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Decarbonizing Germany’s heating sector

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Executive summary

Decarbonizing heating in Germany's residential and commercial sectors, which accounts for 37.4 per cent of final energy consumption (2021), is crucial if the country is to achieve net zero by 2045. Of around 19 million buildings, 5 million are in the countryside or suburbs heated by oil without alternative options (connected to a network) and almost 10 million are in urban areas heated by gas. Decarbonizing the heating of these buildings is therefore imperative. Space heating and warm water are low temperature heat which can be provided by heat pumps (HP) and by waste heat via district heating (DH) (Chapter 1). One of the main challenges comes from the fact that heat demand strongly depends on ambient temperature resulting both in steep capacity peaks and in substantial seasonal variations.

There are three major approaches for zero CO_2 emissions at the point of heating (Chapter 2.1): HPs, DH and switching gas supply from methane to hydrogen. The questions then are (i) how to provide CO_2-free energy needed as input; and (ii) what mix to apply to 15 million buildings that currently use oil and gas (Chapter 2.2):

(i) Heat pumps function with electricity and therefore require CO_2-free power generation which can come from renewables only with direct or indirect (hydrogen) power storage; or from renewables combined with thermal power with carbon capture and storage (CCS). DH offers a multitude of feed-in options: geothermal, large heat pumps, use of waste heat and combined heat and power (CHP) with CCS. When looking at the hydrogen option, switching from large volumes of methane to green hydrogen will not be possible within the timeframe and therefore blue hydrogen from autothermal reformers (ATRs) will dominate.

(ii) Switching 15 million buildings to heat pumps based exclusively on renewable power will not work by 2045, due to the low roll out speed of renewables and heat pumps, lack of storage solutions and lack of capacity in the power system. Equally, an HP-only system but with thermal power with CCS avoiding problems from renewable-only energy supply, would also have problems with the limited roll out of HPs and limits of local power grid capacity, while at the same time, squandering possibilities of DH and of using the existing gas distribution grid. An about equal split between HPs, DH and the methane-to-hydrogen switch (5 million buildings each) would, by contrast, be a robust approach to realistically meet net zero heating by 2045.

In order not to run into technology development or roll out constraints, early actions oriented towards net zero in 2045 should be taken in a manner that is open to different technologies (Chapter 3). Early work on CO_2 collection and further development of CO_2 capture in power plants, as well as early decisions at municipal level on which areas to opt for HPs, DH and methane to hydrogen switching and on early expansion of the DH pipeline system with CO_2-neutral feed-ins are needed. Using existing investment not only saves money but reduces risks as well.

In view of the obligations imposed on the German population by CO_2-neutral heating by 2045, there is a low-risk market for CO_2-free technology and infrastructure. Supporting early investment is therefore a financing issue, which should benefit from Germany's high sovereign credit rating.

While the Climate Protection Act (CPA), as amended in 2021, is technology neutral and defines the 2045 net zero target, recently-enacted laws (the German government's Building Energy Act (GEG)) to implement the CPA are flawed by favouring renewables and HP for paradigmatic reasons, instead of an open technology approach that includes CCS (Chapter 4).

Conclusion: With the CPA Germany has stringent legislation to meet net zero by 2045, but its implementation focusses narrowly on renewables and HPs to the detriment of a balanced approach, including the use of CCS as another major avenue to decarbonization. The discussion must be widened to accept a hybrid solution, instead of betting exclusively on special solutions which foreseeably will not meet net zero by 2045.

1. The challenge of decarbonizing Germany's heating sector by 2045

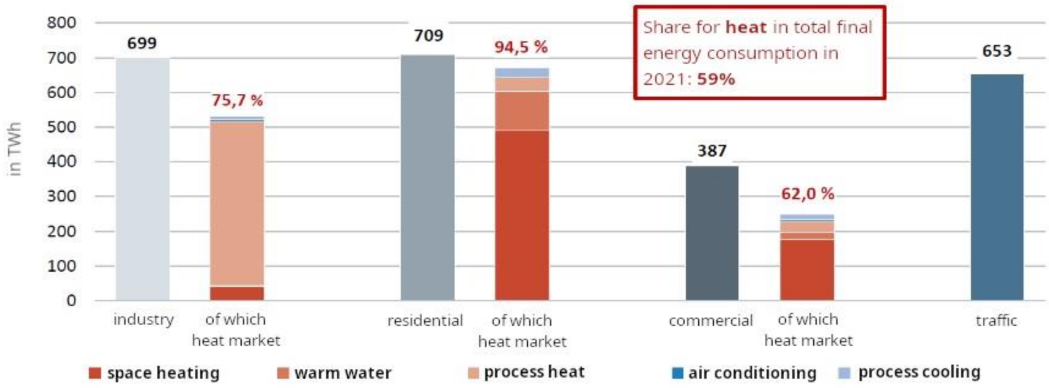
Germany's ambitious decarbonization policy, stipulated in the Climate Protection Act (CPA) of 12.12.2019, as amended on 18.08.2021,[1] stipulates that the country must achieve net zero greenhouse gas (GHG) emissions by 2045, in total and in each economic subsector (industry, residential, commercial, transportation, agriculture and land use, land-use change and forestry (LULUCF)).

