that there would only be a very modest increase to 61 PJ (2015: 54 PJ) or 17 TWh in the final energy demand for the rail sector as a whole.[43] After motorised private transport, goods transport makes up the highest proportion of the total emissions from transportation. As the carbon footprint of the electricity supply improves, a reduction in greenhouse gas emissions from goods transport amounting to approx. 8.6 Mt CO_2 can be achieved by increasing the proportion of freight transported by rail to 25 per cent by 2030 (from 17.7 per cent in 2010).[44]

With today's electricity mix, passenger cars running purely on electric batteries (BEV, battery-electric vehicles) with ranges below 100 km present CO_2 values that are comparable to efficient petrol and diesel engines.[45] However, this only holds true on the basis of the information from manufacturers, which generally does not correspond to the real-world values, as shown by the ICCT (International Council on Clean Transportation) in its recent study: On average, the divergence from the manufacturers' data is estimated to be 42 per cent, even over 50 per cent for larger passenger car models.[46] The balance may improve in favour of electric drives as the CO_2 load of the electricity supply decreases.

Indirect use of electricity from renewables

The use of electrically generated fuels is primarily required in those transport segments where the use of battery-electric drives is technically limited. This relates in particular to shipping and aviation as well as to the share of road haulage that can neither be moved over to rail transport nor be electrified (on the basis of current technical standards). Methane from renewables and obtained in PtG installations is liquefied in the PtL process and can thus also be used in the transport segments mentioned here.

The energy efficiency of electrically generated fuels is, however, lower than that of electricity in direct use in the rail sector and in battery-electric drives. Their use will make a significant contribution to the final energy demand of the transport sector in 2050.

Even in scenarios with a high proportion of direct electricity use in the transport sector and with ambitious assumptions regarding efficiency, it is expected that a large part of the final energy demand for transport will be met by electrically generated fuels (generally in internal combustion engines). The share of their electricity supply provided by renewables – necessary for GHG-neutral transport – is anticipated to be approx. 73–88 per cent in 2050.[47] All studies where PtG or PtL play a crucial role in the energy supply, are also based on the assumption that this energy will be produced entirely from electricity from renewables and is therefore available on a GHG-neutral basis. Against the background of the current electricity mix, electrically generated fuels can still not be used to lower CO_2 emissions in comparison with diesel and petrol engines.

CO_2 abatement potentials

The GHG abatement potential presented by sector coupling in the transport sector can only be realised in connection with a wide-reaching reduction in the total energy demand of transport as well as the accelerated expansion of renewable energies and the associated decrease in the CO_2 load of the electricity supply. Otherwise, additional emissions will be produced through the development of new uses for electricity. Moreover, this risk is introduced as a result of an overall increase in the traffic load, which could cancel out reductions in emissions. Consequently, even in the short to medium term, measures intended to shift and avoid traffic are a prerequisite if sector coupling is to be beneficial for the climate.

By 2030, the greatest GHG abatement potential from the use of electrical energy in the transport sector will, in theory, be in moving the passenger and goods transport load to the railway network. For example, the emission of 8.6 Mt CO_2 could be prevented by increasing the proportion of freight transported by rail to 25 per cent in 2030 (from 17.7 per cent in 2010) as a result of an improvement in the carbon footprint of the electricity supply.[48] The current electricity mix will not yet allow significant CO_2 reductions through sector coupling for battery-electric vehicles. Their contribution to a reduction in transport emissions may increase by 2030, however, as a result of a decline in the CO_2 load of the electricity mix. Nevertheless, both assumptions are ambitious given that they are reliant on a corresponding energy supply from RES as well as investments in rail infrastructure and in the charging network.

