THE VALUE OF HYDROGEN IN THE HEATING MARKET

AN ANALYSIS OF DIFFERENT HEATING TECHNOLOGIES WITH A FOCUS ON HYDROGEN CONDENSING BOILERS AND ELECTRIC HEAT PUMPS

Study for FNB Gas (convenience translation – original study in German)

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Dr David Bothe
+49 221 3371-3106
david.bothe@frontier-economics.com

Dr Matthias Janssen
+49 221 3371-3117
matthias.janssen@frontier-economics.com

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EXECUTIVE SUMMARY

Decarbonising the heating market is challenging

Germany has set ambitious climate targets of a 65% reduction in greenhouse gas emissions by 2030 relative to 1990, and achieving climate neutrality by 2045. The EU is also pursuing ambitious climate goals. EU-wide GHG emissions are to be reduced by 55% by 2030 relative to 1990, and climate neutrality is to be achieved by 2050.

The heating market has a pivotal role to play in achieving those targets. Nearly a quarter of today's greenhouse gas emissions originate in the heating sector. This is due to substantial energy demand - the annual final energy consumption for space and water heating amounts to almost 800 TWh, compared to 770 TWh in the entire transport sector or 550 TWh electricity consumption - and a high share of fossil energy sources of about 80%.

The German government has set a target of reducing GHG emissions in the building sector to 67 million tonnes by 2030, compared to 118 million tonnes in 2020. In the next 10 years, therefore, emissions would have to decrease by 43%. In relative terms this is a similar reduction to the previous 30 years (44% between 1990 and 2019), although the pace of emissions reduction has already slowed noticeably in recent years.

43%

is the target GHG emissions reduction in the building sector in just 10 years, similar to the achieved reduction over the previous 30 years.

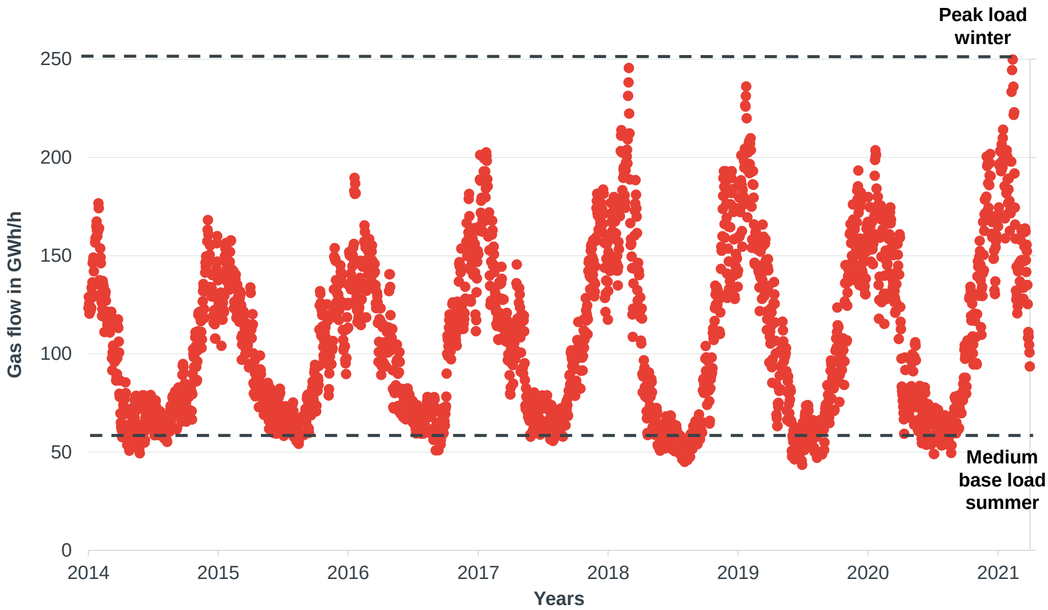
Today, the gas system provides over half of the heating market's supply of capacity and energy

Almost 50% of space and water heating in Germany is currently covered directly by natural gas (see chapter 2.1). The existing gas network supplies more than 9 million residential buildings with around 20 million dwellings and heat demand of almost 400 TWh annually. Additional residential buildings with about 2.5 million dwellings are supplied indirectly by natural gas via district heating.

Even more crucial than the amount of energy provided over the year, however, is meeting energy demand during consumption peaks. Heat demand is characterised by substantial seasonality. Energy demand is significantly higher in winter months than in summer months, which results in high demand for seasonal storage. The gas system is designed to cope with the seasonality of the heating market. For example, the average total gas consumption in the coldest month of the year (January or February) is about three times as high as the consumption in the warmest month (July or August). Daily consumption in winter months is on average four times higher compared to warmer months. This figure includes the relatively steady gas demand of industry, which implies that the seasonal variation in gas consumption for heat is even higher.

Within the framework of this study, a **maximum gas load of more than 250 GW** was identified using actual natural gas flows of the German gas transmission operators (FNB) from 2014 to March 2021 (see Figure 1). The maximum load was measured on 12 February 2021, at a nationwide average outdoor temperature of minus 7.1 degrees Celsius.

Figure 1 Daily intra-German gas flows at transmission level reflect necessary dimensioning of the gas system on the seasonality of the heating market



Source: Frontier Economics based on gas flow data provided by FNB Gas.

Moreover, the basis for the planning and dimensioning of gas infrastructure is an assumed maximum demand case ("1 in 20 winter") that is based on significantly lower daily temperatures (-14 °C)[1] than the temperatures measured in the seven-year period that is analysed here. Regressing the gas load on temperatures using the actual data suggests that a **design-relevant maximum load of 300 GW** would occur if temperatures reached -14°C.

[1] See Kooperationsvereinbarung Gas (2020), p. 37.

Deducting the temperature-independent "base load" (mainly for water heating and process heat in industry) of about 60 GW and taking into account conversion losses in natural gas boilers, this results in a **heating capacity of 230 GW, which the current gas infrastructure provides for the heating market**. In comparison, the historical electricity peak load is just under 80 GW.

230 GW

is the capacity that the gas infrastructure currently provides for the heating market.

In the future, the gas system can be converted to hydrogen and thus make a significant contribution to a climate-neutral heat sector

Fossil fuels as energy sources have no long-term future in light of climate goals. Natural gas (without carbon capture) does not have a role beyond 2045 at the latest.

Aside from green derivatives such as biogas and synthetic methane (SNG), an alternative to using natural gas is the direct use of hydrogen produced in a climate-neutral way.

By using hydrogen, the gas system's ability to meet the enormous and highly seasonal demand for heat can also be utilised in a climate-neutral world (see chapter 2.3 and 3.1):

- The existing gas networks (40,000 km of transport network and 510,000 km of distribution network) can be converted to carry hydrogen. Several European gas network operators have already developed various concepts for this and are testing the conversion of natural gas pipelines in pilot projects. An example conceptualisation of the transmission network is the ‘European Hydrogen Backbone’, which is based on 70% of converted natural gas pipelines across Europe and 90% in Germany. Furthermore, distribution system operators are exploring in various projects how to repurpose distribution gas grids to the use of 100% hydrogen. High conversion rates are generally expected due to the widespread use of polyethylene pipelines in distribution grids.

- According to heating appliance manufacturers, existing gas-based condensing boilers can already accept a blend of 10 percent hydrogen by volume without the need for adaptation. The latest generations of gas-based condensing boilers are expected to safely process up to 20-30 percent by volume of hydrogen without significant additional costs. Moreover, simple and cost-effective retrofit solutions in order to make boilers suitable for "pure" hydrogen

By 2025,

gas heating systems will be available that are 100% "hydrogen-ready".

have been announced by German heating appliance manufacturers and are expected to be available by 2025.

Hydrogen heating technologies are as efficient as alternative heating technologies during cold periods and in existing unrenovated buildings

Nonetheless there is a debate on the use of hydrogen in the heating market; various stakeholders are currently arguing for hydrogen use to be limited to the industry and transport sectors. In addition to a supposed scarcity of (local) hydrogen potentials, they argue that that electricity-based heat appliances such as electric heat pumps are more energy efficient than appliances based on climate-neutral gases such as hydrogen.

However, energy efficiency, i.e. the ratio of (renewable) primary energy to output energy (in this case heat), should not be the sole basis for energy policy decisions. Renewable energy sources such as wind and sun are not in short supply; the bottleneck for deploying electricity-based heat appliances is the required grid and storage infrastructure. Moreover, it is crucial for a secure heat supply that the infrastructure is also designed for phases of very high demand during the cold season.

The energy efficiency of heating technologies depends on the renovation status of the building and weather conditions. We analyse the **overall efficiency of the heat supply**, defined as the ratio of generated heat to the required primary energy, taking into account energy losses through energy conversion and transport. This overall efficiency:

- ... is consistently higher for electric heat pumps than for hydrogen-based heating systems in **new buildings or in fully renovated old buildings** due to the good insulation and low flow temperatures required in the heating circuit. Accordingly, electric heat pumps will undoubtedly play a very important role, especially when it comes to climate-neutral heating in new buildings; and
- ... is of a **similar order of magnitude** for **all analysed heating systems** in **unrenovated or only partially renovated old buildings** under conditions that are relevant for the design of the infrastructure**.** This is due to markedly lower efficiencies of electric heat pumps in insufficiently thermally insulated buildings and in the event of cold outdoor temperatures. In addition, the lack of sufficient wind and solar supply in the winter period makes it necessary to seasonally store significant amounts of energy, which involves immense conversion losses.

This is of great importance because:

- ... only 13% of today's building stock is considered to be fully renovated or newly constructed, while around 36% of buildings are considered to be unrenovated and 51% partially renovated; and
- ... the provision of heat must also be guaranteed in cold periods with a low supply of renewable energies. The heating infrastructure must be designed appropriately for these periods.

87% of the building stock

is unrenovated or only partially renovated. Here, H2 heating systems have **overall efficiencies** in the cold period **similar** to other climate-neutral heating systems.

The gas system can supply peak loads in the heat sector that would otherwise significantly challenge the electricity system under a widespread electrification of heat demand

Analysis of actual gas transmission data has shown that today's gas infrastructure provides 230 GW of capacity for the heating market. According to another projection, the heating oil infrastructure provides another 100 GW of capacity for the heating market (Chapter 4.1).

Today, under 5% of final energy demand for space and water heating is covered directly by electricity. This means that the electricity system has not yet been required to respond to the specific demands of the heating market with enormous demand peaks in cold winters. A widespread electrification of the heating market in order to achieve climate neutrality (in 2045) would therefore pose new challenges for the electricity system:

86 to 124 GW

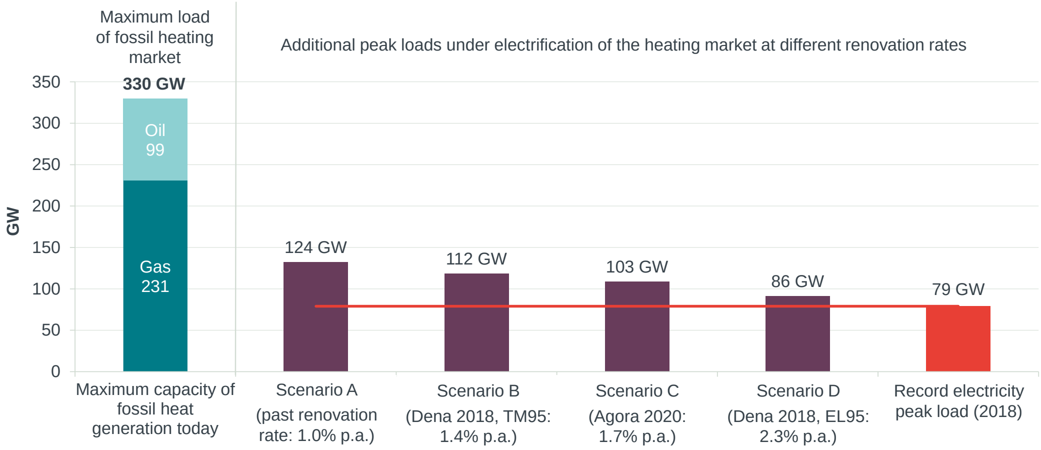
is the additional electricity peak load in the case of a widespread electrification of the heating market through heat pumps - despite an acceleration of renovations. **The electricity peak load of 80 GW today would therefore at least double.**

- **The historical electricity peak load of 80 GW would more than double just by serving the additional space and water heating demand** (Figure 2), which would also significantly increase the already urgent need for electricity grid expansion. This applies despite:
  - the high efficiencies of electric heat pumps through the use of ambient heat, which are significantly lower on particularly cold days (when the peak load occurs) than on an annual average; and
  - an anticipated acceleration of energetic renovations in buildings, which significantly reduce the heating demand compared to the status quo. In the case of a continuation of the historical annual renovation rate of 1% until

2045, this would result in an increase of the electricity peak load of 124 GW. Even under the assumption that the renovation rate can be more than doubled (to an annual renovation rate of 2.3%), the current electricity peak load would more than double (with an additional 86 GW).

- In the course of the **nuclear and coal phase-out,** firm generation capacities amounting to 36 GW (of the previous 100 GW) will be taken off the grid by 2030. In addition, the need for firm generation capacity and grid expansion will increase due to the **electrification of other sectors**. The transport sector alone could cause more than 20 GW of additional peak load in the long term.
- There is therefore a risk that the pace of expansion of electricity generation capacities will be too slow to close the **prospective supply gap** due to increasing demand and simultaneously declining conventional power plant capacities. This applies not only to renewable energies, but also to the required infrastructure of the transport and distribution networks, storage options and firm power plant capacities.

Figure 2 Deep electrification of the heating market leads to a strong increase in electricity peak load



Source: *Frontier Economics based on FNB Gas and Hirvonen and Siren (2017) [and renovation rates from cited studies].*

Note: *See notes in Figure 19 for detailed explanations.*

Hydrogen in the heating market can lower system costs and reduce the cost burden for low-income households

Even if an expansion of the required electricity generation, electricity transport and electricity distribution capacities was successful, the wider use of climate-neutral gases such as hydrogen could reduce the system costs of a climate-neutral energy supply, as a number of German and European studies from recent years have shown. This is due in particular to the fact that the direct use of climate-neutral gases such as hydrogen in all consumption sectors requires fewer power plants, less electricity storage and power grid capacity than in supply scenarios based solely or primarily on electrical appliances. In addition, it would result in lower acquisition costs for new heating systems and in lower renovation costs, especially in unrenovated existing buildings.

This also has implications for the social acceptance of climate-neutral heating, as cost savings from lower heating system purchase costs and lower renovation costs would benefit low-income households in particular. This is due to the fact that low-income households live disproportionately in imperfectly renovated existing buildings and that energy costs also make up a larger share of the budget for these households ("share of wallet") (Chapter 2.5).

Against this background, the option of using hydrogen for the heating market should be maintained.

Hydrogen can be produced in regions rich in sun, wind and space and imported.

Importing hydrogen helps to meet the challenge of limited domestic renewable energy potentials

Meeting Germany's entire future energy demand with renewable energies requires a considerable increase in electricity production volumes, especially from wind and photovoltaics, from under 200 TWh today by a factor of 3 to 10 (depending on the degree of electrification). This would be challenging to achieve purely from domestic locations, particularly given resistance from various societal groups.

However, in other regions of the world - both within Europe and especially outside Europe - there is considerable potential for generating renewable energy at a level that exceeds future energy demand. Therefore, while the regional short term potential for hydrogen supply may be limited, the considerable global potential of renewable energies can be opened up for Germany and other countries through the transport of hydrogen or hydrogen derivatives. From a supply-side perspective there are no obstacles to the use of hydrogen in the heating market.

Hydrogen imports can also take advantage of better wind and solar conditions in other regions

At sunny and/or windy locations, a significantly larger amount of renewable electricity can be produced with the same photovoltaic or wind power plant capacity relative to any location in Germany. For example, the full load hours of a photovoltaic system in North Africa amount to up to 2,500 h per year, while in Germany the geographical average is only 1,060 h. There are similarly large differences for onshore wind power plants.