The limited options for removing CO_2 already emitted into the atmosphere in order to achieve net zero GHG emissions by 2045[2] means that this commitment requires that CO_2 cannot be emitted at the point of final energy consumption. In turn, this means that fossil fuels cannot be used as final energy except where CO_2 from their combustion is abated by CCS. As this is only feasible for large volume emissions, hydrocarbons (natural gas and liquid fuels) will not be able to be deployed in residential or commercial boilers or internal combustion engines. However, this paper demonstrates why natural gas as primary energy with abatement will still be required, mainly to close the gap left by insufficient volumes and reliability (at least in this timeframe) of wind and solar renewables.

1.1 The structure of Germany's heating demand

In 2021, heating dominated German final energy use accounting for 59 per cent (21.6 per cent industry and 37.4 per cent residential and commercial), with transportation a distant second place at 27 per cent. Heating also dominates energy use in the major economic sectors with industry at 75.7 per cent, residential 94.5 per cent and commercial 62.0 per cent, (Figure 1 below[3]). As such, decarbonizing the heating subsector will be critical to the success of Germany's overall target of achieving decarbonization and net zero by 2045.

Figure 1: What share did the heating market have in the final energy consumption of the individual sectors in 2021?*



Source: BDEW, AG Energiebilanzen, own calculations as of 12/2022

Note: * preliminary, adjusted for changes in stocks of heating oil

Heating in industry is predominantly process heating with temperatures varying from 100°C to 1500°C and higher. For temperatures below 500°C, the use of exhaust heat from captive power generation is widespread. Process heat at temperatures above 500°C is best delivered by burning methane or hydrogen, with the use of electricity for these high temperatures still in its infancy. There is little alternative to the use of fossil fuels for power generation and high temperature process heat available until 2045; the use of gas might even increase as it replaces coal and lignite.

[1] The CPA in its original version was amended following the ruling of the Constitutional Court of 29.04.2021, which declared part of the CPA as unconstitutional. Its argumentation was based on the tightly limited CO_2 budget to stay within 1.5°C following the IPCC report on 1.5°C. As Germany could not rely on more than its share in world population (ca. 1%), it must take early and binding actions to stay within its share of the CO_2 budget, in order not to put an unfair burden on younger generations

[2] CDR (carbon dioxide removal) or DAC (direct air capture) could be technological removal plus sequestration of CO_2 or lasting removal by biomass via photosynthesis. Neither will be achievable on a large scale by 2045

[3] BDEW (2022, March 16) chart 7

Decarbonizing final energy demand in industry should be possible by adding CCS to industrial process heat, by introducing CO_2-free electricity from fossil fuels with CCS, or by using renewables. So, the challenge for industrial heating is one of balancing incentives with competitiveness and the main impact on public energy infrastructure will be the need to establish a collection infrastructure for CO_2 resulting from capture processes for sequestration in Germany or abroad.

However, heating in the residential and commercial sectors differs substantially since it is deployed for space heating and hot water at temperatures below 100°C. This low temperature heating can be derived from heat pumps (HPs), solar thermal, geothermal or waste heat from all kinds of processes with demand moderated by improved insulation. However, heating demand in the residential and commercial sectors depends on ambient temperatures which implies seasonal variation in demand and high peaks at low ambient temperature. Low temperature solutions like heat pumps are gradually displacing heating oil and natural gas with their high energy density, which have dominated these sectors, while allowing the flexibility to cover seasonal variations in heating demand.

This paper focuses on the decarbonization of residential and commercial sectors, which is particularly challenging since homes and office/commercial buildings cannot be converted quickly (see Chapter 2 and 3).

1.2 Present and future structure of space heating in Germany

At present, natural gas and heating oil dominate the heating of buildings in Germany. Of approximately 19 million buildings in 2019, about 9.5 million were heated with natural gas and another 6 million with heating oil, together accounting for more than 80 per cent of all buildings. District heating is used in 1.5 million buildings and electric heating, either direct or by HPs, was installed in 1 million buildings in 2019.[4]

Gas and fuel oil have reliably supplied around 80 per cent of space heating plus process heat to industry for decades. But decarbonization means they have to be replaced by 2045 by CO_2-free energy at the point of use. For space heating, CO_2-free final energy can be a combination of HPs, district heating, switching gas from methane to hydrogen and other, more marginal solutions.

In terms of primary energy, electricity generated for the purposes of heating would need to be decarbonized. But since renewables will predictably not be sufficient to meet this challenge[5] and, in any case, because most additions will be in the form of wind and solar[6] which are not suitable for meeting seasonal variations in demand, the gap will have to be bridged by gas with CCS, available on demand from supply sources or storage.

2. Decarbonizing heating in buildings

Decarbonizing heating (space and water) in residential and commercial buildings requires that no CO_2 is emitted at the point of heating, as discussed in Chapter 2.1. In addition, the supply of primary energy must be CO_2-free at the point of heating, as addressed in Chapter 2.2. The resulting supply chains and their restrictions are illustrated in Chapter 2.3, while the impacts on gas demand and requirement for CCS volumes are shown in Chapter 2.4.