With the use of electrically generated fuels, the amount of electricity that must be generated from RES increases disproportionately. Two recent studies into climate protection in the transport sector work on the assumption of a power demand from renewables on the generation side of approx. 2,000 to 2,486 PJ for all transport within Germany, even when taking significant reductions on the consumption side into account, in accordance with the respective anticipated technology mix and its respective efficiency levels. This corresponds to approx. 556 to 691 TWh. It follows that, in order for the transport sector to be supplied with energy in such a way as to be beneficial for the climate, the final energy demand must be reduced significantly and electricity from renewables must be used in the most efficient technologies possible, even assuming the maximum availability of land for additional renewables installations and a high proportion of imports. Because the direct use of electrical energy in battery- or directly-powered vehicles is associated with higher efficiency levels than is the case for PtG and PtL, it is preferred over the use of electrically generated fuels from a CO_2 mitigation perspective. The demand for RES electricity generation is expected to be 3,300 to 3,847 PJ by 2050 with the exclusive use of electrically generated fuels. This corresponds to approx. 917 to 1,070 TWh.[49]

Due to their energy-intensive method of production, electrically generated fuels are also only beneficial to the climate when the power supply is almost entirely based on renewables. They should therefore only be used if no other options are available for the replacement of fossil fuels. From today's perspective, their use would nevertheless appear to be necessary if the goal of a greenhouse gas-neutral transport sector is to be achieved by 2050. In addition, a double benefit is possible through the use of PtG as a means of storage for power systems based on RES. Therefore, electrically generated fuels should continue to undergo gradual development. Most studies see their use in the transport field beginning with a small share from 2030.[50]

Can gas drives contribute towards protecting the climate under current circumstances?

Amongst the fossil fuels currently in use, natural gas has a better carbon footprint than diesel and petrol and also has other environmental benefits during combustion, such as lower nitrogen oxide emissions and less particulate matter from the exhaust. Whilst the electricity mix continues to make the production of PtG or PtL seem impractical, it can be argued that gas is a technology that can support climate protection.

From today's perspective, gas drives for passenger and goods transportation are primarily seen as contributing to air pollution control. With fine particulates and nitrogen oxides, traffic is one of the main causes of air pollution, especially in inner cities, which leads to numerous premature deaths and countless instances of disease every year, together with the associated costs to society. In many municipalities, the air pollution limits are being exceeded. As a result, the European Commission has initiated infringement proceedings against Germany, owing to both fine particulates and nitrogen oxide pollution levels. Alternative, electricity-based drives that do not produce direct emissions are not available in numbers that can remedy the situation in the short term. Natural gas drives, however, are considered state of the art and can be deployed on the market for numerous applications. Even the existing infrastructure offers sufficient potential. Additional efficiency requirements would, of course, still be advisable.

Existing barriers

The absence of provisions for the necessary avoidance of traffic and its modal shift is the biggest obstacle to sector coupling in the transport sector. This includes the failure to introduce CO_2 limits for heavy goods vehicles and passenger cars – or to set ambitious targets for their future development, the decline instead of the steady expansion of rail freight transport infrastructure and the insufficient prioritisation and funding of public transport. Subsidies, such as the company car privilege or the favourable tax treatment of diesel, also hinder the development of eco-friendly transportation.

In addition, there are technical problems with the move away from fossil fuels in the transport sector. The electric vehicles (cars, buses, commercial vehicles) that are currently available are unattractive owing to their poor value for money. Despite falling battery costs, the continued high overall cost of electric vehicles prevents them from penetrating the market more quickly. The same is true with regard to the relative difficulty and slowness of charging these vehicles.

Recommended actions

Actions to avoid traffic, shift it to another mode of transport and to improve the efficiency of existing drives present the greatest potential for GHG abatement by 2030. Looking ahead to 2050, they are vital to reducing the additional demand for electricity from renewable sources to a workable level by means of sector coupling. Numerous studies, including the aforementioned study by the German Federal Environment Agency (UBA) "Klimaschutzbeitrag des Verkehrs 2050", provide a comprehensive overview of the measures required for traffic avoidance and modal shift. In particular, climate protection goals need to be comprehensively incorporated in all transport and infrastructure plans. Until now, however, this has not been sufficiently reflected in political action at various levels. Improvements for a climate-friendly transport system with a focus on public transport should be combined with restrictions on private means of transport. There is a range of fiscal, regulatory and incentive-based measures available for this purpose. Especially in urban areas, the challenges currently under discussion of how to improve the air quality should be seen as an opportunity to get appropriate measures off the ground quickly. The following measures are given as examples:

Traffic avoidance

- Integrated and sustainable planning for urban areas and their surroundings: urban planning measures can contribute to traffic avoidance. According to the "compact city" model, private journeys by motorised transport can be avoided if the destinations can be reached more easily on foot, by bicycle or on public transport.
- The required reduction in traffic represents a particular challenge especially for the transport of goods – not least given the growth forecasts, as previously cited. The response to this challenge cannot be covered in this paper, but requires comprehensive examination elsewhere.