> In sunny regions such as North Africa, PV plants achieve more than twice the utilisation rates as in Germany. This potential can be harnessed through hydrogen imports.

This means that for the same amount of heat generated, less than half as much PV or wind power capacity needs to be built in North Africa as in Germany. This is important in an energy system that is increasingly based on wind and solar energy because costs and GHG emissions depend on the installed capacity of wind turbines and solar plants (in kW) rather than on the amount of energy generated (in kWh).

On the basis of the existing pipeline infrastructure hydrogen use can be supplied by renewable hydrogen imported from countries with much more favourable climatic conditions. In contrast, the power for electric heating systems must essentially be generated in Germany, or at least in surrounding countries, with correspondingly lower plant utilisation rates.

1 INTRODUCTION

Due to its sheer size, the heating market plays an important role on the path to climate neutrality. Hydrogen and other climate-neutral gases are essential for achieving overall climate targets and can specifically contribute to climate neutrality in the heating market.

While the use of hydrogen as a raw material ("*feedstock*") in industry and as fuel in some in parts of the transport sector is generally accepted, its use in the heating market is opposed by various actors. The arguments against the use of hydrogen in heating are based on two factors:

- hydrogen is a scarce commodity and should therefore only be used in sectors where no alternative decarbonisation options are available ("hard-to-abate sectors"); and
- emissions in the heating market can be reduced more efficiently by switching to electric heating technologies in combination with comprehensive energy efficiency measures.

However, a premature and one-sided commitment to specific sectors and technologies is not sensible. It carries the risk that climate neutrality in the heating market will not be achieved or will only be achieved at unnecessarily high economic costs. In this study:

- we summarise the main reasons why the use of hydrogen in the heating market should be considered (Chapter 2);
- we argue that focusing only on average energy efficiencies, often used as an argument against hydrogen in the heating market, does not give the full picture. Instead, we calculate the overall efficiencies of different heating technologies along the process chain for different weather situations and building conditions (old vs new buildings). We show that at cold outdoor temperatures hydrogen-based heating systems in imperfectly renovated old buildings - which make up the majority of today's building stock - have similar overall efficiencies to electric heat pumps (chapter 3);
- we conclude on the basis of actual gas flow data that a widespread electrification of today's gas and oil-based share of the heating market would more than double the electricity peak load relative to today. The generation and transport infrastructure in a future electricity system based on 100% renewables must be designed in such a way that the additional peak load from the heating market can be supplied. However, massively expanding the electricity infrastructure would not be necessary if the existing gas infrastructure remains an integral part of the heating market in the future (Chapter 4).

2 **BACKGROUND** - HYDROGEN IS AN IMPORTANT ELEMENT FOR MEETING THE CHALLENGES OF DECARBONISING THE HEATING MARKET

In this chapter we make the case for an important role for hydrogen in decarbonising the heating market. We base our analysis on the fundamental characteristics of the future energy system based on renewable energy sources as well as on specific energy system requirements of the heating market. Many arguments have already been presented in previous studies on this topic.[2] In the following sections, we summarise the results of these studies, which lead to the conclusion that:

- Achieving climate targets in the heating market requires a technology-neutral approach in the short term and in the foreseeable future (section 2.1);
- The electricity system is currently not designed for a widespread electrification of heat demand (section 2.2);
- Hydrogen is not a scarce commodity from a global perspective. Hydrogen has the potential to make renewable energies transportable and storable (sections 2.3 and 2.4); and
- The use of hydrogen leads to lower and more socially acceptable overall decarbonisation costs (section 2.5).

2.1 **Climate targets** - Achieving climate targets in the heating market requires a broad and technology-open approach

In many sectors heating demand makes up large parts of final energy consumption

The heating market in Germany is very heterogeneous. Depending on the exact definition, total final energy consumption for heating purposes amounts to up to 1,400 TWh per year, about 50% of total German final energy consumption.[3] 'Heating' refers to various applications including:

- space heating,
- water heating,
- air conditioning and
- process heating and cooling

in the household, industry and trade, commerce and services sectors (Figure 3).

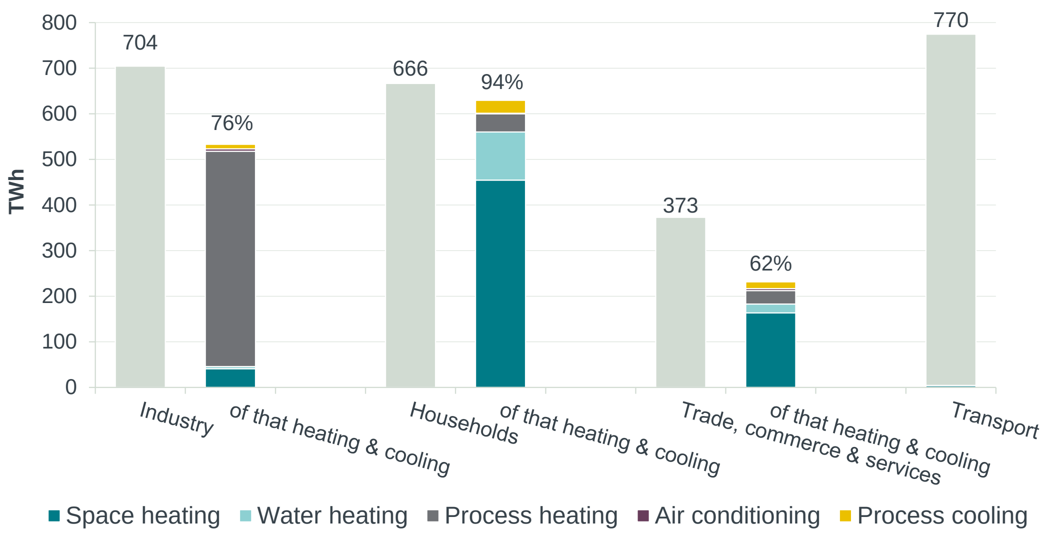
[2] See e.g. Frontier Economics (2021a), " Die Rolle von Wasserstoff im Wärmemarkt, Kurzstudie für Viessmann Climate Solutions ", April 2021; and Frontier Economics (2021b), " Wasserstoff zur Dekarbonisierung des Wärmesektors", study for DVGW, June 2021.

[3] BMWi (2021a).

The largest part of final energy demand in households and in trade, commerce and services is used to supply space and water heating. In industry, most energy is needed for generating process heat.

The focus of our report is on the seasonal or outdoor temperature-dependent areas of heating demand, namely in space and water heating and in small parts of process heating. Therefore, in this report we aggregate space and heating water of all sectors, as well as smalls parts of process heating in industry[4] under the term "heating market". According to this definition the heating market accounts for a final energy consumption of about 836 TWh in 2019.[5]

Figure 3 Final energy consumption by sector and respective share of heating and cooling (2019)



Source: Frontier Economics (2021b) based on AG Energiebilanzen

Various options are available to achieve climate neutrality in the heating market, which we analyse in more detail in this report. For example, carbon emissions in the heating market can be reduced by:

- renovation measures in buildings, i.e. reduction in heat demand;
- switching the heating fuel or replacing the heating system by:
  - electric heat pumps;
  - gas condensing boilers based on hydrogen or other climate-neutral gases;
  - fuel cells;
  - solar heating;

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4 For the generation of process heat with low to medium temperature levels up to 100 degrees Celsius, industrial electric heat pumps are to be considered as an option. However, this only affects about 10% of process heating demand in industry. A large part (90%) of industry's process heating demand involves temperatures above 100 degrees Celsius. This area of process heating can only be sustainably electrified under certain conditions. To determine the parts of heating demand that have to be supplied by alternative heating technologies in the future, we will include the temperature-dependent sub-sector of process heating into our analysis (chapter 4). For our efficiency analysis of alternative heating technologies, we focus on space and water heating (chapter 3).

5 This includes 789 TWh of final energy demand for space and water heating of all sectors plus the relevant share (about 10%) of process heating in industry of ca. 47 TWh.

  - other technologies;
- as well as combinations of the technologies and measures mentioned.

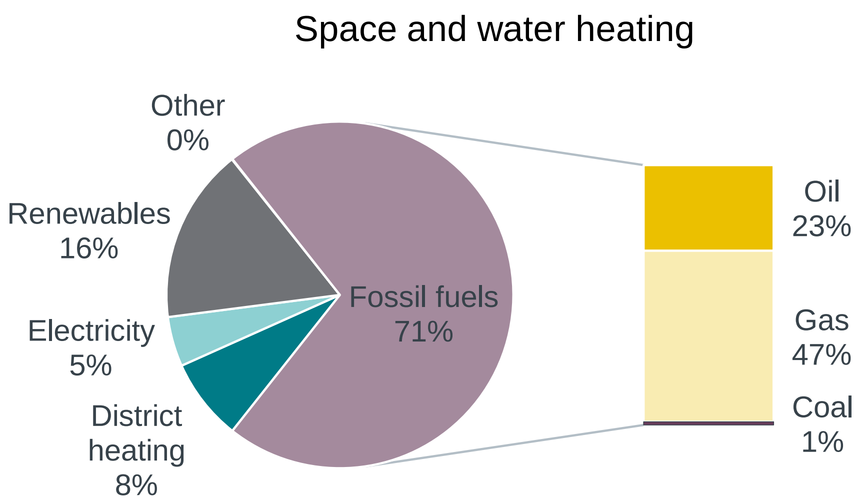
Fossil fuels play a central role in today's heating market

Today, the heating market is still largely supplied by fossil energy sources. In 2019, fossil energy sources accounted for more than 70% of final energy consumption for space and water heating (Figure 4). Taking into account the use of gas, coal and oil in generating the secondary energy sources district heating and electricity, the share of fossil fuels is around 80%.

Gas accounts for almost 50% of today's direct space and water heating demand and supplies over 9 million residential buildings with almost 20 million dwellings via the existing gas network.[6] In addition, gas indirectly supplies another 0.5 million residential buildings and 2.5 million dwellings via district heating. In contrast, only about 5% of space and water heating demand is supplied by electricity.

In process heating (and cooling), the share of gas is just under 40%, compared to a share of electricity of just under 25%.

Figure 4 Proportions of final energy sources in space and water heating (2019)



Source: Frontier Economics based on AG Energiebilanzen

Note: The energy sources electricity and district heating are generated proportionally on the basis of the primary energy sources gas and coal.

The heating market must achieve ambitious climate targets in the coming years

The EU is pursuing ambitious climate goals in which EU-wide greenhouse gas emissions are to be reduced by 55% by 2030 relative to 1990. By 2050, the EU aims to become climate neutral. At the national level, Germany has set the goal of reducing its emissions by 65% by 2030 relative to 1990. In the latest amendment

[6] BDEW (2019), P. 23.

to the Climate Protection Act, Germany has further tightened its long-term targets so that climate neutrality is to be achieved as early as 2045.[7]

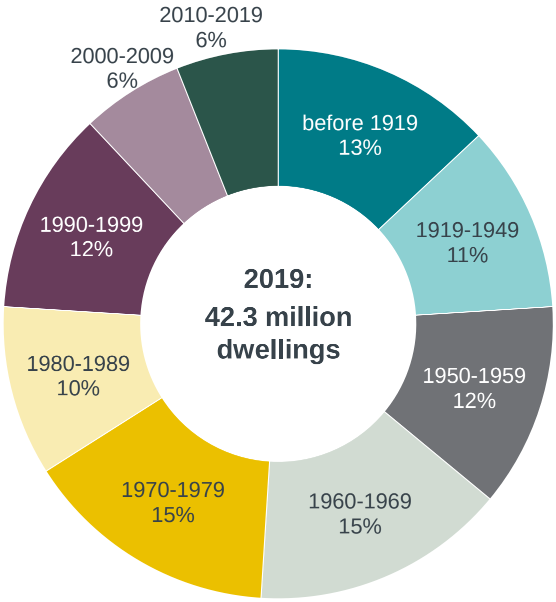
The heating market plays an important role in achieving climate targets. Approximately 14% to 25% of German greenhouse gas emissions are generated in the heating market, depending on whether only direct emissions from the generation of space and water heat are taken into account, or also the proportionate emissions generated in the energy industry that can be indirectly attributed to the heating market.[8]

The German government's current climate targets for the buildings sector call for a reduction of 67 million tonnes of GHG by 2030 (compared to 118 million tonnes of emissions in 2020).[9] In the next 10 years, emissions in the building sector would therefore have to decrease by 43%. By comparison, during almost 30 years between 1990 and 2019 GHG emissions in the buildings sector were reduced by a similar order of magnitude (about 44%), with about half of these reductions happening in the decade after the reunification from 1990 to 2000. This illustrates the magnitude of the challenge that lies ahead.

The building stock is very heterogeneous and there are significant hurdles to achieving the required renovation rates

The condition, age and ownership structure of the building stock in Germany is very heterogeneous. Two thirds of the just over 42 million dwellings were constructed before the first “Wärmeschutzverordnung” (thermal insulation regulations) in 1977. Only 12% of dwellings were built within the last 20 years (Figure 5).

Figure 5 Proportion of dwellings by year of construction



Source: Frontier Economics based on BDEW (2021).

[7] Federal Government (2021),

[8] Federal Government (2019), p. 50.

[9] Federal Government (2021).

Note: *Taken into account are all dwellings on the territory of the Federal Republic of Germany that have a heating system of any kind..*

In addition, the renovation status of the building stock is low: only 13% of existing buildings are considered to be fully renovated or newly constructed. In contrast, around 36% of buildings are classified as unrenovated and around half as partially renovated.[10] Typical renovation measures consist of:

- heating system renewal,
- installation of solar heating,
- façade/roof/basement ceiling insulation,
- window replacement.

In the current building and housing stock, predominantly gas and oil-based heating systems are installed; the share of dwellings heated with gas or oil remained steadily high at approx. 75% over the last two decades.[11]

To achieve climate targets in the buildings sector, the federal government has so far primarily relied on efforts to upgrade the energy performance through comprehensive energy-oriented building renovations.[12] An annual renovation rate of 2% would be required in order to succeed. However, the renovation rate in Germany over the last 20 years has not reached above 1% per year.[13] In addition, the EU Commission has pointed out that only 0.2% of buildings are renovated annually to such an extent that energy consumption is reduced by 60% ("*deep renovation*"). At this renovation rate, achieving climate neutrality in the buildings sector would take "centuries".[14]

The potential to double the renovation rate appears to be in doubt from the supply side - among other things, there is already a very high utilisation of craftsmen's businesses[15] and a shortage of skilled workers.[16] On the demand side, there are hurdles to a substantial increase of energy-oriented renovations. For example, high investment and financing requirements, long amortisation periods and the age

"At this pace of renovation, achieving climate neutrality in the building sector would take centuries."

EU Commission

[10] German Environment Agency (2019), p. 76.

[11] BDEW (2021), P. 22.

[12] There is no uniform definition of the degree and depth of renovations. According to the German Environment Agency, a building is considered fully renovated if at least four measures leading to energy savings have been carried out. Buildings are considered partially renovated after only one energy-saving renovation measure has been carried out, see German Environment Agency (2019), p. 67.

[13] DIW (2019).

[14] European Commission (2020), p. 2: "*The weighted annual energy renovation rate is low at some 1%. Across the EU, deep renovations that reduce energy consumption by at least 60% are carried out only in 0.2% of the building stock per year and in some regions, energy renovation rates are virtually absent. At this pace, cutting carbon emissions from the building sector to net-zero would require centuries.*"

[15] For example, the utilisation rate of operating capacity in the construction sector was 90% in 2019 (Q3 2020: 88%) and in the renovations sector 89% (Q3 2020: 89%). Capacity utilisation in these trades relevant for renovations was therefore still significantly higher than the average for the skilled crafts sector as a whole (2019: 84%, Q3 2020: 78%). See ZDH (2020).