2.1 Final energy for space heating in buildings

German space heating is predominantly supplied by natural gas and heating oil.[7] For the time being, gas and oil provide seasonal space heating with gas storage of some 280 TWh th working gas and with 6 million

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[4] BDEW (2019, October) As circa half a million buildings built after 2019 conform with low energy and CO_2 emission standards, focussing on the situation in 2019 is a fair reflection of the structural changes needed

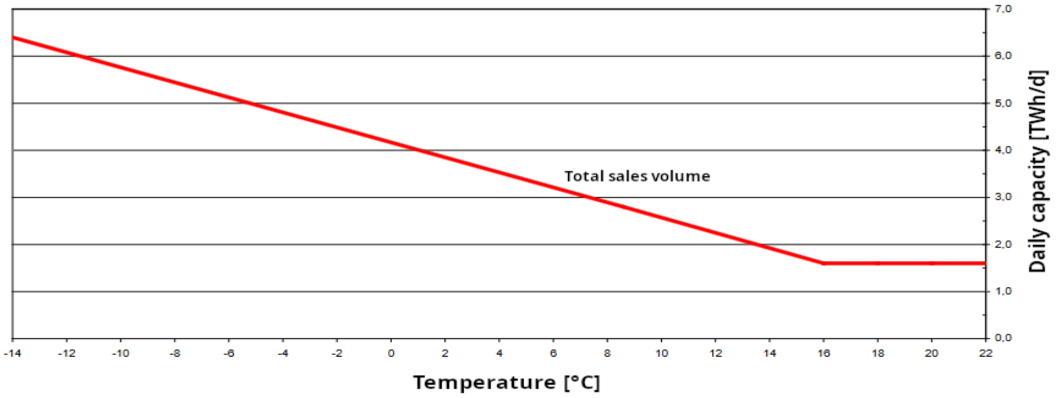
[5] OIES paper ET13 demonstrated that even with the very ambitious assumptions of the Coalition Agreement of the present government (in place since December 2021), the net zero target will be substantially missed, while the real roll out of renewable generation does not even meet 50% of the targets of the Coalition Agreement

[6] Germany's hydropower potential is very much limited, geographically, and already used. It is predominantly run of river power

[7] Source: BDEW (2019, October) reflecting the situation in 2019. Buildings finalised after 2019 were predominantly low energy low CO_2 emission buildings. Referring to the status in 2019 will not affect the order of magnitude of the principal considerations beyond the uncertainties included

individual tanks installed in oil-heated buildings. Due to their high energy density, oil and gas are well suited for storage. Demand for heating and therefore for gas is inversely correlated with ambient temperature (see Figure 2 below[8]).

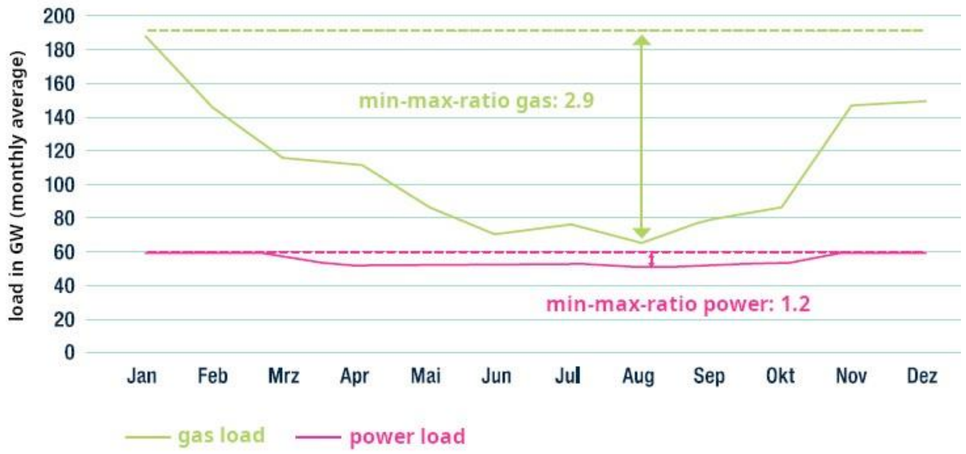
Figure 2: Regression line of gas sales vs. temperature



Source: Derived from Möller, A., Zander, W. 2002

While better insulation reduces the overall need for heating, it mainly reduces heating requirements during periods of mild temperatures, but it does not substantially lower peak heating demand during a sequence of cold days. Therefore, seasonality remains and becomes even more accentuated. In an all-electric heating system this variability in demand must be absorbed by the new, decarbonized power system beyond its existing load. (See Figure 3 as an illustration, which includes all final demand for gas[9]).

Figure 3: Seasonality of gas vs. power demand



Source: DVGW 2022

Decarbonizing the heating of current building stock boils down to different combinations of HPs, municipal district heating systems, both using low temperature heat from the environment, and for DH, also waste heat, geothermal and switching from methane to hydrogen. Converting biomass waste to biomethane can replace natural gas for local or regional gas grids, although it is subject to the limitations of LULUCF. The use of purpose-grown biomass is limited by the need to prioritize land for food production.

The following section discusses the options for net zero emissions at the point of heat consumption, while the potential for reliable primary energy supply to yield zero CO_2 energy is discussed in Chapter 2.2.

[8] Derived from Möller, A., Zander, W. (2002, November 18) p. 4
[9] DVGW 2022 p. 11

2.1.1 Heat pumps

Heat pumps operate on the same principle as a fridge except in reverse,[10] extracting heat from a low temperature environment.