Modal shift

- Shift of goods from road to rail: by 2030, 100 per cent of Germany's railways should be electrified and capacity expanded by 2035 thanks to additional lines, noise protection and goods loading stations. A special investment programme for accelerated electrification and further expansion is required for this purpose. The adjustment of track usage charges and the further development of the HGV toll system should bring an end to the existing inequalities in competition between the different modes of transport.
- Modal shift of passenger transport: this can be achieved, on the one hand, by expanding the public transport services available and, on the other, through restrictive measures such as parking management, the introduction of a city congestion charge and car tolls on all roads, based on mileage and emissions. Better conditions for travel on foot and by bicycle can contribute towards a modal shift, especially in urban areas, because 50 per cent of journeys in cities and towns are under 5 kilometres. The taxation of kerosene should be part of a comprehensive approach towards a shift from short-haul flights to rail.

Improved efficiency

- The development of future technologies in terms of types of drive and alternative fuels will also be determined by their cost compared with petroleum-based products and drives. Greater attention must be paid to this in the future in terms of taxation or duties.
- Adjust energy taxes with CO_2 emissions as the assessment criterion: fossil energy sources must be made more expensive as a result, by realigning the tax rates to factor in the environmental follow-up costs, thus improving the competitiveness of energy-efficiency measures and renewable energies.
- The fleet limits for CO_2 emissions for passenger cars and light commercial vehicles must be reduced further. For this instrument to be effective, an independent, comprehensive and regular testing and monitoring procedure for emissions in real driving conditions, including substantial sanctions, is of utmost importance.
- The introduction of CO_2 limit values for heavy goods vehicles will also boost the available energy-saving potential and is therefore long overdue.
- For limited energy resources to be used efficiently, efficiency standards must be developed for all drive systems in real driving conditions.
- As regards vehicle taxation, CO_2 intensive vehicles should bear an exponentially higher burden and those vehicles that fall well below the future CO_2 limit values should be subject to correspondingly lower taxes.

Behavioural change

- A good provision of public transport is the foundation for the acceptance of multimodality, the use of various modes of transport, with the aim of avoiding private motorised traffic.
- Travel guidance systems and smartphone apps, which suggest alternative modes of transport and guide the user towards them, open up new transport options.
- Speed limits or the use of on-board speed limiters control the behaviour of vehicle users first and foremost, but can also influence the future requirements profile of new vehicles.

Flexibility and electricity demand through sector coupling

Flexibility through sector coupling

Sector coupling through heat pumps, electrode boilers, battery-electric mobility options and electrically generated fuels can also be used as flexibility options, which are intended to contribute to the integration of RES into the system. In an electricity system with high proportions of RES, the number of hours where the supply exceeds the demand increases. By 2020, this is only likely to be the case for a few hours per year, which is why no additional flexibility in the system is required. With proportions of RES of 60 per cent and over, this phenomenon is expected to occur more frequently and for longer periods of time from 2030, and additional options to provide flexibility will be required.[51]

Avoiding the curtailment of renewable electricity

In 2015, 4.7 TWh[52] of electricity generated from renewables – predominantly in northern Germany – could not be fed into the grid because of a lack of grid capacity. With the expansion of renewables, which has already been approved, as well as the high coal-fired power station capacities that are still connected to the grid, this figure will continue to grow until the planned expansion of the transmission grid is complete.[53] The reduction of "must-run" operation at coal-fired power stations may help to avoid curtailments, where necessary, until the grid extension is complete. In addition, the direct regional use of electricity, for example through heat pumps, electric vehicles or electrode boilers, is a subject for discussion.