[16] The number of apprentices in the German skilled crafts sector, for example, has fallen by 40% in the last 20 years, from over 616,000 at the end of 1999 to just under 370,000 (in 2019). See ZDH (2019).

demographic of owners[17] often lead to owners deciding against investing in renovation measures, even though these measures would economically pay off in the long term.

To achieve the decarbonisation targets, a technology mix in the heating market should be deployed

Focusing on upgrading energy performances and on individual electricity-based technologies, such as electric heat pumps, does not make sense from a climate policy, economic and time perspective. This is due to a combination of the heterogeneity of the building stock, the high market penetration of gas- and oil-based heating systems, the challenges of energy-oriented renovations and the remaining time to achieve climate neutrality.

Instead, a technology-open approach allows local conditions to be taken into account and differentiated solutions for the various building types. The use of gas-based heating technologies based on hydrogen is a sensible addition to the technology mix. In the following sections we discuss further reasons for the use of hydrogen in the heating market:

- the limited potential of additional electricity generation capacity from renewable energies in Germany (section 2.2);
- the lack of necessary import and transmission capacities for electricity (section 2.3); and
- the lack of seasonal storage options for electricity in order to meet heating demand (section 2.4).

2.2 **Electricity system** - Power generation and transmission infrastructure is not designed for large-scale electrification of energy consumption

The expected expansion of electricity generation from renewable energies may not keep pace with future electricity demand

In 2020, electricity generation from renewable energy sources (RES) in Germany amounted to about 250 TWh and thus about 45% of total German gross electricity consumption.[18] According to the federal government's climate protection programme, RES-E generation is expected to increase to just under 380 TWh by 2030 (Figure 6). This would represent an increase in generation of 50% compared to 2020, driven in particular by the expansion of offshore wind power (+50 TWh relative to 2020), photovoltaics and onshore wind power (each +40 TWh relative to 2020).[19]

[17] For example, almost 40% of property owners in Germany are 65 years of age or older. This age group is often not inclined to make long-term investments into energy-saving renovations and heating system replacements.

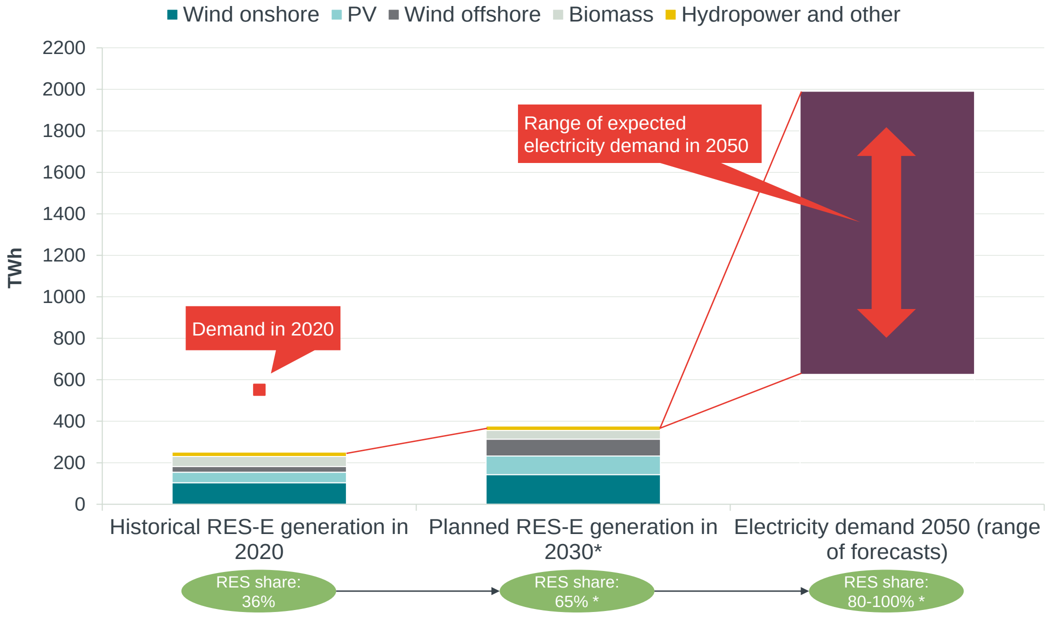
[18] BMWi (2021a)

[19] Federal Government (2019)

With today's electricity consumption, this would achieve the federal government's goal of increasing the share of renewable energies in electricity consumption to 65% by 2030.

However, the majority of estimates for future electricity demand in 2030 assume that electricity demand will increase significantly in the future, driven in particular by the electrification of applications in the transport and heating sectors. In 2050, according to forecasts, electricity demand could be more than three times today's demand (in the extreme case with maximum electrification almost 2000 TWh/year) (Figure 6). Compared to today's electricity production from wind power and photovoltaics, electricity generation volumes would have to multiply by 2050 by a factor of 3 to 10 in order to achieve the goal of climate neutrality in the electricity sector in 2045.

Figure 6 Planned expansion of electricity generation from renewable energies and expected future electricity demand



Source: Frontier Economics based on BMWi (2021a) and various studies forecasting electricity demand.

Hint: The lower end of the range of estimated electricity demand is defined by Prognos & Boston Consulting Group (2018) with 626 TWh in 2050 in a 95% climate path. The upper end comes from Enervis (2017) with 1,991 TWh in 2050 in a scenario with maximum electrification. The most recent long-term scenarios for the German government expect an electricity demand in 2050 of between 800 and 1,000 TWh (Fraunhofer ISI et al. (2021)).

However, there are a number of barriers in the way of the required sharp increase in RES-E generation:

- The **potential for the expansion of RES-E production capacity** is very limited, especially on land, due to limited space available; the expansion of onshore wind power capacity is already lagging far behind the expansion targets set by the German government.
- A massive **expansion of the electricity network infrastructure** would be necessary to transport future renewable electricity (for example from offshore wind farms) to the centres of demand. Current expansion projects for major power lines already struggle with long delays and high cost increases.

- **Social acceptance** in Germany for the expansion of RES-E generation capacity and the expansion of power transmission grids is very low. Against this background, the required near-term expansion of Germany's renewable electricity generation and grid infrastructure is difficult to achieve.
- Due to the decision to **phase out nuclear power and coal,** renewable energies would have to replace large parts of existing firm generation capacity in Germany in the next few years. However, intermittent renewable energies are not permanently available and are only able to provide base-load power generation capacity to a very limited extent. In order to guarantee secure power supply at all times, flexible power plant capacities (e.g. based on climate-neutral gases) will therefore be required as back-up on a large scale.
- The **seasonality of energy demand**, with a high increase in demand in winter months because of heating, is not reflected by the profile of electricity generation from wind and photovoltaics. The supply profile of photovoltaics is inverse to demand: during the cold period in winter, the feed-in from PV is systematically lower due to lower solar radiation. In addition, there is a lack of large-volume seasonal storage options for electrical energy.

These challenges show that the electricity system is not designed for a widespread electrification of all consumption sectors in the foreseeable future. The risks to the security of supply and the failure to meet climate targets can be reduced by combining electrification with alternative technology options.

Germany will continue to be dependent on energy imports in the future

Germany will continue to be dependent on energy imports, even in the medium to long term, in order to meet expected energy demand. The potential for importing electricity is very limited. Germany's electricity import capacities currently amount to approx. 25 GW[20] - this amounts to only a fraction of the existing gas import capacities of approx. 350 GW.[21] Moreover, especially in periods with a seasonally high demand for electricity, e.g. on cold, dark winter days, Germany cannot count on "carbon-free" electricity imports from neighbouring countries being reliably available.

2.3 **Global market** - Hydrogen is abundantly available from a global perspective and, unlike electricity, can be transported over long distances

There is extensive global potential for the production and export of climate-neutral hydrogen

The German Hydrogen Strategy contains targets for the expansion of electrolyser capacities in Germany from 5 GW by 2030 to 10 GW by 2035 or 2040.[22] This corresponds to a domestic production of about 14 TWh of hydrogen in 2030 for an

[20] ENTSO-E & ENTSO-G (2018)

[21] ENTSO-G Transmission Capacity Map 2019, https://www.entsog.eu/maps.

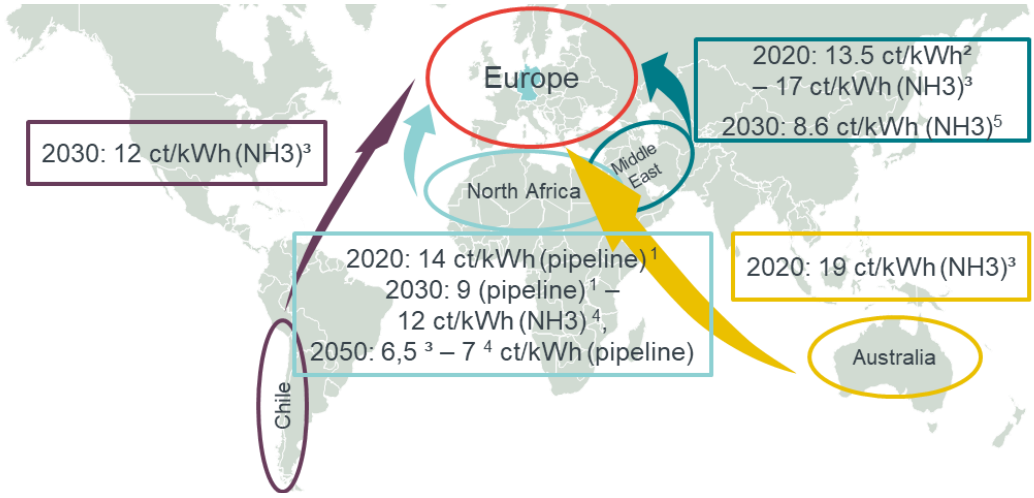
[22] Federal Government (2020), p. 2.

expected hydrogen demand in Germany of 90 - 110 TWh.[23] **Due to the limited spatial potential for renewable electricity generation in Germany (but also in Europe), hydrogen imports will likely be required to meet future demand**.

In the medium term, a **global hydrogen market** is expected to evolve because:

- **There is significant worldwide potential for the production of climate-neutral hydrogen.** Many countries outside the EU, such as Scotland, Norway, Ukraine, Morocco, the United Arab Emirates (UAE), Chile or Australia, have favourable conditions to[24] produce green hydrogen from wind power or photovoltaics, or a combination of both, in amounts that exceed their own energy needs. Traditional natural gas producing countries such as Norway or Russia are already preparing to produce and export blue or turquoise hydrogen in the future. The extent to which these potentials will be harnessed depends largely on whether sufficient incentives are created for investments in the necessary production, conversion and transport capacities in those countries.[25]
- **Importing hydrogen to Germany and Europe has economic appeal in the medium term.** More favourable production conditions worldwide lead to lower costs for hydrogen compared to production in Germany. Including transport cost, this results in prices for hydrogen imports to Germany of 9 to 12 ct/kWh (approx. 3 - 4 EUR/kg) in 2030 (Figure 7). In comparison, current production costs for green hydrogen in Germany are on average between approx. 10 and 15 ct/kWh (approx. 3.3 - 5 EUR/kg). The lower end of this range can only be realised through broad exemptions from regulatory cost drivers (e.g. grid charges, taxes and levies on power purchases).[26]

Figure 7 Import prices for green hydrogen to Europe



Source: Frontier Economics (2021b) based on [1] Leiblein et al. (2021), [2] Frontier Economics et al. (2018), [3] Guidehouse & Tractebel Impact (2020), [4] Frontier Economics et al. (2018) and IEA (2019), [5] Hydrogen Council (2020).

23 Federal Government (2020), p. 2.

24 These include climatic conditions and the availability of water and suitable land.

25 See e.g. Frontier Economics & IAEW (2019). In addition, individual countries could rely on producing hydrogen by electrolysis on the basis of nuclear power.

26 Frontier Economics (2021b).

Importing hydrogen helps to meet the challenge of limited domestic renewable energy potentials

Supplying Germany's entire future energy demand with renewable energies requires a substantial increase in production volumes of electricity from wind and photovoltaics, from just under 200 TWh today to 3 to 10 times this amount (depending on the degree of electrification). This is unlikely to be achieved (in a socially acceptable way) in domestic locations.

However, in other regions of the world - both within Europe and especially outside Europe - there is considerable potential for generating renewable energy at a level that exceeds future energy demand. Therefore, while the regional short term potential for hydrogen supply may be limited, the considerable global potential of renewable energies can be opened up for Germany and other countries through the transport of hydrogen or hydrogen derivatives. From a supply-side perspective there are no obstacles to the use of hydrogen in the heating market.

Hydrogen imports can take advantage of better wind and solar conditions in other regions

At sunny and/or windy locations, a significantly larger amount of renewable electricity can be produced with the same photovoltaic or wind power plant capacity relative to any location in Germany. For example, the full load hours of a photovoltaic system in North Africa amount to up to 2,500 h per year, while in Germany the geographical average is only 1,060 h. There are similarly large differences for onshore wind power plants.

This means that for the same amount of heat generated, less than half as much PV or wind power capacity needs to be built in North Africa as in Germany. This is important in an energy system that is increasingly based on wind and solar energy because costs and GHG emissions depend on the installed capacity of wind turbines and solar plants (in kW) rather than on the amount of energy generated (in kWh).

On the basis of the existing pipeline infrastructure hydrogen use can be supplied by renewable hydrogen imported from countries with much more favourable climatic conditions. In contrast, the power for electric heating systems must essentially be generated in Germany, or at least in surrounding countries, with correspondingly lower plant utilisation rates.

The existing gas grid has the capability to transport hydrogen

Aside from extensive gas import and gas storage capacities, Germany also has well-developed gas transmission and distribution networks. Those networks could potentially be used for the import and transport of climate-neutral hydrogen or other climate-neutral gases in the future. This can be achieved, for example, through:

- the conversion of gas pipelines to pure hydrogen transport,
- processing hydrogen into synthetic natural gas (SNG), or
- blending hydrogen into the existing natural gas grid.

Several European gas network operators have already developed various concepts for this and are testing the conversion of natural gas pipelines in pilot projects. An example conceptualisation of the transmission network is the ‘European Hydrogen Backbone’, which is based on 70% of converted natural gas pipelines across Europe and 90% in Germany. Furthermore, distribution system operators are exploring in various projects how to repurpose distribution gas grids to the use of 100% hydrogen. High conversion rates are generally expected due to the widespread use of polyethylene pipelines in distribution grids.[27]

In addition, hydrogen from countries that do not have pipeline connections to Germany and Europe can be imported by ship in the form of liquid hydrogen or hydrogen derivatives such as ammonia or methanol (so-called power-to-liquids).

2.4 **Storability** - Hydrogen can be used to seasonally store renewable energy.

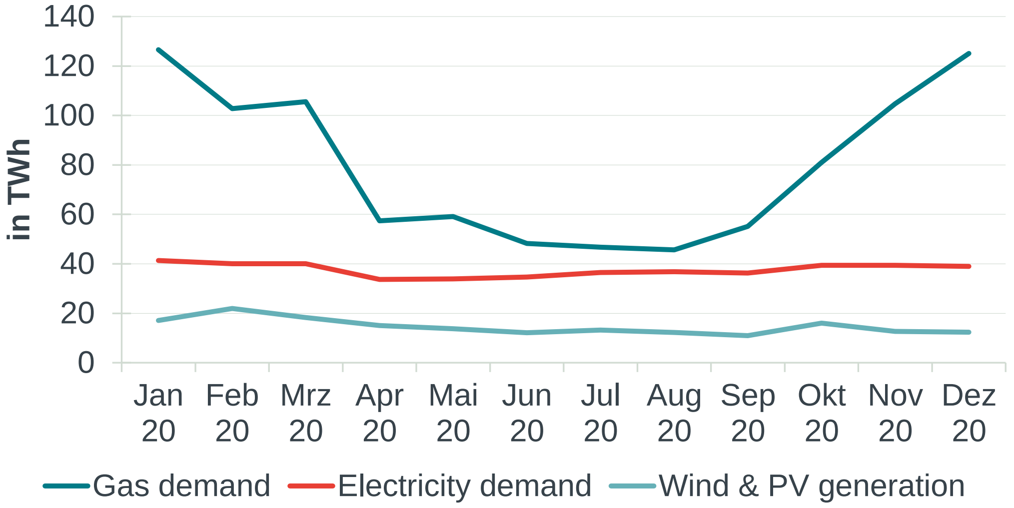
Due to seasonal fluctuations in demand in the heating market, final energy consumption is characterised by a high difference between summer and winter. (Figure 8).