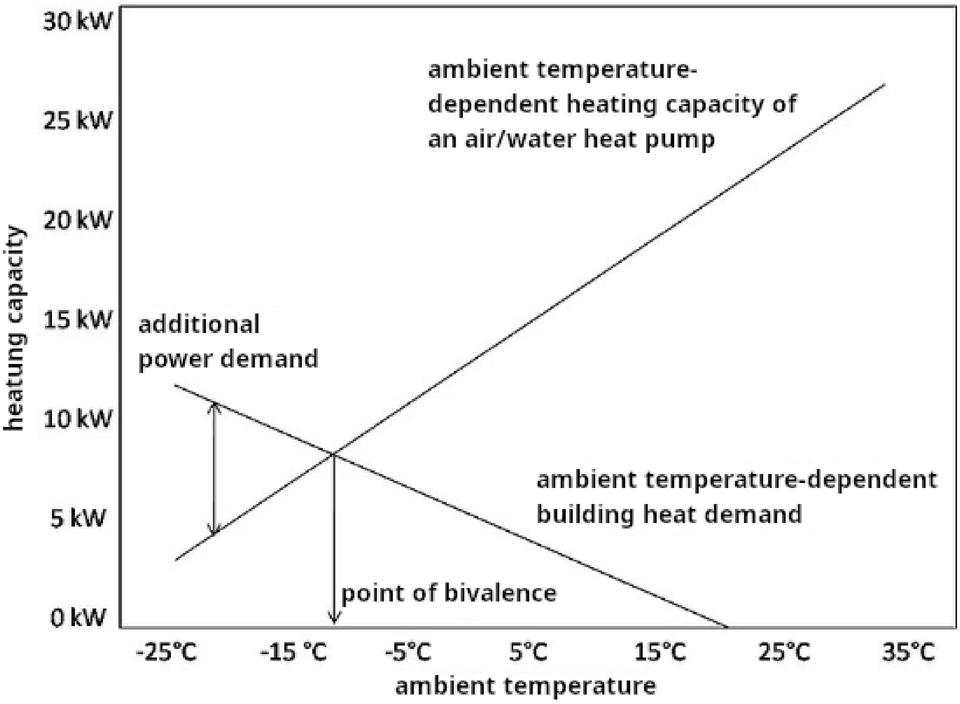
There are two types of HP, depending on the environment from which they absorb heat:

(i) HPs absorbing heat from an environment that is not dependent on ambient temperature (deep soil, drilling into deep water reservoirs, waste heat from wastewater) are water-to-water heat pumps. Their efficiency is unaffected by ambient temperature and typically they deliver 4 kWh th of heat for every 1kWh el of electricity used. The electricity capacity demand increases with heat demand in line with decreasing temperatures.

These heat pumps have limited applications in urban areas and require sufficient surface space for equipment, making them more expensive. Heat pumps can absorb heat from the soil starting at a depth of about one metre, where usually a constant temperature of 4°C prevails, but the coils for heat exchange require space. These conditions are more easily met in rural than in urban areas.

(ii) Air-to-water heat pumps absorb heat from the ambient air. As temperatures fall, their efficiency drops to a ratio of 1 kWh th for 1 kWh el at the bivalence point. For temperatures below this point, additional direct electrical heating is required at a ratio of 1 kWh el to 1 kWh th (see Figure 4).[11] The bivalence point depends on the individual building and the individual HP and is subject to economic considerations and local climate. It is often at temperatures of about -10°C.[12] Power demand by HPs will increase with falling temperatures, not only due to increased heating requirements, but also due to decreasing efficiency of absorbing heat from the ambient air and finally by the need for additional direct electric heating.

Figure 4: Point of bivalence of air-to-water heat pumps



Source: Greenhouse Media GmbH, 2022

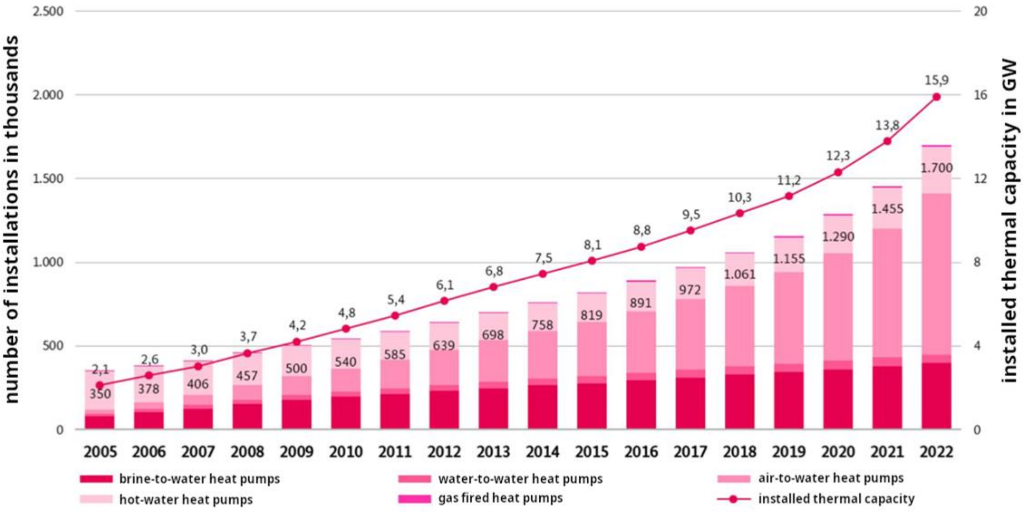
In general, both kinds of heat pumps are a good fit in rural areas, but with different costs. For urban areas – except for larger heat pumps that would, for example, feed into a DH system – water-to-water heat pumps