However, it does not appear very realistic to expect that heat pumps or electric vehicles will be available at the relevant capacities in the regions affected by curtailments by 2030. Not only are sufficient investments by private users and an appropriate infrastructure prerequisites for this, but the load transfer potential of both applications is also limited and subject to high degrees of uncertainty. So, to begin with, both variants initially represent an additional use of electricity, which must be supplied from the electricity mix. Whilst heat pumps are already showing potential for GHG abatement today, this is not yet the case for electric vehicles.

Using the current electricity mix, and in contrast to heat pumps, electrode boilers still do not represent a viable option for sector coupling from a climate protection perspective. They can be used as a complementary element in an existing district or local heating system, but only to take up electricity from renewables that would otherwise be curtailed. However, this would require the existence of an adequate heating supply structure.

PtG as flexibility option where there are high proportions of renewables in the system

Electrically generated fuels can be stored to some extent (hydrogen) or entirely (synthetic methane) in the gas network and used in the heating and transport sectors, as well as in reconversion to electrical energy. Here, the existing gas infrastructure can be seen as an advantage. Yet, even in a system where at least 60 per cent of electricity is sourced from renewables, the necessary flexibility for the integration of RES can foreseeably still be provided through options with higher efficiency levels than can be achieved through the conversion of electricity into synthetic fuels. These options include managing users (demand-side management), such as electric vehicles and heat pumps in private homes, to the extent that this is possible in the light of usage requirements. This also applies to the potential offered by load shifting on an industrial and commercial level. Balancing the supply via the European grid structure as well as through pumped storage and battery storage also ensures flexibility. Curtailing renewable electricity can, to a certain extent, also represent a useful flexibility option.[54] PtG notably has a useful role to play in stabilising the electricity system when prolonged shortfalls need to be bridged in circumstances where RES make up a relatively high share of the supply of between 60 and 80 per cent. For a GHG reduction target of 95 per cent to be reached, the capacity from conventional power plants will need to be replaced by means of these long-term storage options alongside other measures.[55]

Recommended actions

- Permit experimental legislation: on account of the complex dependencies of existing regulations on the electricity market and new fields of application as regards sector coupling, experimental legislation could be useful for projects with climate-protection benefits.[56]
- Support the research and development of conversion technologies: PtG and PtL conversion technologies are today still associated with high costs and energy losses in conversion. Although there are already a number of pilot projects, the research and development of demonstration projects should be given greater support than has previously been the case.

Demand for electricity from renewables

If decarbonised transport and heating sectors are to be supplied with energy from renewable sources, this will involve a substantial increase in demand for renewable electricity in excess of the quantities of renewable electricity currently being curtailed. The additional electricity demand must, therefore, be made possible through an additional expansion of renewable energies. Previous studies have reached a wide range of different conclusions when it comes to the amount of additional renewable electricity required. This is largely dependent on the role they attribute to PtG in the future energy system.

According to a meta-analysis by Germany's Renewable Energies Agency (AEE), which compared the assertions of 25 studies, an additional electricity demand of 37 TWh by 2030 and 75 TWh by 2050 for heat generation can be expected in a scenario where greenhouse gas emissions are reduced by 95 per cent by 2050. For the electrification of the transport sector – without PtG and PtL – the range of estimates lies between a few TWh and 25 TWh of additional electricity demand by 2030 when compared with 2015. If significantly more renewable electricity is required owing to the increased demand for it from PtG and PtL between 2030 and 2050, the expected additional renewable energy demand from PtL technology then ranges from 30 to 600 TWh.[57] According to two more recent studies on climate protection in the transport sector, a generation-side renewable electricity demand of approx. 556 to 691 TWh is expected by 2050 exclusively for transport. Both studies base these figures on the assumption that ambitious efficiency measures are implemented and electricity-based fuels in the transport sector are only used where the direct use of electricity is not anticipated from today's perspective.[58]

In 2015, the share of renewable energies in gross electricity consumption amounted to 31.5 per cent.[59] In accordance with Germany's 2017 Renewable Energy Act (EEG), a 55 to 60 per cent share should be achieved by 2035. Provided that the annual expansion of installed capacity stipulated in the EEG is actually realised, 141 GW of installed capacity from renewables could be connected to the grid in 2030, producing around 280 TWh of renewable electricity.[60] Depending on the assumed level of gross electricity consumption, this could lead to a share of around 47.5 to 52.5 per cent renewable electricity being realised by 2030.[61]

According to the German Federal Government's energy policy from 2010, energy consumption is expected to fall by 10 per cent by 2020 (compared with 2008). By 2015, however, a drop of only 3.4 per cent had been achieved.