- The **seasonality of heat demand is** clearly reflected in monthly natural gas demands. While in the relatively mild winter peak of 2020 gas demand in Germany was around 130 TWh/month, it fell just below 50 TWh/month in summer.[28]
- In contrast, the **monthly electricity demand is** relatively constant over the year at around 40 TWh/month.
- **Monthly power generation from wind and photovoltaics** in 2020 fluctuated between 12 and 22 TWh/month due to weather conditions.

[27] See Gas for Climate (2020) and Gas for Climate (2021).

[28] Aside from natural gas, other fossil fuels such as heating oil are used to supply the seasonal demand in the heating market as well. All fossil energy sources would have to be replaced by climate-neutral forms of energy in the future.

Figure 8 Monthly electricity and gas consumption versus power generation from wind and PV (2020)



Source: Frontier Economics based on Eurostat, Destatis and Fraunhofer ISE.

In order to supply high winter heat demand under widespread electrification of the heating market, it is necessary to temporarily store electrical energy in large quantities and over long periods of time. Despite improved battery technologies, batteries alone are unlikely to be able to manage seasonal storage of large amounts of electricity in the future.

However, extensive intermediate storage of electricity is possible in the future by converting electricity into hydrogen during periods of low electricity demand (or high electricity production), which can be stored in existing gas storage facilities. In times of high electricity demand (or low electricity production), the hydrogen can then be used directly (e.g. in the seasonal heating market) or be converted back into electricity. The existing gas storage infrastructure has been designed to store large amounts of energy to meet seasonal heat demand. For example, Germany's gas storage capacities amount to about 260 TWh - the existing electricity storage capacities, at 0.04 TWh, are only a fraction of that.[29] Currently, apart from chemical storage in the form of hydrogen or its derivatives, no other mature technology is available that can store large amounts of energy over the required periods of time.

[29] Gas Infrastructure Europe - AGSI+ Aggregated Gas Storage Inventory, and Geth et al. (2015).

2.5 **System costs** - Hydrogen can help to achieve climate targets at lower overall costs and in a socially acceptable manner

An important aspect that is often neglected when looking at individual technology options is the economic question of the total energy system costs associated with the transition to climate neutrality.

From an overall system perspective in 2050, the use of climate-neutral gases leads to cost benefits

A number of German and European studies in recent years have looked at the **total system costs** in **scenarios with a high degree of electrification** (i.e. **without** a relevant role for hydrogen and other climate-neutral gases) compared to **scenarios with a lower degree of electrification** (i.e. **with** a substantial role for hydrogen and other climate-neutral gases).

The majority of studies conclude that the use of hydrogen and other climate-neutral gases results in cost benefits in the long term compared to an "all-electric" scenario. This is because of cost savings in these following areas:[30]

- **Electricity grids** - The (continued) use of existing gas grids and gas storage facilities reduces the costs for electricity grid expansion;
- **Power plant park** - The use of climate-neutral gases requires less power generation capacity and fewer electricity storage facilities;
- **Heating systems** - The (continued) use of gas-based heating systems reduces the need to invest in new heating systems or leads to lower renovation costs, especially in previously unrenovated old buildings.

Hydrogen in the heating market can reduce the cost burden for low-income households

Another important aspect of moving towards climate neutrality in the heating market is the potential cost burden on households. That is particularly relevant in the context of social fairness. One study examined this question using the city of Essen as a subject. The study comes to the conclusion that the share of costs for heating in the household budget ("share of wallet") would double from 2.3% to 4.6% in a scenario of pure "electrification with heat pumps" compared to the status quo.[31] In contrast, a scenario that allows for the use of "green gases" such as hydrogen results in a household budget share of costs for heating of 3.5%, and thus about 30% lower than in a pure electrification scenario. The general increase in costs for heating would also have a disproportionate impact on low-income households because energy costs account for a larger share of their household budget. Furthermore, the cost of investing in electric heat pumps in single-family

[30] E.g. Frontier Economics et al. (2017), Dena (2018) for Germany and Frontier Economics & IAEW (2019) for the EU.

[31] E.ON (2021).

houses is lower than in multi-family houses whose residents also have lower incomes on average than the residents of single-family houses.

3 **EFFICIENCY ANALYSIS** - AN EXTENDED EFFICIENCY COMPARISON SHOWS THAT FOCUSSING ONLY ON TECHNICAL EFFICIENCIES OF ALTERNATIVE HEATING TECHNOLOGIES DOES NOT GIVE THE FULL PICTURE

Apart from sector coupling and necessary expansion of renewable energy capacities, improving energy efficiency ("the triad of the energy transition") is an important component of the German government's strategy to achieve climate goals:

> "*The Federal Government is pursuing the goal of shaping the German economy into the most energy-efficient economy in the world and halving primary energy consumption by 2050 relative to 2008.*" (Effizienzstrategie 2050)[32]

There is consensus in the scientific as well as in the energy policy debate that energy efficiency will be an important part of the energy transition in Germany. Upgrading energy performance, i.e. improving the ratio of primary energy (input) to usable final energy (output) can be achieved both through more efficient conversion of primary energy (e.g. wind or solar energy) to secondary energy (e.g. electricity or hydrogen) and through more efficient conversion of secondary energy to final energy (e.g. heat), for example through better-performing end appliances. When considering the use of alternative low-emission or emission-neutral technologies in the heating sector, it is often argued that electricity-based appliances are superior to appliances based on climate-neutral gases for energy efficiency reasons .

Political decisions should not be based on efficiencies alone

Energy policy decisions should not be based on energy efficiencies alone. Rather, a holistic analysis of the different technologies is necessary to inform energy policy decisions with consequences for the choice of technology. This includes the economic costs associated with various technologies (for end appliances as well as for energy generation, energy conversion, energy storage, energy transport and energy distribution), the greenhouse gas emissions during the life cycles of the technologies, and the feasibility and acceptance of the respective technologies.

When efficiencies are nonetheless used for decision-making, it is important that these are appropriately calculated and reflect all relevant effects along the energy supply chain. Therefore, we consider the overall efficiencies of different heating technologies as well as other important aspects. Comparing the efficiencies of different energy paths in the heating sector is by no means as clear-cut as it is often portrayed in the public debate. Rather, the results depend substantially on

[32] BMWi (2019).

the assumptions regarding the conditions along the entire efficiency chain (e.g. cold winter day vs. mild autumn day; old building vs. new construction). Taking these factors into account gives a more heterogeneous picture of the different technologies.

An appropriate efficiency analysis of alternative heating technologies should take into account real climatic conditions and the status of building stock in the heating market. We go into this in more detail and describe:

- which **characteristics of the heating market** should be considered in an efficiency analysis (section 3.1);
- the results of an efficiency analysis under favourable conditions in comprehensively renovated buildings. (section 3.2);
- the **overall efficiencies of** the different technologies under realistic conditions in existing buildings (section 3.3).

In the following text box, we first summarise the central results of our extensive efficiency analysis of heating technologies.

THE RESULTS AT A GLANCE

A meaningful efficiency analysis of alternative electricity- or hydrogen-based heating technologies takes into account not only the technical efficiencies of the different technologies but also the actual climatic and building conditions in the heating market. Focussing only on technical efficiencies of end appliances does not give the full picture as it does not reflect the reality of the heating market, which is characterised by heterogeneity of the building stock with different renovation statuses and high seasonality of demand.

The results show that:

- **electric heat pumps have an important role to play in decarbonising the heating market**, as they can achieve high overall efficiencies by using ambient heat in buildings with high insulation standards, especially in new constructions;
- however, the **efficiency advantage of electric heat pumps** over **hydrogen-based heating technologies diminishes** if:
  - they are used in **unrenovated or only partially renovated buildings**, which account for **87% of the current building stock**; and / or
  - due to **cold climatic conditions,** a considerable proportion of energy has to be taken from **seasonal intermediate storage.** Such cold periods are crucial for the design of the generation and grid infrastructure.

3.1 **Characteristics of the heating market** - A meaningful efficiency comparison of heating

technologies must take into account the actual climatic and building stock characteristics

The heating market in Germany is characterised by a high degree of heterogeneity in the building stock with different renovation statuses and high seasonality in demand.

Currently, almost 80% of space and water heating demand in Germany is supplied by fossil energy sources, which equates to about 670 TWh based on a total final energy demand in 2019 of 836 TWh in this segment (see section 2.1).

If large parts of final energy demand for space and water heating are to be supplied by renewable energies in the future, the characteristics of the heating market will change fundamentally. In particular, because of a strong increase in production from intermittent generation technologies such as wind power and photovoltaics, electricity will not always be available in sufficient quantities in location where it is needed.

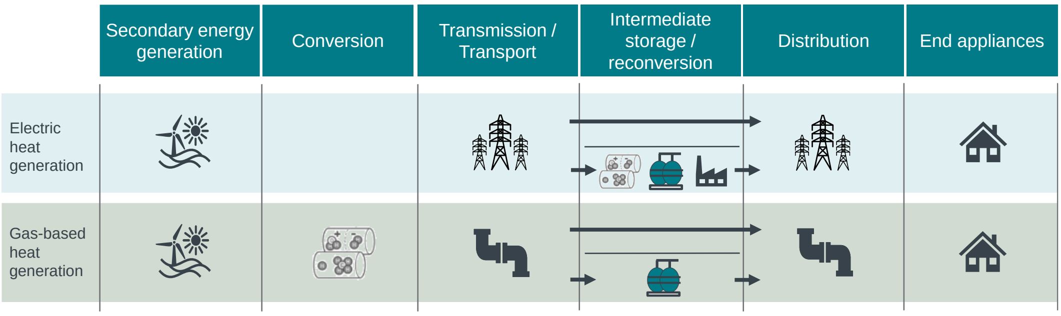
In order to supply the seasonal demand in the heating market, transportability (from the place of production/storage to the place of consumption) as well as large-scale and long-term storability will be crucial features of energy carriers (see section 2.4).

The current lack of large-scale storage options for electrical energy and the requirement to meet peak demand of the heating market in winter means that significant amounts of electricity must be converted into storable gaseous energy carriers, such as hydrogen, and seasonally stored in gas storage facilities. Only the use of gaseous energy carriers and gas infrastructures can guarantee a sufficient and secure energy supply in the heating market.

To assess the overall efficiency of technologies, efficiency losses along the entire process chain must be taken into account

For a meaningful comparison of efficiencies of individual heating technologies, the entire energy supply chain from generation to final consumption should be analysed. Efficiency losses can occur along the supply chain, which can have significant effects on the overall efficiencies of individual heating technologies. Figure 9 presents illustrative supply chains for electric and gas-based heating technologies that are based on electricity generated from renewable energy sources.

Figure 9 Simplified illustration of analysed stages of the supply chain of electric and gas-based heating technologies.



Source: *Frontier Economics*

Note: *At the storage stage a certain proportion of the total amount of energy goes directly from generation to end appliances via electricity or gas transmission and distribution networks. Intermediate storage is not required for that proportion of energy.*

The factors that affect the overall efficiency of individual heating technologies in each stage of the supply chain are as follows:

- **Energy supply:** We assume that only electricity generated from domestic renewable energy sources in Germany is available.
- **Conversion**:
  - In the case of gas-based heat generation, losses result from the conversion of electricity into hydrogen (and oxygen) in water electrolyzers.
  - In the case of electric heat generation, there are no conversion losses.
- **Transmission/transport and distribution:** With electricity, a fraction of energy is lost to resistance when it is transmitted or distributed over power lines. With hydrogen, some energy is needed to compress the gas into pipelines and transport it to its destination, resulting in efficiency losses.
- **Intermediate storage:** In preparation for increased heating demand in cold periods, a proportion of the secondary energy is stored temporarily. Our assumption is that seasonal storage is conducted in the form of hydrogen, which can be stored in gas storage facilities:
  - In the case of electric heat generation, efficiency losses occur due to the conversion of electricity into hydrogen required for intermediate storage, the storage process itself (e.g. compression) and the reconversion into electricity in hydrogen-fired power plants.
  - In the case of gas-based heat generation, the efficiency losses at this stage are limited to losses from the process of storing hydrogen (mainly compression).[33]
- **End appliances:** The technical efficiencies of electric heating appliances in particular depend on a number of external factors such as the condition of the building and the climatic conditions. We address these factors in more detail next.

[33] Conversion losses from electricity to hydrogen are already taken into account at the second stage (conversion).

The efficiencies of end appliances in heating depend on a number of different factors

Our efficiency analysis considers a number of alternative heating technologies that could be used in a future decarbonised heating market. The following factors affect the end-use efficiencies of heating technologies:

- **Technology-specific factors:** The efficiencies of individual heating end appliances are determined by the exact technical specifications of the heating system.
- **Climatic conditions:** For heat pumps, the efficiencies depend strongly on the temperature of the heat source (e.g. the ambient air for air source heat pumps or the soil temperature for ground source heat pumps). On normal days, heat pumps achieve high coefficients of performance (COP).[34] However, on cold winter days when the difference between the source temperature and the flow temperature of heating circuit is particularly high, the COP drops sharply.[35] The appliance efficiencies of condensing boilers or fuel cells are generally constant regardless of climatic conditions.
- **Building conditions:** The coefficient of performance of heat pumps is also determined by the energy performance of a building. Fully renovated buildings or new constructions with high thermal insulation standards and panel heating only require low heating flow temperatures (~35 °C) to produce pleasant indoor temperatures (e.g. 20 °C). In these settings, heat pumps achieve higher efficiencies than in unrenovated buildings or old buildings, where higher flow temperatures (~60 °C) are required to produce the same indoor temperatures. The appliance efficiencies of condensing boilers or fuel cells are again largely independent of the building condition.

In the following, we provide an overview of the analysed heating systems. The table in Figure 10 presents a summary of the assumptions used in our analysis for end appliance efficiencies of the different heating systems.

- **Electric heat pumps:**
  - **Air source heat pumps** (ASHP) absorb heat energy from ambient air and transfers it to a water circuit that releases the heat on the inside of the building. Under optimal conditions on a mild day in a new construction or a comprehensively renovated old building, a typical air source heat pump operates with a coefficient of performance of 460%. This means that with one unit of electricity input (not taking into account possible efficiency losses on the upstream stages), the heat pump generates 4.6 times the amount of useful heat energy. Under non-optimal conditions, however, the coefficient of performance drops sharply. On very cold days (ca. -15 °C outside temperature) in an unrenovated old building, the ASHP operates with a

[34] The coefficient of performance (COP) describes the ratio of electrical energy input to thermal energy output of a heat pump. The COP is highly dependent on operating conditions (building conditions, outdoor temperatures). The weighted average of COPs over a range of outside air conditions over a year is called the seasonal energy efficiency ratio (SEER). The SEER reflects the ratio of total thermal energy generated over the year to electrical energy consumed.