[10] For a detailed description see for example IEA (2022)
[11] Greenhouse Media GmbH (2022, December 20)
[12] Temperatures of -10°C and below happen in the Eastern part during cold Continental weather and can expand to the Central and Western parts while temperatures in the Alps tend to be low due to the altitude

will be subject to space restrictions. Air-to-water heat pumps, on the other hand, have few technical restrictions, but may require changes in the building's internal heating system design and greater insulation. They may also be subject to noise protection rules and restrictions issued by housing associations.

By 2022, some 1.7 million HPs had been installed with a total thermal capacity of 15.9 million kW th (see Figure 5[13]). The majority of almost 1 million HPs are air-to-water HPs, while for HPs not dependent on ambient air about 450,000 are brine to water HPs, 50,000 water-to-water HPs and 250,000 wastewater-to-water HPs. The number of gas-powered HPs is negligible.

Figure 5: Development of the heat pump stock in Germany



Source: BMWK on the basis of Arbeitsgruppe Erneuerbare-Energien-Statistik (AGEE-Stat); Status 02/2023

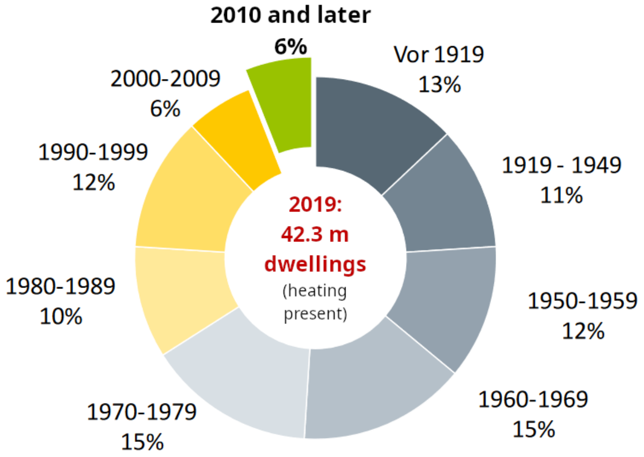
At an average ratio of 1 kWh el to 3 kWh th, air-to-water HPs will save fossil energy and CO_2 emissions, but they also require increased power supply when the ambient temperature drops. Therefore, the challenge for HP deployment will be in scale since it will amplify temperature-dependent power demand. Temperature variation for electric power demand for heating will rise the more air-to-water heat pumps are installed, creating greater peaks of demand. This means that reliable heating will have a significant impact on demand for power capacity, a factor that will not be so visible in assessing average electricity consumption over the heating season.

Impact on the power system to date

It has been pointed out that the installation of HPs to date has had little impact on electricity demand.[14] This study refers to the situation when about 1 million HPs had been installed, that is, before 2020. At that time, total additions were less than 100,000 HPs per year, with a small majority installed in new buildings with high energy efficiency standards. Also at that time, HP installations in existing buildings were usually part of refurbishment, so that new HPs had a limited impact on electricity consumption. The bulk of old buildings (three quarters of dwellings are older than 30 years, see Figure 6[15]), which tend to be in urban areas and have low efficiency standards, are yet to be converted to HPs. This ratio reversed after 2020 and in 2022, about 60,000 HPs were installed in new buildings and some 160,000 HPs in refurbished buildings.[16]

[13] BDEW (2023, May 31) chart 52
[14] Pehnt, M. (2022) p. 65, 66
[15] BDEW (2023, August 31) p. 24
[16] BWP (2023) p. 9

Figure 6: Housing in Germany by year of construction



Source: Statistisches Bundesmat Zensus 2011 ber. Baufertigstellungen und Wohnungsabgänge 2012-2019

The study also only refers to the overall electricity volume consumed (5 TWh) – just 1 per cent of the total consumption of 500 TWh, but not to the contribution of HP to peak demand.

Of the 6 million buildings heated with oil in Germany, 4 million are in rural areas. Of the remaining 2 million buildings, only one million can be linked to the gas grid or district heating (DH). This means there are some 5 million oil heated buildings that cannot be reached by DH or gas grids. The use of water-to-water HPs, whose efficiency is unaffected by ambient temperature, appears to be an energetically reasonable, albeit expensive, alternative for the 5 million oil-heated buildings in rural areas and on the outskirts of cities. Air-to-water heat pumps can replace oil heating as well, but they require high power capacity at low temperatures, especially when extra direct heating is triggered below the point of bivalence.

2.1.2 District Heating

In urban areas, dense DH grids are an obvious alternative to heat pumps. Advances in the insulation of DH pipelines have reduced heat losses, making it possible to reach up to 30 km from the heat source.[17] However, DH systems, with few exceptions such as the STEAG system in the Ruhr area, are not interconnected and usually confined to an individual municipality.

The capacity of a DH grid depends on the size of the double pipeline,[18] the temperature spread between the two pipelines and the circulation speed as a result of the pumping capacity, which can be adapted to changing requirements.[19] Heat can be fed into the DH system at various points.