If the efficiency target is missed and an additional quantity of electricity amounting to approx. 60 TWh is needed by 2030, the achievement of the EEG target of a renewable electricity share of 60 per cent by 2035 is in doubt. The fact that the demand for renewable electricity for PtG could increase exponentially in all sectors between 2030 and 2050 must also be taken into consideration. By itself, the adaptation of the renewables development trajectory, planned for 2030, to meet the additional electricity demand from sector coupling anticipated by then is, therefore, not sufficient. To achieve a GHG reduction target of 95 per cent by 2050, an electricity mix with the smallest feasible carbon footprint must be made available for sector coupling at the earliest possible opportunity. With this in mind, RES should make up a higher share of consumption by 2030 than previously planned.

Recommended actions

- The next amendment to the EEG should make provision to raise the growth trajectory to a target of at least 65 per cent by 2030 and set a corresponding expansion pathway for RES to be newly installed, taking into account the additional demand from sector coupling.
- For this share of electricity consumption to be reached, it is also necessary that sector-specific efficiency targets are defined, inclusive of their ambitious implementation, and that the gradual reduction of coal-fired electricity generation continues. The introduction of a CO_2 component into energy taxes is warranted in support of this development.
- The comprehensive expansion of RES must be supported by society. Public opinion will therefore need to be shaped on the ground and new, integrated approaches to planning will be necessary to boost public involvement.