[35] For ground source heat pumps, this applies only to a limited extent. The ground close to the surface reacts less strongly and only with a delay to changes in outside temperatures. From a depth of about 10 metres, ground temperatures remain constant throughout the year. With further increasing depth, the average temperature rises due to geothermal heat.

relatively low COP of 160%. In cases when the electric heat pump cannot supply the full heat demand (i.e. at very low outdoor temperatures) a heating rod comes into use to support or even substitute the heat pump. The efficiency drops to 100% when the heating rod is operating without the heat pump. Electric air source heat pumps currently make up the majority of the heat pump stock in Germany, with a share of about 60%.[36] In recent years, the share of air source heat pumps in all heating heat pumps sold has risen steadily and was as high as 80% in 2020. [37]

  - **Ground source heat pumps** (GSHP) work on the same principle as air source heat pumps by extracting thermal energy from the ground. For this purpose, ground collectors are laid close under the surface or a ground probe is sunk into the earth up to 100 metres deep. Ground source heat pumps are generally more efficient than air source heat pumps. Since the temperature in the ground remains relatively constant relative to the ambient air, efficiency losses on cold days are less pronounced than with air source heat pumps. However, installation is significantly more complex and cost-intensive than for air source heat pumps. In addition, GSHP cannot be installed in many types of buildings (e.g. existing apartment buildings) because of the necessary earthworks. Since ground source heat pumps cannot be considered a viable alternative heating technology for the majority of existing buildings, **we focus our analysis on air source heat pumps.**

- **Hydrogen condensing boiler:** The concept of a hydrogen condensing boiler is the same as that of a condensing boiler fuelled with natural gas. In addition to the heat generated by the combustion of gas, these boilers also use the energy contained in the exhaust gases. Heat extracted from the exhaust gases is converted into additional heating energy. Compared to constant-temperature and low-temperature boilers, high efficiencies of up to 98% can be achieved with gas condensing boilers. With market shares of 60% to 70%, natural gas condensing boilers represent the major share of heating appliances sold in the years 2015 to 2020 in Germany.[38] According to heating appliance manufacturers, existing gas-based condensing boilers can already accept a blend of 10 percent hydrogen by volume without the need for adaptation. The latest generations of gas-based condensing boilers are expected to safely accept up to 20-30 percent by volume of hydrogen without significant additional costs. Moreover, simple and cost-effective retrofit solutions in order to make boilers suitable for "pure" hydrogen have been announced by German heating appliance manufacturers and are expected to be available by 2025.

- **Hydrogen heat pumps**: Similarly to electric heat pumps, gas-based heat pumps use thermal energy from the air, ground or water. In contrast to electric heat pumps however, gas-based heat pumps have a different operating principle: thermal energy extracted from the environment is not brought to a higher temperature level through the use of electricity, but rather by burning natural gas or hydrogen. Basically, there are three different types of gas-based

[36] BDEW (2021), p. 44. The remaining heat pump stock is divided between ground source heat pumps (20%) and, with minimal shares each, water source heat pumps, gas heat pumps and water heating heat pumps.

[37] Bundesverband Wärmepumpe e.V. (2021)

[38] BDEW (2021). S. 51.

heat pumps.[39] Gas-based heat pumps currently account for only a very small proportion of the heat pump stock in Germany. [40] Heat pumps operated on the basis of hydrogen will be available in the foreseeable future.

- **Hydrogen fuel cells:** Fuel cells use hydrogen, which is usually produced from natural gas in a reformer. This step becomes obsolete if the fuel cell is directly supplied with hydrogen. Fuel cell heating systems simultaneously cogenerate electricity, which is made usable for the consumer by converting it into alternating current, and heat, which can be used directly or via a buffer storage tank to heat the domestic heating circuit. The overall efficiency of a fuel cell heating system is usually indicated in simplified terms as the sum of the electrical efficiency of electricity production and the thermal efficiency of heat generation. This does not take additional benefits of decentralized on-site power generation into account. A higher value may therefore be attributed to fuel cells compared to heating technologies that are "heat-only". For example, in periods of high heating demand, the energy system as a whole could benefit from using surplus electricity produced to support electric heat pumps in the immediate vicinity.

Figure 10 End appliance efficiencies of heating technologies under different building and climatic conditions

Heating technology	Specification	New construction (=low flow temperature of 35°C)		Old building (=high flow temperature of 55°C)	
		Mild outdoor temperature (15°C)	Cold outside temperature (-15°C)	Mild outdoor temperature (15°C)	Cold outside temperature (-15°C)
Electric heat pumps	Air source	460%	240%	270%	160%
Hydrogen condensing boilers	Hydrogen	98%	98%	98%	98%
Hydrogen heat pumps	Air source / gas absorption	160%	130%	145%	100%
Hydrogen fuel cells	Hydrogen	90%	90%	90%	90%

Source: *Frontier Economics based on Hirvonen and Siren (2017), ASUE (2019), Herrmann et al. (2018), EnergieSchweiz (2019), Dodds et al. (2015) and Sadler et al. (2016).*

Notes: *In new constructions, the heating system is usually set to low flow temperatures of approx. 35 °C. In old buildings however, relatively high flow temperatures of at least 55 °C must be reached. For the heat pumps, a "mild" use case of a mild day in autumn with low heating demand is assumed and we apply the appropriate coefficient of performance. In the "cold" use case, we make the assumption of a cold winter day with low outdoor temperatures of down to -15 °C. Again, we apply the coefficient of performance accordingly. End appliance efficiencies of hydrogen condensing boilers and fuel cells are constant and independent of climatic conditions. For fuel cells, the efficiency is calculated as the combined efficiency of heat and power cogeneration. Hydrogen heat pump are defined as absorption heat pumps here.*

[39] In **gas engine heat pumps,** a gas-powered engine compresses the refrigerant used. In **absorption heat pumps,** the temperature level is increased by dissolving refrigerant vapour in a special solvent (e.g. an ammonia/water mixture), which then releases absorption heat. In contrast, in **adsorption heat pumps,** the refrigerant is not dissolved in a liquid. Instead, water is used as the refrigerant, which evaporates by absorbing the environmental heat and is deposited (adsorbed) on the surface of a solid (e.g. activated carbon or zeolite). This process generates adsorption heat. In practice, gas absorption heat pumps are most common.

[40] BDEW (2021), p. 44.

3.2 **Efficiency analysis under favourable conditions** - Electric heat pumps achieve the highest overall efficiencies in comprehensively renovated buildings

In order to compare the different heating technologies under realistic heat market conditions, we analyse the efficiency losses and/or gains along the supply chain of the technologies.

In our detailed study of each supply chain stage, we compare electric air source heat pumps (currently the most common variant of the electric heat pump) with hydrogen condensing boilers (currently boilers are the most common gas-based technology).

We assume that electricity produced in Germany from renewable energy sources is used as the secondary energy source for both technologies. We then analyse the overall efficiencies for different use cases in which both the climatic conditions (mild day vs cold day) and the building types (new construction or fully renovated old building vs unrenovated or partially renovated old building) are varied. For the classification of building types we assume that in a new construction (or fully renovated old building) heating is possible with low flow temperatures of about 35 °C due to modern thermal insulation (e.g. KfW standard 55) and the use of surface heating systems (underfloor or wall heating). In the case of unrenovated or partially renovated old buildings, we assume that the energy performance of the building does not meet today's standards. Compact or steel radiators are usually installed as heat transfer systems, and higher flow temperatures of approx. 55 °C or more are required.

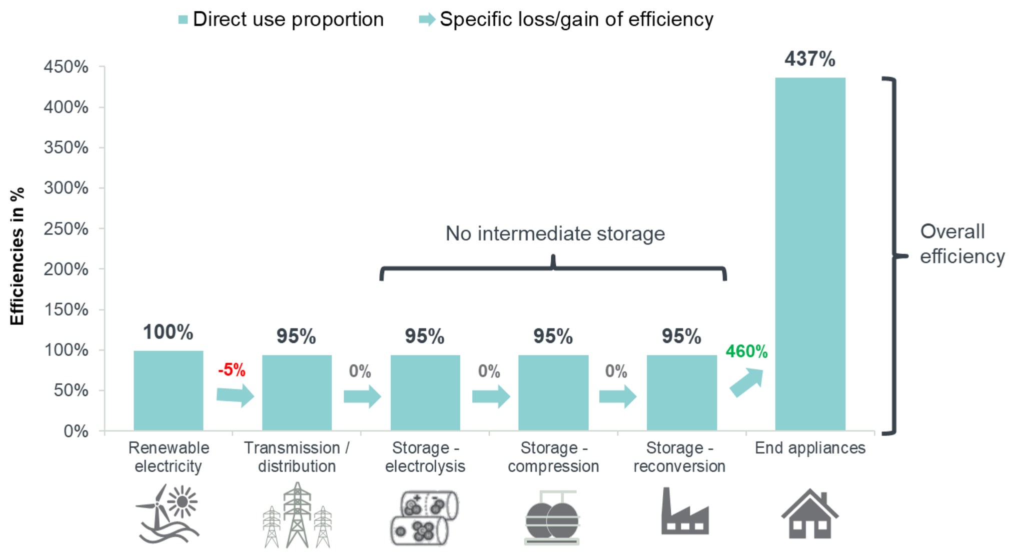
The alleged efficiency advantage of electric heat pumps over alternative heating technologies is based on their high efficiencies under favourable building and climatic conditions

Figure 11 contrasts the efficiencies of electric air source heat pumps and hydrogen condensing boilers for the use case of a new construction (or fully renovated old building) on mild days (average autumn day with mild outdoor temperatures of about 15 degrees Celsius and thus low heating demand). A sufficient amount of renewable electricity is generated and no energy needs to be taken from seasonal storage facilities, e.g. hydrogen cavern storages. In this case, **electric air source heat pumps** can fully exploit their high technical efficiencies (coefficient of performance of 460%) by using energy from ambient air and perform to an **overall efficiency of 437%** (based on 100% renewable electricity). Hydrogen **condensing boilers** on the other hand, only achieve an **overall efficiency of 62%** (based also on 100% renewable electricity), with efficiency losses mainly resulting from the conversion of electricity into hydrogen by means of electrolysis (-33%), minor efficiency losses stemming from hydrogen transport (-5%)[41] and efficiency losses of the condensing boiler (-2%).

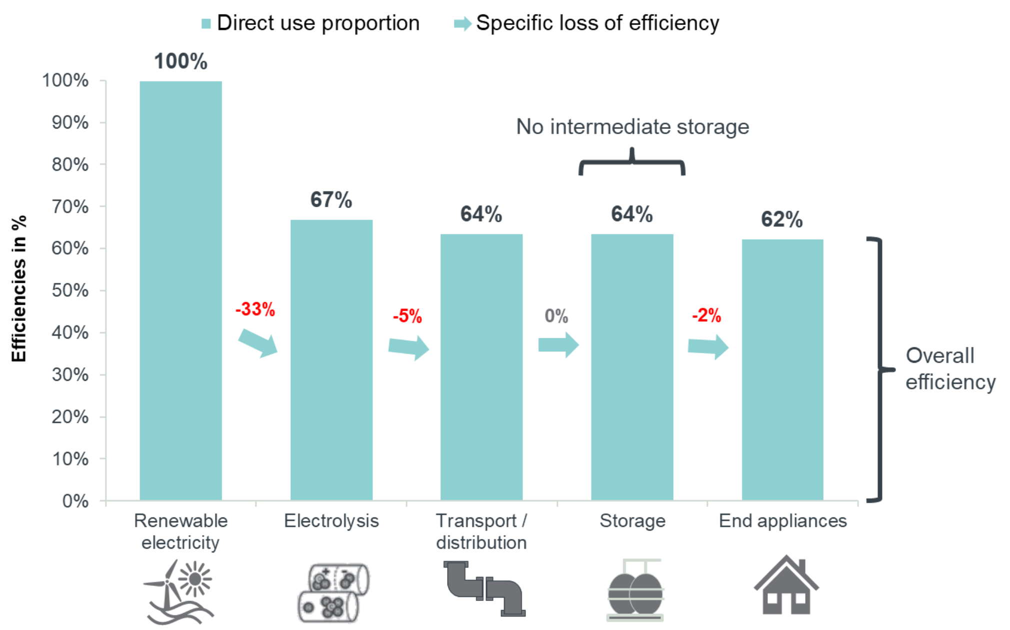
[41] Energy losses from hydrogen transport are determined, among other things, by the distance between hydrogen production and hydrogen consumption. In local/decentralised systems, losses from transport are

Figure 11 Efficiency losses of electric heat pumps and hydrogen condensing boilers along the process chain in % ("mild day without intermediate storage")

Electric air source heat pump („mild day“, new construction, no intermediate storage)



H2 condensing boiler („mild day“, new & old building, no intermediate storage)



Source: *Frontier Economics*

Note: *Based on the following assumptions on the efficiencies at each stage: electricity/gas transmission efficiency: 95%, electrolysis efficiency: 67%, ASHP coefficient of performance: 460% (at outdoor temperatures of 15 °C), hydrogen condensing boiler efficiency: 98%.*

Under these conditions, the overall efficiency of the electric heat pump is higher than that of an hydrogen condensing boiler by a factor of 7. This is the unrealistic comparison of efficiencies that is often presented in the political debate, in order to

negligible, which means that these systems can achieve even higher overall efficiencies under the same conditions.

argue against the use of hydrogen in the heating market. In the following section, however, we show that the results are significantly different in other relevant use cases - and significantly more positive for the use of hydrogen in the heating market.

3.3 **Efficiency analysis under realistic conditions** - In the majority of existing buildings, hydrogen-based heating technologies are similarly efficient as heat pumps on cold days.

Our analysis up to this point was based on assumptions that depict a textbook case (from the perspective of electric heat pumps), but which do not actually reflect the **realities of the heating market**. These assumptions included, in particular, mild climatic conditions and buildings that are either newly constructed or comprehensively renovated. Both of these conditions indicate a high coefficient of performance and thus a high overall efficiency of the heat pump. However, in reality heat pumps are not the first heating technology of choice (or even not an option at all) in 87% of the building stock, i.e. in unrenovated or only partially renovated old buildings. That is because old buildings with poor insulation often cannot be sufficiently heated with heat pumps.[42]

If the efficiency analysis is carried out under realistic conditions, **the overall efficiency advantage of the electric heat pump disappears** (Figure 13). On cold winter days (with outdoor temperatures down to -15 degrees Celsius) without substantial production from photovoltaics or wind power, only a small portion of the electricity demand for heating can be supplied directly by local RES production. Instead, a large part of energy supply has to come from power storage capacities, i.e. from reconversion of stored hydrogen supply. The need for intermediate storage and reconversion can therefore be derived from the share of intermittent renewable electricity in total electricity demand (see text box). On this basis, we assume that on a **cold winter day, 80% of required energy demand for heating** must be supplied by **seasonal intermediate storage.**

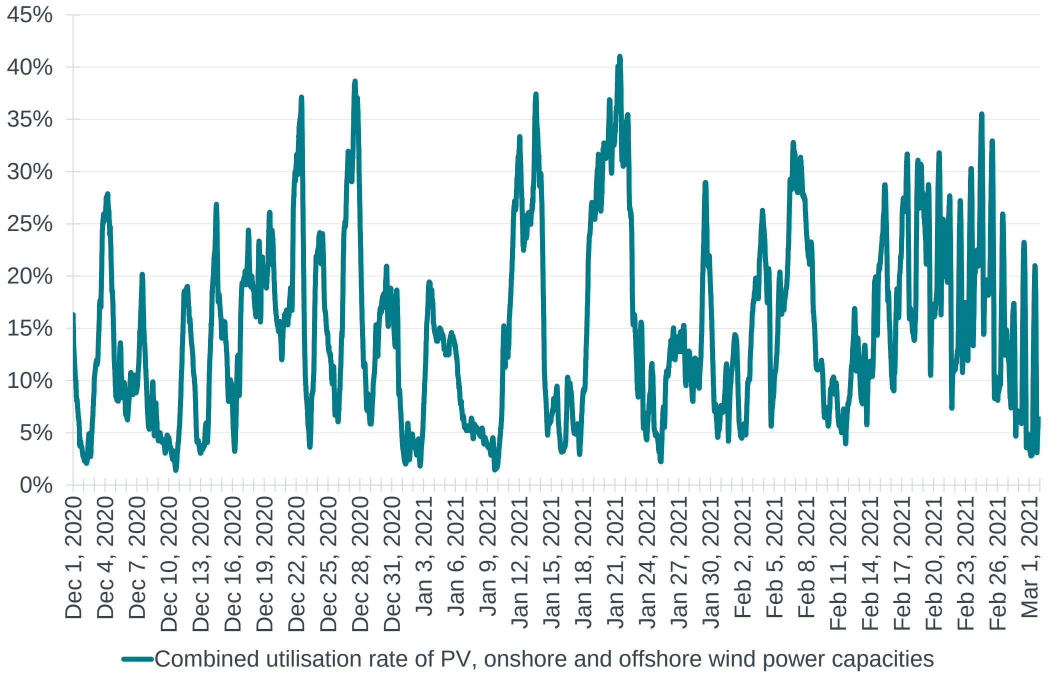
Intermediate storage is needed for the use of renewable electricity in the heating market

Figure 12 shows the combined utilisation rate of photovoltaics, onshore wind and offshore wind power capacities in Germany in the period from 1 December 2020 to 1 March 2021. The charts indicates that the utilisation rate of PV and wind plants is usually around 20% or significantly below - often even below 5% on several consecutive days. Higher utilisation rates of 30 - 40% are rarely achieved. Firm

[42] *For* example, ifeu & Hamburg Institute Research (2020), p. 57, states: *"In buildings that are not sufficiently insulated, the required flow temperature in the heating system is so high that it cannot be economically supplied by a heat pump. This can be mitigated to a certain extent by replacing old-fashioned radiators. According to Jochum et al. (2017), economic heat pump operation is not possible above a final heat demand limit of 120 kWh/m²a. However, this limit only applies under ideal conditions in the heating circuits. If the existing radiators are not all designed for the same specific heating load, are not balanced or, if individual rooms require higher flow temperatures due to an exposed location or higher setpoint temperatures, the potential for using heat pumps are even lower. In practice, heat pumps can hardly be installed in buildings with heating demand above 90 kWh/m²a."*

capacity provided by PV and wind power is therefore only a fraction of actual required capacity, especially in phases of "dark lulls" with low solar and wind supply. In order to meet electricity demand at any time in a system based on intermittent energy sources such as wind and solar power, it is necessary to build up large amounts of storage capacity.