About 1.5 million buildings in Germany are heated with DH. In 2021, the share of DH for space heating in households was 8.7 per cent, and 2.4 per cent in the commercial sector. [20] In industry the share was 4.9 per cent. See Figure 7.

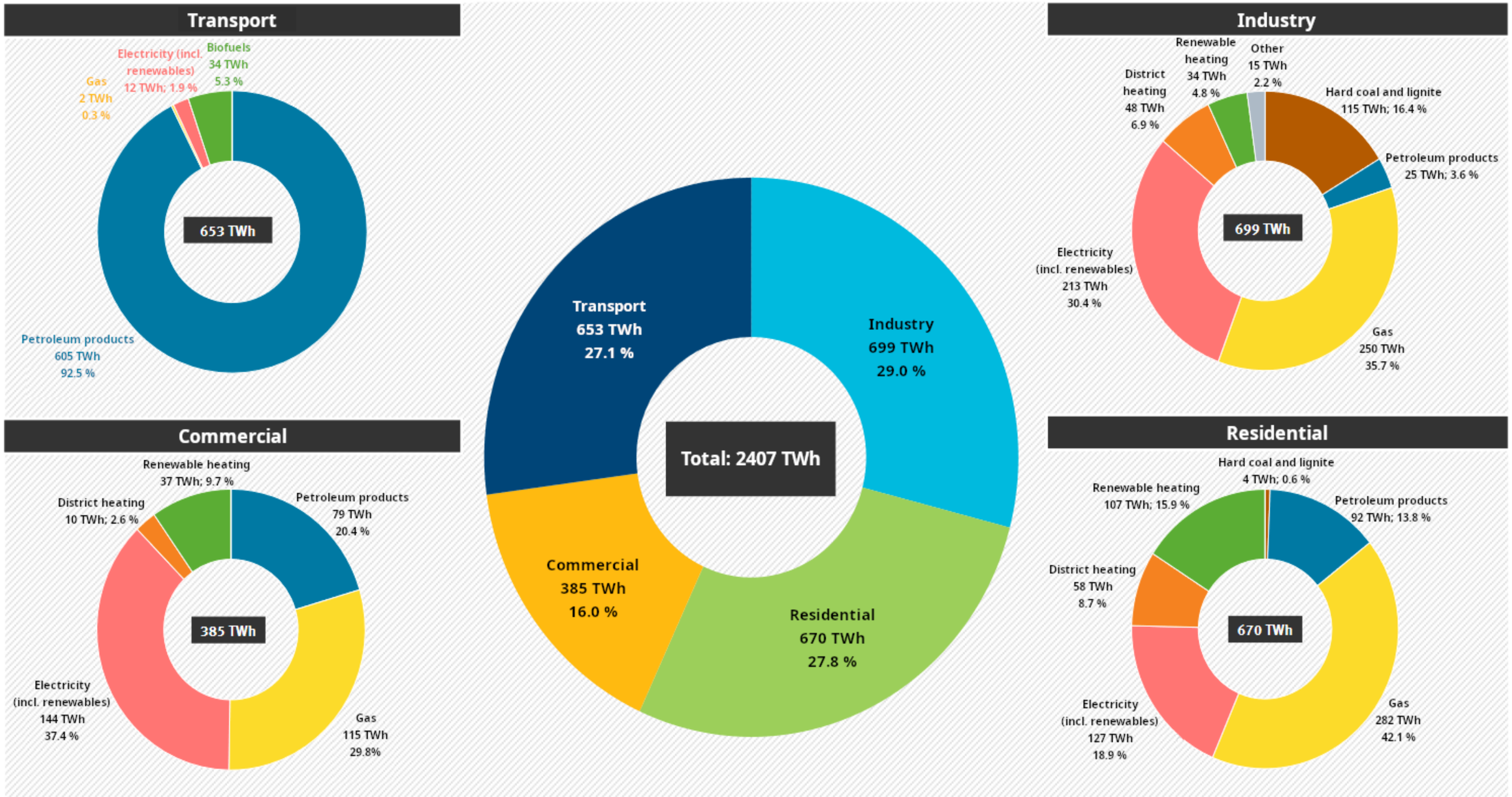
[17] Vaillant Deutschland GmbH & Co. KG (n.d.)

[18] DH systems usually consist of one pipeline to supply the hot water to the customers and one pipeline to return the water with lower temperature using the temperature differential for heating

[19] Nussbaumer, T., Thalmann, S. (2017, February 1), graph 1

[20] UBA (2022, September)

Figure 7: Final energy consumption 2021 by sectors and energy sources*



Source: Umweltbundesamt on the basis of AG Energiebilanzen, Auswertungstabellen zur Energiebilanz der Bundesrepublik Deutschland, status 09/2022

Note: * preliminary data

In 2018, of the 82 German cities with more than 100,000 inhabitants (27.2 million total), 95 per cent had a DH system supplying a total of 88 TWh th per year, while half of the 629 towns with between 20,000 and 100,000 inhabitants (23.2 million total) [21] had a DH system supplying a total of 20 TWh th per year.