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Endnotes

1 The buildings sector includes residential and non-residential buildings where energy is consumed for space heating, space cooling, water heating and building equipment and appliances. It accounts for approx. 32% of Germany's final energy consumption and 16% of the country's greenhouse gas emissions.
2 Industrial process heat requires separate consideration owing to the significantly higher temperature levels and other technological approaches. This would go beyond the scope of this paper and must be examined in greater focus in future follow-up projects.
3 "Energy Efficiency Strategy for Buildings", German Federal Ministry for Economic Affairs and Energy (BMWi), 2015.
4 "Was bedeutet das Pariser Abkommen für den Klimaschutz in Deutschland?", Greenpeace, 2016.
5 The target value for an 80% reduction in the primary energy demand by 2050 is 240 TWh.
6 Calculations by the Institute for Energy and Environmental Research (ifeu) show that, in the target scenario "Efficiency", the installed electrical capacity for heat generation would be 24 GW in 2050. In the target scenario "Renewable energies", the electricity demand for heat generation would increase to 31 GW in 2050. Cf. "Optionspfade und Abhängigkeiten für die Wärmeversorgung", lecture by Peter Mellwig, ifeu, 17.10.16.
7 Cf. Efficiency triad in the "Green Paper on Energy Efficiency", German Federal Ministry for Economic Affairs and Energy (BMWi), 2016.
8 "Optionspfade und Abhängigkeiten für die Wärmeversorgung", lecture by Peter Mellwig, ifeu, 17.10.16.
9 Heated living space/floor space in million m2 in 2050, cf. "Sektorübergreifende Energiewende – Robuste Strategien, kritische Weichenstellungen 2030: Schwerpunkt Wärmesektor", lecture by Norman Gerhardt, Fraunhofer IWES, Berliner Energietage, 13.04.2016.
10 "Hintergrundpapier zur Energieeffizienzstrategie Gebäude", Prognos/ifeu/IWU, 2015
11 "Hintergrundpapier zur Energieeffizienzstrategie Gebäude", Prognos/ifeu/IWU, 2015
12 "Die neue Wärmewelt", AEE, study commissioned by Bündnis 90/Die Grünen, 2016
13 "Wie sieht der Wärmemix der Zukunft aus? Optionspfade und Abhängigkeiten", lecture by Peter Mellwig, ifeu, Berliner Energietage, 13.04.16.
14 "Sektorkopplung – von der Stromwende zur Energiewende", Gesine Schwan et. al, Humboldt-Viadrina Governance Platform, 2016.
15 "Sektorübergreifende Energiewende – Robuste Strategien, kritische Weichenstellungen 2030", lecture by Norman Gerhardt, Fraunhofer IWES, Berliner Energietage, 13.04.2016.
16 "Wärmepumpen im zukünftigen Strom- und Wärmesektor", Marek Miara, Fraunhofer ISE, 2015.
17 "Energiesystem Deutschland 2050", Hans-Martin Henning, Andreas Palzer, Fraunhofer ISE, 2013.
18 "Flexibility concepts for the German power supply in 2050", acatech/Leopoldina/Academieunion (ed.), 2015.
19 "Integration of Power to Gas/ Power to Liquids into the ongoing transformation process", German Federal Environment Agency (UBA), 2016.
20 "Klimaneutraler Gebäudebestand 2050", UBA, 2016.
21 "Interaktion EE-Strom, Wärme und Verkehr", Fraunhofer IWES/IBP with ifeu/Stiftung Umweltenergierecht, 2015.
22 "Wie sieht der Wärmemix der Zukunft aus? Optionspfade und Abhängigkeiten", lecture by Peter Mellwig, ifeu, Berliner Energietage, 13.04.16.
23 German Heat Pump Association (BWP), 2016: https://www.waermepumpe.de/presse/zahlen-daten/absatzzahlen/.
24 "Sektorübergreifende Energiewende – Robuste Strategien, kritische Weichenstellungen 2030", lecture by Norman Gerhardt, Fraunhofer IWES, Berliner Energietage, 13.04.2016.
25 "Wärmepumpen im zukünftigen Strom- und Wärmesektor", Marek Miara, Fraunhofer ISE, 2015.
26 See EnEv 2014 §10 "Nachrüstung bei Anlagen und Gebäuden".
27 To produce one kilowatt-hour of electricity for final consumption, 565 grams of carbon dioxide are currently emitted as direct emissions from the combustion of fossil energy sources (cf. GEMIS database version 4.95, 11/2016).
28 "Efficiency of Heat Pumps in Real Operating Conditions", Marek Miara, Fraunhofer ISE, 2015.
29 "Interaktion EE-Strom, Wärme und Verkehr", Fraunhofer IWES/IBP with ifeu/Stiftung Umweltenergierecht, 2015.
30 "Wie sieht der Wärmemix der Zukunft aus? Optionspfade und Abhängigkeiten", lecture by Peter Mellwig, ifeu, Berliner Energietage, 13.04.16.
31 "Energy Efficiency Strategy for Buildings", German Federal Ministry for Economic Affairs and Energy (BMWi), 2015.
32 Federation of German Heating Industry (BDH) "Marktentwicklung Wärmeerzeuger 2005-2015": www.bdh-koeln.de/fileadmin/user_upload/Daten_Fakten/BDH_Marktentwicklung_2005-2015.pdf.
33 "Strompreisanalyse November 2016", German Association of Energy and Water Industries (BDEW).