Figure 12 Utilisation rates of PV and wind power capacities in the period from 1 December 2020 to 1 March 2021

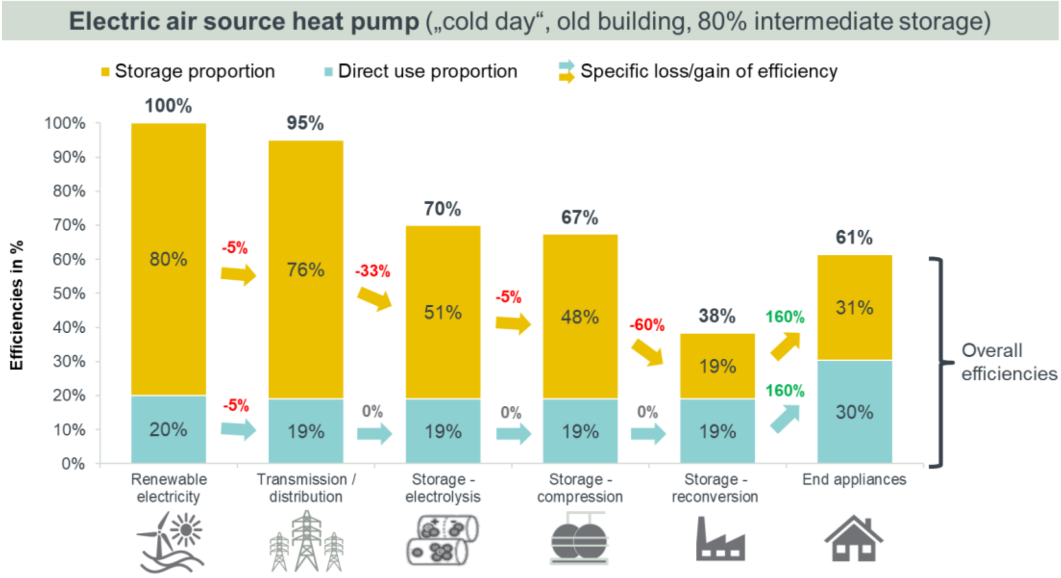


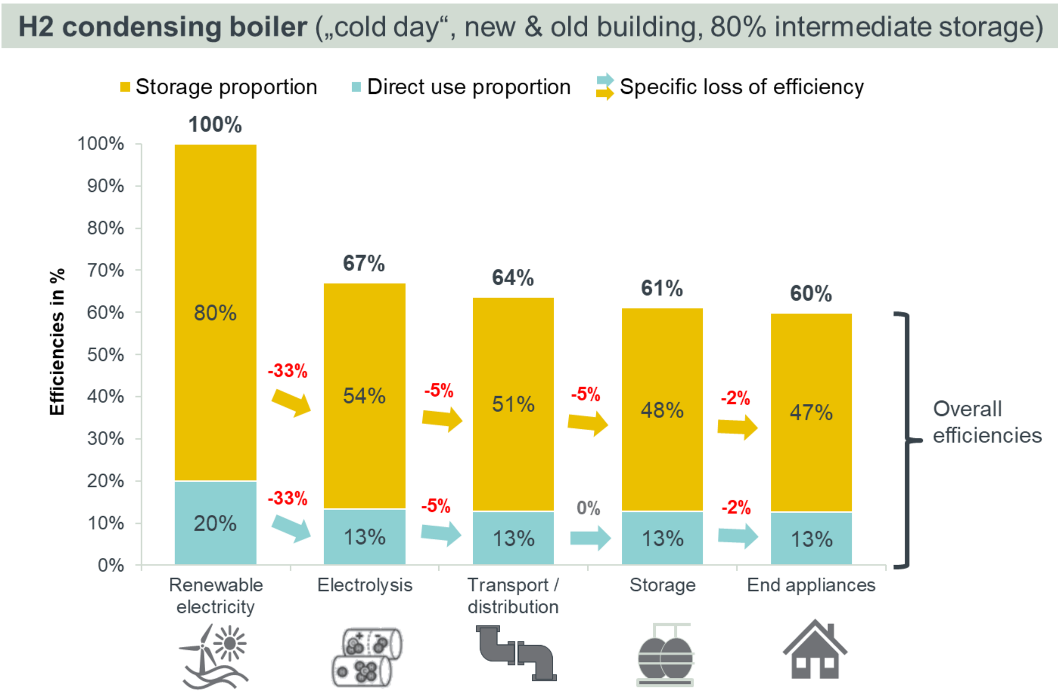
Source: Frontier Economics based on actual electricity generation data from smard.de and energy-charts.info

While short-term storage (e.g. of a few hours) of renewable electricity can be provided in the future by storage facilities such as pumped hydro storage and batteries, **intermediate storage of RES-E for longer periods** (e.g. of several weeks or months, as explained in section 2.4) will realistically only be possible in **the form of hydrogen**. Because 80% of the electricity demand of electric heat pumps must be temporarily stored as hydrogen, efficiency losses have to be taken into account. These losses occur during electrolysis (-33%), the storage process itself (-5%) and reconversion into electricity in hydrogen-fired turbines (-60%) (Figure 13).

Furthermore, the **coefficient of performance of heat pumps under cold outdoor temperatures and in unrenovated or partially renovated old buildings is much lower** than under optimal conditions. Air source heat pump efficiency gains of only 60% (based on a coefficient of performance of 160%) are to be expected under these conditions, compared to efficiency gains of 360% (based on the coefficient of performance of 460%) under mild temperatures in buildings with high insulation standards. As a result, **electric heat pumps** can only achieve an **overall efficiency of 61%.** This outcome is roughly on the same level as the **overall efficiency of hydrogen condensing boilers (60%)** that is generally independent of external climatic and building conditions.

Figure 13 Efficiency losses of electric heat pumps and hydrogen condensing boilers along the process chain in % ("cold day with intermediate storage")





Source: Frontier Economics

Note: Based on the following assumptions on efficiencies at each stage: electricity/gas transmission efficiency: 95%, electrolysis efficiency: 67%, storage efficiency: 95%, reconversion efficiency: 40%, ASHP coefficient of performance: 160% (at outdoor temperatures of -15 °C), hydrogen condensing boiler efficiency: 98%.

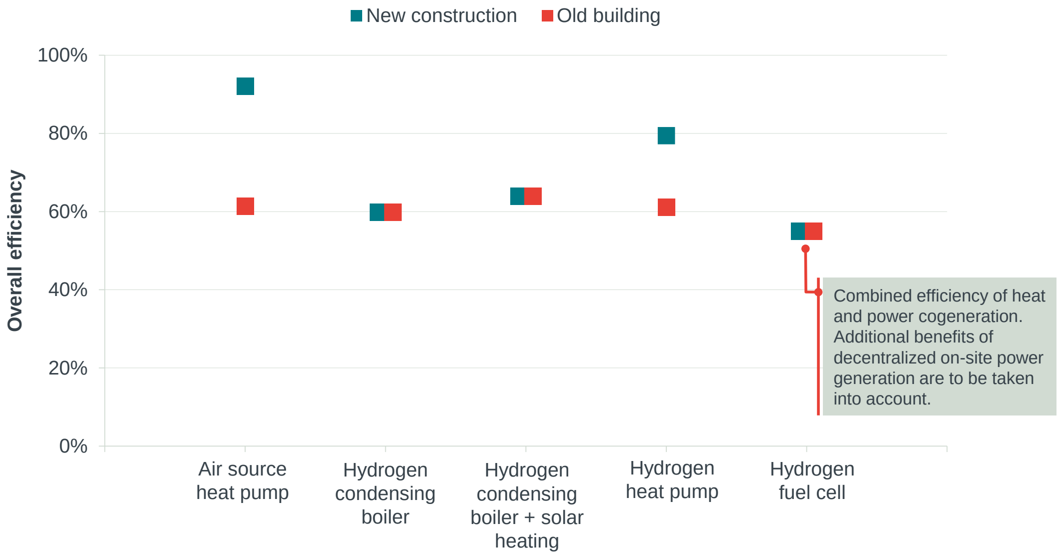
Extreme use cases are relevant for the design of the system - in these, electric heat pumps do not show any advantages over hydrogen-based heating technologies

In this section, we compare the **overall efficiencies of all analysed heating technologies**. Aside from those technologies already examined in detail (electric air source heat pump and hydrogen condensing boiler), we include the combination of hydrogen condensing boilers with solar heating, hydrogen heat pumps and hydrogen fuel cells into our analysis of alternative heating technologies.

Figure 14 illustrates the range of overall efficiencies of these heating technologies for cold days and with intermediate storage. Such cold periods are relevant for the design and dimensioning of generation, transport and storage infrastructure, because the system must be able **to provide security of supply even in extreme situations with peak heating demand**.[43]

In this design-relevant use case, **hydrogen-based heating technologies** are **equivalent to electric heat pumps in terms of overall efficiency,** especially in buildings that have not been thoroughly renovated. Hydrogen condensing boilers (60%), hydrogen condensing boilers in combination with solar heating (64%) and hydrogen heat pumps (61%) operate at similar or slightly better overall efficiencies as electric air source heat pumps (61%). Regarding hydrogen fuel cells, we explicitly note the additional benefits of decentralised on-site power cogeneration, which could potentially supply local heat pumps with electricity and thus lower the stress put on electricity grids in high-demand situations .

Figure 14 In design-relevant use cases, hydrogen-based heating technologies are at least as efficient as electric heat pumps



Source: Frontier Economics

Note: Assumptions on efficiency losses along the process chain are the same as in Figure 11 and Figure 13. For assumptions on coefficients of performance and end appliance efficiencies see Figure 10. The overall efficiency of fuel cells are calculated as the combined efficiency of heat and power cogeneration.

[43] Use cases relevant for the design of the energy system are also crucial because in a future system based on 100% renewable energies, costs and greenhouse gas emissions will almost exclusively incur from the provision of generation and transport infrastructure, while electricity generation itself - unlike in a system based on fossil fuels - will only have negligible costs and emissions.

4 **CAPACITY ANALYSIS** - FUTURE POWER DEMAND IN THE ELECTRICITY MARKET INCREASES SHARPLY UNDER DEEP ELECTRIFICATION OF THE HEATING MARKET

In the previous chapter, we have shown that the overall efficiencies of technologies along the entire process chain of heating depend on different external factors such as climatic conditions and the renovation status of buildings. In the context of the heating market, the performance of heating technologies in extreme situations on cold winter days are particularly important because the results have a direct impact on the design and dimensioning of energy infrastructure (including generation, transport, distribution and storage).

Based on these findings, we analyse how the transition from fossil fuels to electricity in the heating market could affect future electricity peak load.

THE RESULTS AT A GLANCE

Heating demand in Germany is characterised by considerable seasonal fluctuations. Today, about 70% of heating demand is directly supplied by fossil fuels, natural gas and heating oil. When electricity generated by natural gas, coal and oil and used for heating and district heating is taken into account, the share of fossil fuels in heating is around 80%. Gas and oil infrastructures have been designed to reliably meet seasonal heating demand, even in extreme winter.

An analysis of daily gas flow data from gas transmission networks shows that the thermal capacity provided by the current gas system is significant, with a maximum load of 230 GW for the temperature-dependent heating market. In addition, the oil system currently provides approximately 100 GW of additional capacity for the temperature-dependent heating market.

Completely switching from fossil fuels to electric heat pumps would hypothetically lead to 86 GW to 124 GW of additional electricity peak load (see section 4.2). The current electricity peak load (of about 80 GW) could therefore more than double due to deep electrification of the heating market alone.

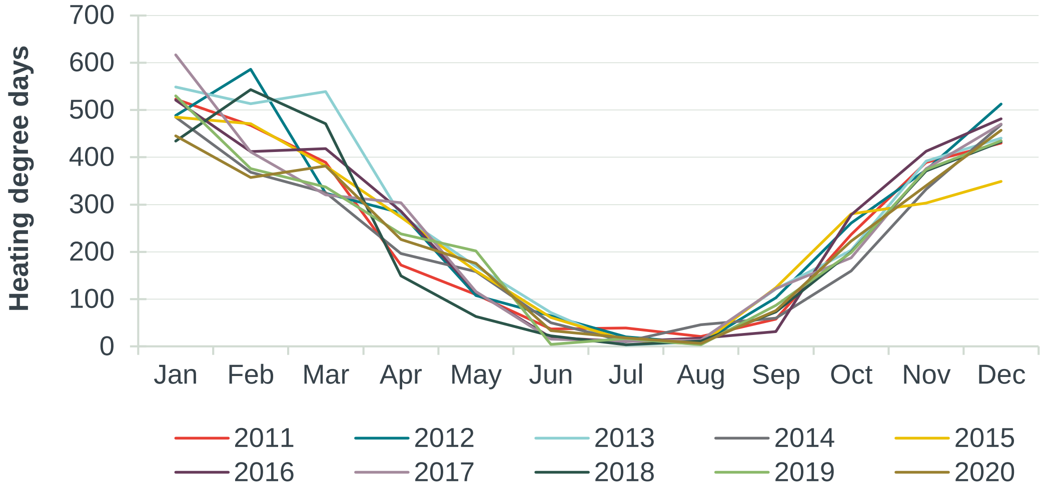
Even if such an extreme scenario is unlikely to come to fruition since realistically other technologies will and should also be used, it nevertheless illustrates that the transition from fossil fuels to electric heating technologies heating market will have a significant impact on the amount of required firm capacity in the future power system.

The phase-out of nuclear energy and coal-fired power generation, in conjunction with additional electricity demand from electromobility, exacerbates the risk of gaps in firm power generation capacity and in the expansion of electricity network capacity.

4.1 **Seasonal heating demand** - The demand for heat in Germany is characterised by considerable seasonality and is currently mostly operated by gas- and oil-based heating systems

The climatic conditions in Germany lead to highly seasonal demand in the heating market. In winter months, when outdoor temperatures are regularly low, there is high demand for heating. Demand levels off as temperatures rise in spring and it reaches its low point in summer (see Figure 15). Temperature-dependent heat demand is particularly pronounced in the area of space and water heating and in small parts in process heating in industry.