Most DH systems use hot water and less than 10 per cent use steam. The overall length of DH systems in Germany in 2020 is 31,252 km (Table 1).[22] This is just 6 per cent of the total length of gas distribution grids (550,000 km).[23]

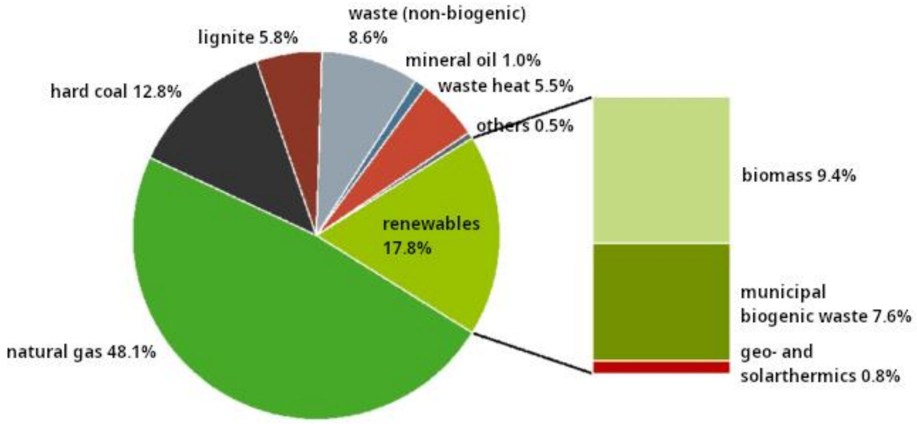
Table 1: Length of DH systems (km)

Heat carrier	2018	2019	2020
Water	25,760	26,939	28,695
Steam	2,870	2,539	2,557
Total	28,629	29,468	31,252

Source: AGFW (n.d.)

Figure 8 shows that 48.1 per cent of the feed-in for district heat generation in 2020 came from natural gas, 17.8 per cent from renewables, while coal and lignite together still accounted for 18.6 per cent. Waste heat provides 5.5 per cent.[24] While much of the heat fed into district heating systems is from Combined Heat and Power, it is based on fossil fuels. The options to decarbonize the feed in into DH are discussed in Chapter 2.2.2.

Figure 8: Net heat generation* by energy source in Germany (for grid-bound heat supply 2020: 126 TWh)**



Source: Destatis, BDEW, as of 12/2020

Note: * of heat suppliers as well as feed-ins from industry and others. **preliminary, partially estimated

Finally, at the consumer level, the DH option triggers limited disruption as connecting a boiler-heated building to DH is easily done by replacing the existing boiler with a heat exchanger connected to the DH grid in the street. No changes are required to the building hull, internal pipework or radiators. The rapid rollout of DH grids in central areas of communities can provide a timely and cost-effective alternative to replacing gas and oil boilers by heat pumps. Some municipalities are offering refurbished boilers for lease until the DH grid is ready, so that consumers can avoid having to buy a new boiler if the old one breaks down.

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[21] Wikipedia (2023, November 6)
[22] AGFW (n.d.)
[23] DVGW Deutscher Verein des Gas- und Wasserfaches e. V. (2023, February)
[24] BDEW (2023, May 19)

2.1.3 Switching from methane to hydrogen

Switching gas supply from methane to hydrogen is driven by the fact that, unlike methane, hydrogen produces no CO_2 at the point of combustion. Out of 550,000 km gas distribution pipelines serving 9.5 million buildings, 95.9 per cent are made from plastic or H_2-compatible steel, which means they can be switched to 100 per cent hydrogen, according to a recent study by DVGW.[25] Only 0.2 per cent are not suitable, while 3.9 per cent are still under investigation. Also, most grid linked facilities, like meters and regulators, are hydrogen-compatible. Overall investment in the adaptation of gas distribution grids is estimated at just about €30 billion, leaving aside investment needed for customer switching costs.

Some manufacturers have announced they will manufacture boilers which can be easily switched to 100 per cent hydrogen for roll out from 2024.[26] Switching will have to happen district by district and all devices within a district would have to be switched simultaneously, which may not be an easy task as experienced by the L- to H-gas switch. For the transmission grid, a parallel supply of both gases by two separate systems would therefore be needed for a period.

2.2 Supply of reliable, CO_2-free primary energy for heating

The last chapter analysed the three key ways of achieving zero emissions at the point of heat consumption. The following chapter addresses how to supply reliable and decarbonized primary energy, the related conversion instruments as well as the delivery infrastructure. It also addresses costs and feasibility by the 2045 deadline.

2.2.1 All individual HP systems

If a single solution had to be found for 15 million buildings it would be HPs, as only they can heat the 5 million buildings which are not grid-connected and currently use heating oil, while connecting to a gas or DH grid remains non-viable for these buildings (despite the potential to decarbonize by that route). These buildings are, however, connected to the power grid, so HPs can be installed.

This section considers the case where all 15 million buildings use individual HPs. The issue is then what reinforcement of the power grids at local, regional and national levels is needed and how the heating demand can be covered by the power system. On the generation side, the two principal options are (i) an all-renewable power generation system or (ii) a hybrid system which includes decarbonized fossil thermal plants.[27]

(i) 15 million HPs supplied by renewable power

This scenario would require all 15 million buildings to be heated by individual HPs powered by renewables. It corresponds to the assumptions of the scenario framework for the power grid development plan NEP 2023,[28] which implies 16.3 million deployed HPs in 2045 compared to 1.7 million in 2022, supported by some limited DH connections to existing grids.