34 "Efficiency of Heat Pumps in Real Operating Conditions", Marek Miara, Fraunhofer ISE, 2015.
35 Emission values: direct emissions without upstream chains. Cf. "Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2015", AG Energiebilanzen, 07/2016; "Treibhausgas-Emissionen nach Gasen und Quellkategorien Deutschland", German Federal Ministry for Economic Affairs and Energy (BMWi), 07/2016; "Transport in figures 2016/2017", German Federal Ministry of Transport and Digital Infrastructure (BMVI), 2016.
36 Cf. "Renewbility III", German Institute for Applied Ecology (Öko-Institut)/German Institute of Transport Research (DLR)/ifeu/INFRAS, 11/2016.
37 Cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016.
38 This would involve, for example, supporting travel by bicycle and on foot and shifting traffic to rail and/or to public transport. In this connection, among other actions, the DUH calls for the presentation of a master plan for the expansion of public transport as well as the introduction or development and improved monitoring of ambitious efficiency targets and CO_2 caps for existing and future drive systems.
39 Cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016.
40 "Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2015", AG Energiebilanzen, 07/2016.
41 Cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016.
42 Cf. "Klimaschutz: Der Plan", Greenpeace 11/2015; "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016; "Renewbility III", Öko-Institut/DLR/ifeu/INFRAS, 11/2016.
43 Cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016.
44 Data on emissions from goods transport include direct and upstream emissions. Assumptions based on: "Finanzierung einer nachhaltigen Güterverkehrsinfrastruktur", INFRAS/Fraunhofer ISI [UBA], 06/2016.
45 This calculation is based on the GHG balance of the power supply being 622 g CO_2/kWh, cf. "Weiterentwicklung und vertiefte Analyse der Umweltbilanz von Elektrofahrzeugen", ifeu [UBA], 08/2015.
46 Cf. "Real-world fuel consumption and CO_2 emissions of new passenger cars in Europe", ICCT, 11/2016.
47 Cf. "Renewbility III", Öko-Institut/DLR/ifeu/INFRAS, 11/2016; cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016. The scenarios cited in these studies are based on the wide-ranging, ambitious implementation of available measures, which together reduce the final energy demand of transport by 60 per cent.
48 Cf. "Finanzierung einer nachhaltigen Güterverkehrsinfrastruktur", INFRAS/Fraunhofer ISI [UBA], 06/2016.
49 2000 or 3300 PJ: cf. "Renewbility III", Öko-Institut/DLR/ifeu/INFRAS, 11/2016; 2486 and 3847 PJ, respectively: cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016. International transport is not taken into account. For the lower value in each case, both scenarios assume ambitious efficiency gains and a high proportion of direct electricity usage.
50 Cf. "Flexibilität durch Kopplung von Strom, Wärme und Verkehr", AEE, 04/2016.
51 Cf. "Ökologische Bereitstellung von Flexibilität im Stromsystem", Öko-Institut, 11/2016.
52 Cf. "Network and system security. Data for the year 2015", German Federal Network Agency (BNetzA), https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/SecurityOfSupply/NetworkSecurity/Network_security_node.html#doc697250bodyText4, on 06.01.2017.
53 Cf. "Ökologische Bereitstellung von Flexibilität im Stromsystem", Öko-Institut, 2016.
54 "Sektorenkopplung", lecture by Max Rathmann, BMWi, at the Deutsche Umwelthilfe symposium "Nutzen statt Abschalten" on 20.09.2016; "Ökologische Bereitstellung von Flexibilität im Stromsystem", Öko-Institut, 11/2016.
55 Cf. "Ökologische Bereitstellung von Flexibilität im Stromsystem", Öko-Institut, 11/2016.
56 Cf. "Experimentierklauseln im Energierecht", Stiftung Umweltenergierecht, 03/2016.
57 Cf. "Metaanalyse zur Flexibilität durch Sektorkopplung", AEE, 04/2016.
58 Cf. "Renewbility III", Öko-Institut/DLR/ifeu/INFRAS, 11/2016; cf. "Klimaschutzbeitrag des Verkehrs bis 2050", ifeu/INFRAS/LBST [UBA], 05/2016. International transport is not taken into account.
59 "Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2015", German Federal Ministry for Economic Affairs and Energy (BMWi)/German Working Group on Renewable Energy Statistics (AGEE-Stat), 12/2016.
60 Based on the following assumption: installed capacity of approx. 60 GW onshore wind, 15 GW offshore wind, 52 GW photovoltaics, 6 GW hydropower, 8 GW biomass; full-load hours – onshore wind 1,800 h, offshore wind 3,500 h, PV 1,000 h; biomass generation 50 TWh, hydropower 20 TWh.
61 Cf. "Die Energiewende im Stromsektor: Stand der Dinge 2015. Rückblick auf die wesentlichen Entwicklungen sowie Ausblick auf 2016", Agora Energiewende, 01/2016.

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