Figure 15 High seasonality of heating demand in Germany, illustrated by the number of heating degree days in 2011 - 2020



Source: Frontier Economics based on Eurostat

Note: Heating degree days are a measure of how much (in degrees) and for how long (in days) outside air temperature was lower than a specific base temperature. It is a measure designed to quantify the demand for energy needed to heat a building. The assumption is that buildings are only heated when the average outdoor temperature of a day is 15 °C or lower.

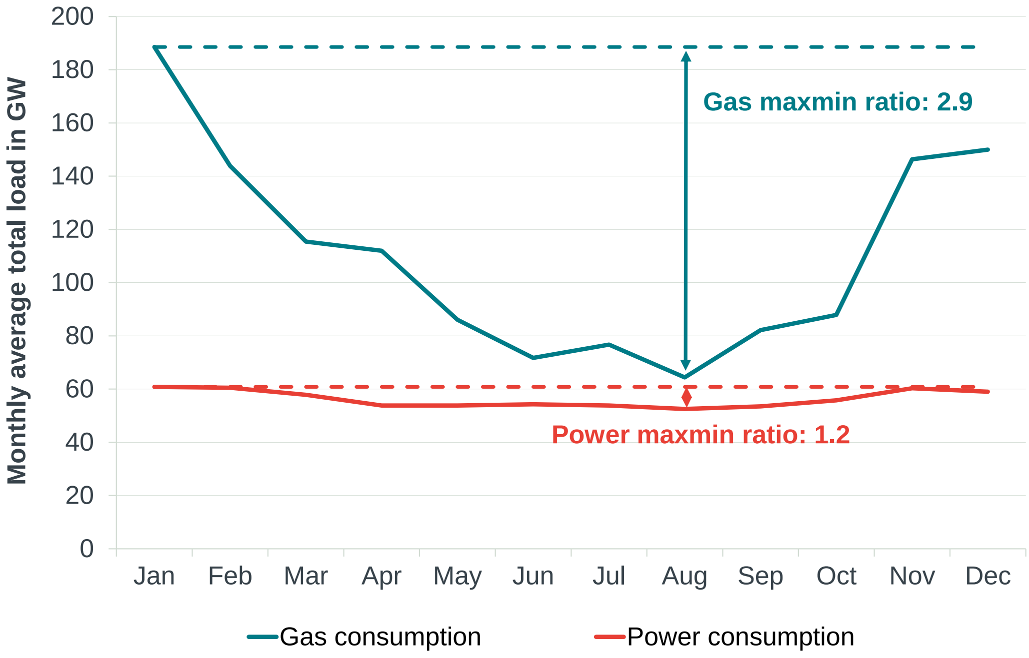
Fossil fuels are mainly used to meet today's demand for space and water heating; total heating capacities are substantial

As explained in section 2.1, natural gas and heating oil are the most used energy sources in the heating market. Their direct share in space and water heating is currently about 70% combined, with natural gas accounting for 47% and oil accounting for 23%. Because district heating has a share of 8% in heating demand

and about half of total district heat supply is generated by natural gas, indirectly gas as a primary energy source accounts for further 4%. In contrast, only 5% of heating demand is currently supplied by electricity, (cf. Figure 4).

Illustrations of real data on monthly energy consumption show the significant seasonal differences in gas consumption during a year, as shown in Figure 16 which is based on an average cold year (2017).

Figure 16 Actual monthly energy consumption curves show high seasonality of gas consumption relative to power consumption, in an average cold year (2017)



Source: Frontier Economics based on IEA Statistics and ENTSO-E Transparency Platform

Note: The maxmin ratio is defined as the ratio of the absolute monthly maximum to the monthly minimum, each calculated separately for gas and electricity consumption.

Gas infrastructure - like oil infrastructure - is designed to deal with seasonal heat demand and extreme winters

In order to reliably meet demand for heating, generation, storage and network infrastructure must not only be designed to produce and transport sufficient amounts of energy during regular seasonal fluctuations, but also in nearly all conceivable extreme situations, i.e. in exceptionally cold winter periods ("extreme winters"). Gas infrastructure in Germany has always been designed according to the "1 in 20 winter" concept, i.e. a winter as cold as can be expected only once every 20 years.[44]

We calculate today’s total heating capacities of natural gas-based heating systems using real gas flow data from gas transmission networks.

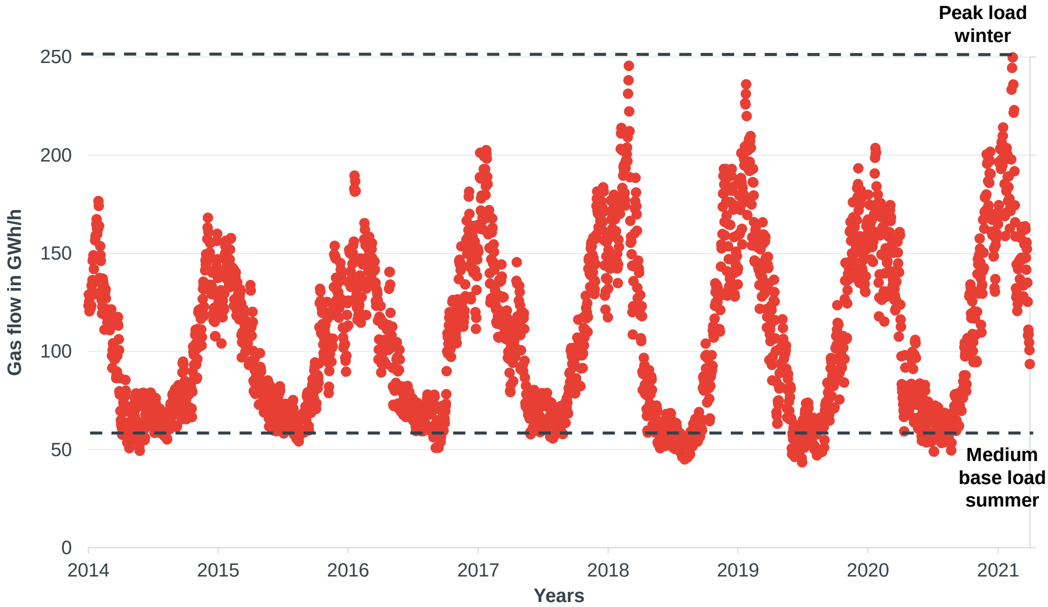
[44] Cf. ENTSO-G (2017), p.8.

The actual capacity of the gas system measured on a daily basis amounts to 250 GW and shows it is designed for high fluctuations in demand

The actual capacity of the gas system in Germany today can be calculated by using daily domestic natural gas flow data at transmission grid level, illustrated in Figure 17. The data points show measurements of average daily loads taken at network exit points to industrial and power plant customers and at transfer points to downstream distribution networks. Any gas transports to European neighbours (transit volumes) are not included.

These daily load data points show that the real maximum capacity of the gas system on cold winter days with high heating demand is much higher (at around 250 GW) than the maximum monthly averages presented in regular statistics (e.g. around 190 GW in 2017, see Figure 16). The maximum load data point of 250 GW, measured in the analysed period from January 2014 to March 2021, was taken on 12 February 2021. On this day, the nationwide average outdoor temperature was minus 7.1 degrees Celsius, which is more than 3 degrees below the 30-year average temperature for the month of February.

Figure 17 Daily domestic gas flow data (without transit volumes) at transmission grid level (1 January 2014 - 31 March 2021)



Source: Frontier Economics based on gas flow data provided by FNB Gas.

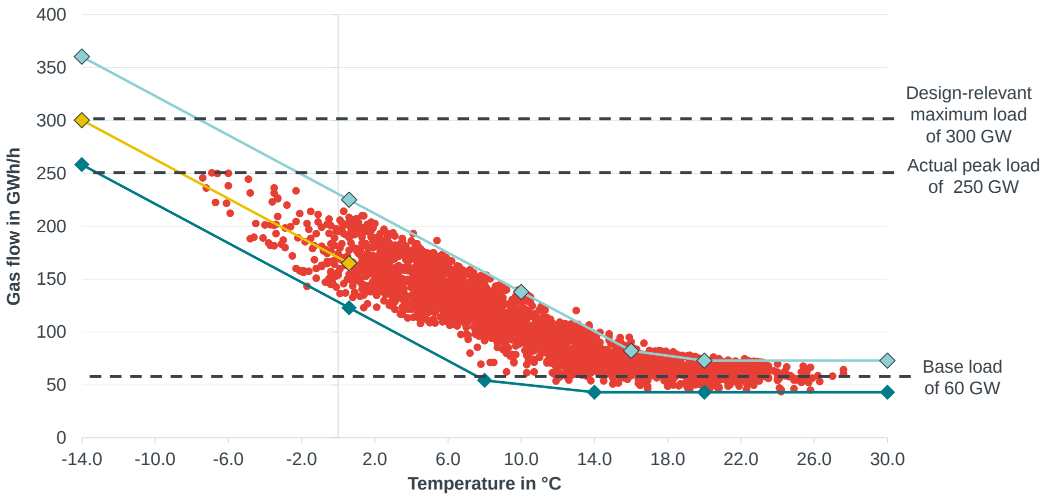
Note: The gas flows in this illustration are based on gas flows measured by gas TSOs on each day (without transit volumes) divided by the number of hours per day (24). Therefore, peak load is defined as daily average peak load. In individual hours or quarter hours, load can be significantly higher than the daily average, since gas load for heating at night, for example, is significantly lower than during daytime.

The maximum load relevant for the design and dimensioning of gas infrastructure is around 300 GW, which corresponds to a thermal capacity of over 230 GW for the temperature-dependent heating market

The basis for the design and dimensioning of gas infrastructure is an extreme case ("1 in 20 winter" concept), which is based on significantly lower volume-weighted temperatures (of -14 °C) than the minimum volume-weighted temperatures (of -7.1 °C) observed in our analysed seven-year period.[45]

Figure 18 shows daily gas flows in relation to observed outdoor temperatures. It illustrates the high temperature-dependency of gas flows.

Figure 18 Daily gas flows at transmission grid level in relation to observed outdoor temperatures (period from January 2014 to March 2021)



Source: Frontier Economics based on gas flow data provided by FNB Gas.

Note: Four-day averages are used as the basis for the analysis, as these show the highest correlation between performance data and temperatures due to the inertia of heated buildings.

To determine the capacity required in the extreme case, linear regression was carried out in accordance with “Kooperationsvereinbarung Gas” (gas cooperation agreement).[46] A volume-weighted design temperature of -14 degrees Celsius results in a design-relevant maximum load of 300 GW. A load significantly higher than the peak load of 250 GW actually measured in February 2021.

The maximum capacity that today's gas infrastructure provides for the heating market is then calculated on the basis of the **design-relevant maximum load of 300 GW minus:**

- **base load** not induced by the heating market. This base load can be quantified in spring and summer, when outdoor temperatures of 15 degrees Celsius or higher are observed (Figure 17 and Figure 18). This largely temperature-independent base load amounts to about **60 GW** and includes in particular gas demand for process heating in the industry sector, gas demand for water heating and gas demand (not used for heating purposes) of power plants.

[45] The design temperature relevant for planning varies nationwide depending on local meteorological conditions. For this analysis, an average nationwide design temperature is used, that reflects a volume-weighted average of the different regional design temperatures.

[46] The linear regression is based on actual load data of the 120 coldest days of a year, which is then extrapolated to the relevant design temperature. Cf. Kooperationsvereinbarung Gas (2020), p. 37.

- the seasonal portion of **gas-fired power plant capacity** amounting to about **4 GW**;[47] and
- efficiency losses in end appliances (assuming an efficiency of gas heating systems of 98%).

As a result, the capacity provided by the gas system for the heating market amounts to just under **230 GW**.

230 GW

is the capacity that gas infrastructure currently provides for the heating market.

Oil-based heating systems back up the heating market through almost 100 GW of additional capacity

Heating oil also plays an important role in the total capacity of the fossil heating market, as it currently is the second largest fossil fuel to supply energy for temperature-dependent heating. The share of heating oil in final energy demand for space and water heating was just under half the share of natural gas-based heating demand in 2018. The characteristics of heating demand for oil- and gas-based heating technologies can be assumed to be almost identical.

On this basis, the capacity of oil-based heating systems on the heating market can be determined in a simplified way:

- Final energy consumption for space and water heating supplied by heating oil amounts to 46% of the final energy consumption for space and water heating supplied directly by natural gas.[48]
- The average end appliance efficiency of oil heating systems is just under 90% (compared to 98% for gas heating systems);

As a result, oil-based heating systems - assuming infrastructure design similar to that of the gas system for a "1 in 20 winter" (with a volume-weighted design temperature of -14 °C, based on the gas system) – provide ca. 100 GW of additional capacity to the temperature-dependent heating market.[49]

[47] Gas consumption for electricity generation of power plants includes a relatively small seasonal component, which we exclude from our analysis. This is based on the assumption that current temperature-dependent gas demand by gas power plants does not need to be replaced by electric heat pumps. In 2017-2020, the difference in demand of gas power plants between winter peaks and summer peaks was around 4 GW. Cf. Fraunhofer ISE Energy Charts, www.energy-charts.info

[48] Cf. BDEW (2020a), slide 24.

[49] The result is calculated as 236 GW (design-relevant capacity of the gas system for the heating market before efficiency losses are taken into account) multiplied by 46% and multiplied by 90%.

4.2 **Future electricity peak load**: Deep electrification of the heating market leads to high additional peak loads in the power system

The current electricity system is not designed to meet substantial seasonal heating demand

Today just under 5% of final energy demand for space and water heating is supplied directly by electricity (see also Figure 4). Therefore, the electricity system has not been designed to meet substantial heating demand with enormous consumption peaks in cold winters. This is reflected, for example, by a largely flat electricity demand profile over the course of the year. As illustrated in Figure 16, in an average cold year such as 2017, the maximum monthly electricity demand in winter was only 1.2 times the minimum monthly demand in summer (if measured on a daily basis, the maxmin ratio is 1.7), while this ratio was 2.9 for gas consumption (a ratio of 3.6 on a daily basis).

Deep electrification of the heating market would increase electricity peak load by 103 GW to 124 GW in scenarios with realistic renovation rates, and by 86 GW with a very optimistic renovation rate

To achieve climate neutrality by 2045, fossil fuels must be completely replaced by climate-neutral alternatives over time. According to EU Commission guidelines, 49% of generated heat should be renewable by 2030.[50] If current technologies based on fossil fuels were to be fully substituted by electric heat pumps, this would have a significant effect on required capacities in the electricity system. This is because the seasonal fluctuations that are currently covered by heating systems based on natural gas and heating oil would need to be entirely supplied by the electricity system.

Figure 19 demonstrates the additional demand on top of electricity peak load that would arise in 2045 (when the heating market must be completely climate neutral) if fossil fuels were to completely be replaced by electric heat pumps. The actual level of new peak load would depend on several factors:

- **Alternative climate-neutral heating systems**
  - Capacity that is currently provided by fossil fuels could in the future be replaced by alternative, non-electricity-based, climate-neutral technologies. This may occur because the use of electric heat pumps in unrenovated or only partially renovated old buildings does not seem appropriate from a technical and economic point of view. In our simplified analysis, we assume that fossil fuels will completely be replaced by electric heat pumps. We do not take into consideration the potential use of alternative heating systems such as hydrogen condensing boilers or district heating; if this was taken into account, the level of additional electricity peak load would be lower.
  - We assume that in the majority of existing buildings where the heating system has to be replaced, heat pumps with air-source-technology will be

[50] European Commission (2021).

installed, especially in urban areas. The more efficient ground source heat pumps are viable options only for new constructions. And even there, the use of ground source heat pumps is restricted. In our analysis, we therefore make the assumption that air source heat pumps will be installed in 90% of existing old buildings and ground source heat pumps in 10%.[51]

- **Future progress in building renovations** - The future electricity peak load of the heating market will primarily be determined by future renovation rates. Energy-oriented renovations of buildings have two key effects on future peak load:
  - **Electric heat pumps** can achieve **higher coefficients of performance in fully renovated buildings and in new construction** rather than in unrenovated old buildings. The better the energy performance of the future building stock, the higher the achievable coefficients of performance of electric heat pumps and the lower the effect of additional peak load in the electricity system.[52] We take a conservative approach and do not take the effects of the use of heating rods into account. We assume that heating can be shifted within a day, and therefore electric heating systems could be circuited in such a way that simultaneous use of heating rods is minimised.[53] However, if heating rods are used, they typically have twice the input capacity of actual heat pump compressors, thereby doubling the individual effect on peak load.
  - **Energy-saving renovations in buildings reduce heating demand and** reduce peak **load from heating**. The higher the energy performance of buildings, the lower heating demand and load.[54] We start our impact assessment on future heating demand (and load) of energy-saving renovations in buildings by calculating living space-weighted heating demand in existing building stock in Germany for each building age class. After energy-saving renovation measures have taken place, heating demand (or load) is reduced as follows:[55]
    - by 25% compared to prior demand in the case of partial renovation of the building;[56]

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51 In addition, we assume similar coefficients of performance compared to today. We refrain from assuming technological progress (which in the case of the relatively mature electric heat pump technology can be expected to be moderate at best anyway).

52 This means a coefficient of performance of 240% for air source heat pumps (390% for ground source heat pumps) for the design temperature of -15 °C at flow temperatures of 35 °C assumed for new constructions, and a coefficient of performance of 120% for air source heat pumps (or 260% for ground source heat pumps) for old buildings at assumed flow temperatures of 65 °C.

53 In fact, electric heat pumps may only be disconnected from the grid for a maximum of 6 hours, the "Sperrzeit" (blocking period). Cf. https://www.bosch-thermotechnology.com/de/de/wohngebaeude/wissen/heizungsratgeber/waermepumpe/evu-sperre/.

54 Heating demand and heating load are defined for the various energy standards of buildings in the Wärmeschutzverordnungen (thermal insulation regulations), Energieeinsparverordnungen (energy savings regulations) and in various KfW "Efficiency House" standards. The heating load corresponds to the heat loss through the building envelope. The higher the heating load, the more heat must be generated by the heating system and the heating consumption increases accordingly. Cf. https://www.net4energy.com/de-de/smart-living/heizlast-niedrigenergiehaus.

55 Based on IWU (2015) and IWU (2018).

56 Based on German Environment Agency (2019) and https://www.co2online.de/.

- to the energy performance standard of a new construction (currently classified as “KfW 55 Effizienzhaus”) by a full renovation of the building.[57]

Since future annual average renovation rates are subject to a high degree of uncertainty, we consider various scenarios:

- **Moderate renovation rate** - In 2020, only 13% of buildings in Germany were considered to be newly constructed or fully renovated. The annual renovation rate of around 1% over the last 20 years has fallen significantly short of the German government's target of 2%.[58] In scenario A, we calculate the quantitative implications on electricity load of deep electrification in the heating market by assuming that the renovation rate remains at the **historical level of 1.0%** per year.
- **More ambitious renovation rates** - In scenarios B, C and D, we assume that German’s annual renovation rate can be significantly increased in the short term. Based on several external studies, we use more ambitious annual renovation rates from **1.4%** (Dena study, Scenario TM95) **to 2.3%** (Dena study, scenario EL95).[59]

86 to 124 GW

is the additional electricity peak load under deep electrification of the heating market by heat pumps. **Electricity peak load (of 80 GW today) would at least double.**

The result shows that a (hypothetical) **complete transition from fossil heating technologies (which today have a capacity of about 330 GW_{th})**[60] **to electric heat pumps would lead to considerable additional electricity peak load.** In scenarios with realistic renovation rates (below 2.0%), additional electricity peak load would amount to 103 GW_{el} - 124 GW_{el}. In a scenario with a very optimistic renovation rate (of 2.3% per year), additional electricity peak load would still be 86 GW_{el}.[61]

Future electricity peak load would exceed record electricity peak load by a factor of about 2 to 2.5. This means that the **heating market alone** - without taking into account electrification in other sectors - would produce at least a **doubling of the peak load of the current power system** in the future.

57 Achieving the KfW 55 standard ("lowest energy house") will be mandatory for new constructions in Germany from 2021.

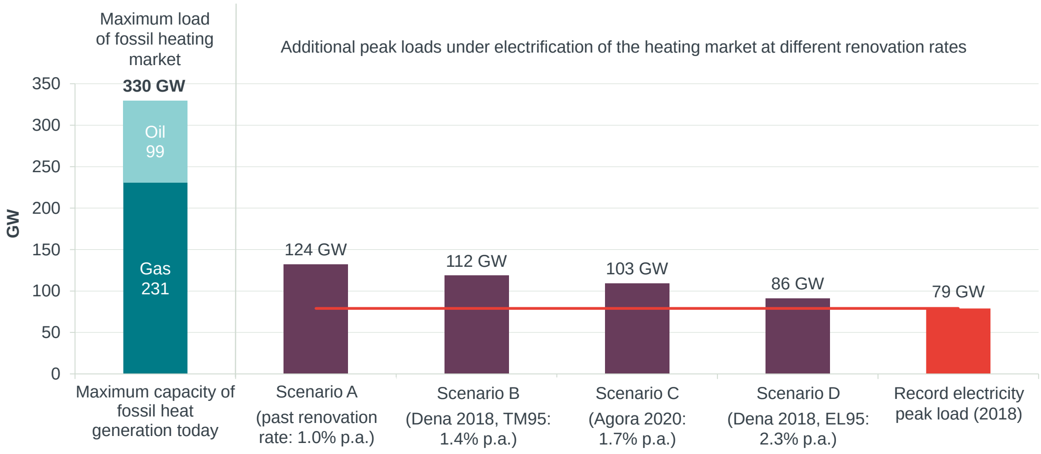
58 See BDEW (2020a), German Environment Agency (2019) and DIW (2019). For a summary, see Frontier Economics (2021a).

59 In light of the mentioned obstacles to increasing the historically low renovation rate, this is a very ambitious assumption. More realistically, a slow increase in the renovation rate would have to be expected, which would reduce the rate of renovation assumed here.

60 This number is based on 230 GW of design-relevant capacity of the gas system for the heating market and 100 GW capacity of the heating oil system.

61 For comparison: A bottom-up analyses carried out by Frontier Economics on behalf of Viessmann had shown an additional peak load from heat pumps of up to 127 GW in 2050. This result is based on the assumption of additional installations of 15.7 million electric heat pumps by 2050 (following the EL95 electrification scenario of the Dena study, see Dena (2018)). A lower number resulted with 3 kW peak load demand per unit and 80% simultaneous use of heat pumps. A higher result was achieved with 9 kW demand per unit (e.g. due to the use of the heating rod) and 100% simultaneous use. See Frontier Economics (2021a).

Figure 19 Deep electrification of the heating market leads to high additional electricity peak load even with optimistic renovation rates



Source: Frontier Economics based on FNB Gas and Hirvonen and Siren (2017) and renovation rates from the studies indicated.

Note: The maximum load provided today by natural gas and heating oil is based on the measurement of daily average values. It can be assumed that the maximum values in individual hours or even quarter hours are significantly above these daily averages, as the heating load at night, for example, is significantly lower than during the day. When calculating the increase in electricity peak load when switching to electric heat pumps, it is assumed that the electric heating systems are flexible enough so that electricity demand for heating purposes can be shifted within a day (i.e. heat can be produced at night to be used during the day, for example, through heating storage appliances). This is a conservative assumption. In practice, a lower flexibility of electric heat pumps can be assumed, so that there would actually be a higher increase in the electricity peak load. For assumptions on coefficients of performance in order to calculate the equivalent heat pump capacity, see Figure 10.

4.3 **Future power system**: In order to reliably meet the peak load of an electrified heating market, renewable power generation and infrastructure capacities must be massively expanded

In addition to the electrification of the heating market, other factors also have an impact on future capacity requirements in the electricity system

Capacity requirements in the electricity system in the future are determined by an increasing level of electrification of end appliances in all sectors. Apart from heating, transport is the sector that will likely be most affected by electrification: the additional demand for firm power generation capacities from the transport sector could amount to 22 GW or above in the long term, depending on the actual numbers of additional e-vehicles, vehicle performances and charging profiles. [62]

[62] Based on Dena (2018), 11 kW of power capacity per e-vehicle are estimated on the basis of approx. 40 million additional vehicles in 2050 and a rate of simultaneous charging of approx. 5%. Cf. Frontier Economics (2021a).

On the other hand, gains in energy efficiency in areas of traditionally high electricity consumption (e.g. lighting or stationary motors) can have a decreasing effect on future power demand and would partly compensate for the increase in peak load due to the electrification of heating and transport.

An increasing need for capacity from the electrified heating market is made even worse by a sharp decline in firm power generation capacity due to phase-out of nuclear and coal

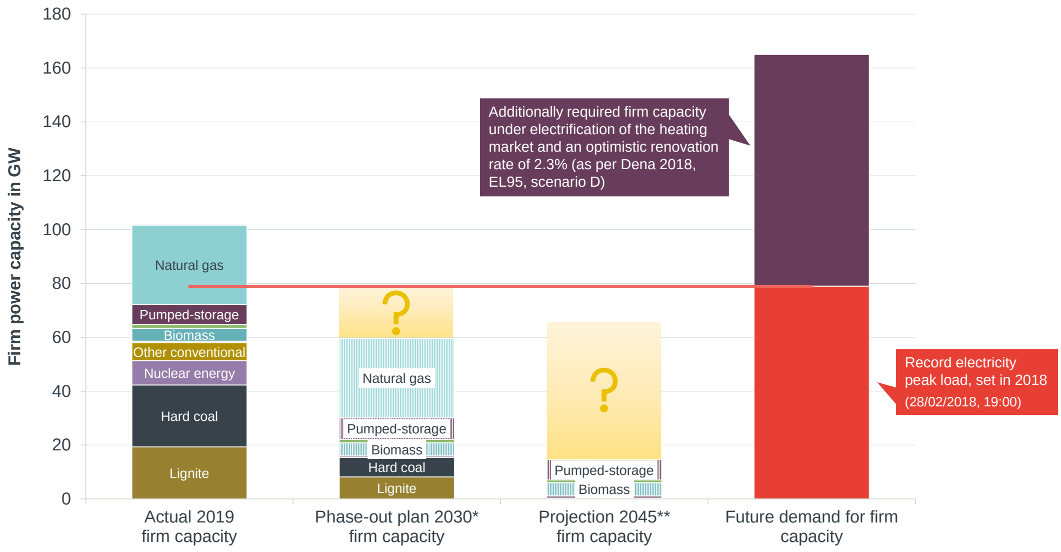
Currently, Germany still has large firm electricity generation capacities from nuclear energy, lignite, hard coal and natural gas to provide sufficient amounts of energy in times of highest demand. With existing firm capacities, security of supply in the electricity market is currently ensured (Figure 20, left-hand side).[63]

However, due to the phase-out of nuclear energy and coal-fired power generation, a sharp decline in firm power generation capacities in Germany is expected in the coming years. According to the German government's plans, the phase-out of nuclear energy by the end of 2022 and the agreed-upon coal phase-out path will result in 36 GW of firm capacity being taken off the grid by 2030. This represents about one third of current firm capacity. On the other hand, it is unclear how much firm capacity beyond the contribution of coal-fired power plants can be provided by other forms of electricity generation in the future (Figure 20, centre). The implications of declining firm power generation capacities become even clearer in 2050 (Figure 20, right-hand side). Due to Germany's complete phase-out of all fossil and nuclear power generation, the firm capacity in 2050 would have to be completely provided by renewable energy generation .

However, even a massive expansion of wind power and photovoltaics would not automatically result in an increase of firm capacities due to the intermittency of these renewable energies. Therefore, reliable and controllable back-up power plant capacities must be installed on a scale that ensures security of supply even in times of cold dark lulls. The expansion of flexible gas-fired power plants (based on climate-neutral gases) that would provide back-up capacity is subject to high uncertainty, which may lead to insufficient investment incentives for the construction of new capacities.

[63] The firm capacity used to assess the security of electricity supply is defined as the generation capacity that is permanently available with a high degree of certainty. The four electricity transmission system operators (TSOs) in Germany evaluate the installed electricity generation capacities as part of the annual report of a power balance. Each generation technology is assessed with a probability of availability at the time of a potentially critical reference day that sees particularly high electricity consumption (typically an evening hour in a winter month). These probabilities are calculated by the German transmission system operators on the basis of historical feed-in profiles. For renewable energies, on the other hand, the availability rates are 1% (wind onshore/offshore) and 0% (PV) (cf. Transmission System Operators (2020)). The unavailability rates of conventional fuels are analysed on the basis of the outage probability used in the Ten-year network development plan of 2018 (ENTSO-E & ENTSO-G (2018)) (in sheet DE as "Normal conditions Average Forced Outage Rate"): For conventional power plants, availability rates of 91% (lignite and hard coal), 93% (natural gas) and 95% (nuclear energy) were calculated. For mixed fuels, an average rate was estimated (8%).

Figure 20 The long-term trend of firm power generation capacities is very uncertain - but an electrified heating market creates high additional demand



Source: *Frontier Economics based on Bundesnetzagentur (2021a), Übertragungsnetzbetreiber (2020) and BMU (2020).*

Note: ** We assume that the firm capacity of coal-fired power plants decreases over time according to the phase-out path established by the German federal government and that the firm capacity of other energy sources remains constant. ** In 2045, firm capacities must be provided entirely by climate-neutral energy sources. *** Future demand for firm power generation capacity is determined by additional load due to electrification of the seasonal heating market and by constant peak load from other sectors.*

Due to the slow pace of expansion of renewable energies and electricity networks, there is a risk of gaps in electricity supply in the medium term up to 2030

There is a real risk that the pace of expansion of renewable energy generation, transport and distribution networks, storage facilities and firm power plant capacities will be too slow to close the expected supply gap created by declining conventional power plant capacities.

In their latest grid development plan, the electricity transmission system operators announced substantial delays of several years in the expansion of extra-high voltage grid. Particularly affected are the important north-south routes for transporting wind power from the north to the consumption centres in the south and in the south-eastern power corridors (SuedLink and SuedOstLink).[64] The delays in the expansion of the power lines – in addition to other issues such as land availability and social acceptance – may negatively impact the ability to achieve expansion targets for renewables as well as Germany's ambitious climate targets.

[64] Tagesspiegel (2021).

Consequently, high additional costs are to be expected due to the additional expansion of electricity grids and the renewable generation capacities required because of deep electrification. Further costs arise from those capacities that must be installed to back up intermittent renewable generation and provide security of supply in the future electricity market (potentially at least an additional 86 GW of capacity for the heating market). The additional costs could be reduced by a broader technology-open approach in the energy system that includes different energy sources, infrastructures and end appliances.[65]

A high degree of electrification of the heating market would further exacerbate the existing challenges of the electricity system

From today's perspective, it is unclear how firm electricity capacities can be provided in a future electricity system that is based on solely on renewable energies. A significant expansion of flexible generation capacities will be unavoidably necessary. However, investment incentives are currently lacking.

Converting large parts of today's heating market from gas- and oil-based heating systems to electric heat pumps would further exacerbate the problem of providing sufficient quantities of electricity and required firm capacities. Alternative options are available in the heating market. The potential for switching to climate-neutral gases such as hydrogen should be taken into consideration, as they can be transported and stored on the basis of existing infrastructure and used in existing and future heating end appliances (as a blend in the gas mix or as a pure product). The use of gas-based climate-neutral alternatives is necessary due to the implications for future peak load in the electricity system, the short timeframe for the transition and the ambitious climate targets.

[65] Dena (2018).

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