Of all dwellings in Germany, about two thirds were built before 1979 (Figure 6), many with poor post-war, low oil price insulation standards. This scenario requires electricity generated at the time of demand or drawing on storage of renewable electricity to cover discrepancies between demand and supply. This is very close to the assumptions of the scenario framework for the NEP 2023. The figures shown in Table 2 are the values for 2037 and 2045 of the main scenario B of the scenario framework for the NEP 2023. The values for scenarios A and C are of a similar order of magnitude, except that scenario A provides for an even higher capacity of electrolysis (40/80 GW in 2037/2045 instead of 26/50 GW in scenario B). The last

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[25] Press release: DVGW (2023, March 28); Study: Steiner, M., Marewski, U., Silcher, H. (2023, January)
[26] Preißler, S, Blaschke, J. (2023, August 21)
[27] Nuclear is not an option in Germany: the German phase out of nuclear plants over the period from 2011, following the disaster in Fukushima, until the closure of the last three German reactors deferred by 3 months to 31 March 2023 is now de facto irreversible. There is no legal framework for the commercial generation of nuclear power in Germany, no nuclear fuel supply, the operators have dissolved all teams operating the last nuclear plants and the dismantling process on the last three reactors has also started. The cases of new nuclear reactors in EU with construction times of 15 years and more (not accounting for planning) suggest that any new nuclear reactor in Germany would be too late to contribute to net zero in 2045.
[28] Bundesnetzagentur (2022, July) p. 4

two columns (in red) are the factors (not percentages) of the value of scenario B for 2037 and 2045 relative to 2021's value.

To achieve the NEP Scenario Framework 2023 based on mostly renewable primary energy, several aggressive assumptions need to be made about the roll out of renewables; the means of transforming intermittent power into reliable power on demand; the production of hydrogen for industrial use; and for hydrogen-fired power plants as shown by the excerpt in Table 2 from the Scenario Framework for the NEP electricity 2023.[29] Not shown are the strong assumptions on imports of CO_2-free, green hydrogen. In spite of strong assumptions on the capacity of electrolysers, the regulator BNetzA in its approval of the scenario framework assumes a share of imported hydrogen above 50 per cent. [30]

Table 2: Scenario assumptions as approved by BNetzA

	2021	Scenario B 2037	Scenario B 2045	***Factor B 2037 vs 2021***	***Factor B 2045 vs 2021***
Conventionel installed capacity (GW)					
Gas fired power**	32,1	> 38,4	>34,6		
Pump storage, other	14,10	12,10	12,1		
total conventional power	92,9	>50,5	>46,7		
Wind Onshore	56,1	158,2	160	*2,82*	*2,85*
Wind Offshore	7,8	58,5	70	*7,50*	*8,97*
Photovoltic	59,3	345,4	400	*5,82*	*6,75*
Bio, hydro, other	15,5	10,8	8,3	*0,70*	*0,54*
Total renewable	138,7	572,9	638,3	*4,13*	*4,60*
Total capacity	231,6	623,7	685,3	*2,69*	*2,96*
net electricity consumption (TWh) *	478	891	1025	*1,86*	*2,14*
BEVs, heating, flexibilities					
BEV (mln)*	1,2	31,7	37,3	*26,42*	*31,08*
Power to heat (GW)*	0,8	16,1	20,4	*20,13*	*25,50*
Heat Pumps (HH, commercial, mln)*	1,2	14,3	16,3	*11,92*	*13,58*
Wallboxes (GW)*	1,3	67,4	97,7	*51,85*	*75,15*
Large batteries (GW)*	0,5	23,7	43,3	*47,40*	*86,60*
DSM (Industry, commercial, in GW)*	1,2	7,2	12	*6,00*	*10,00*
Electrolysis (GW)*	0,1	26	50	*260,00*	*500,00*

Source: Network Development Plan 2037/2045 (2023)

Note: *values for 2020 instead of 2021. ** Gas fired power, first based on natural gas, later on hydrogen

[29] Ibid
[30] Bundesnetzagentur (2022, July) p. 27

The resulting network plan[31] foresees a substantial reinforcement by 2045 of 4,400 km of new high voltage direct current (HVDC) lines including five additional HVDC lines (mainly North – South) each with 2 GW. Plus upgrades of 179 km of HVDC lines; 1,714 km of high voltage alternating current (HVAC) lines; a 6,125 km upgrade of existing HVAC lines (total 12,413km), and reinforcing of North-South and North-East connections in the German power grid. This extra capacity compared to the previous NEP (2021) is mainly needed in winter to supply the heat pumps in the south with wind power from the north, backed by hydrogen-fired power from green hydrogen stored in salt caverns in the north. The resulting grid should be in place by 2037 with only minor changes anticipated between 2037 and 2045. At the end of 2023 power lines with a total length of 1276 km had been approved by the BNetzA.[32] The extra investment for the onshore grid, compared to NEP 2021, is €106 billion by 2037, of which €46 billion is allocated for HVDC lines and €60 billion for HVAC lines.

This approach implies an almost complete workover of the heating (and structure) of buildings, of all cars, of most energy applications in industry, of all primary energy supply and much of the appliances of final energy supply, adding conversion processes like electrolysis at a globally unprecedented level.

Today, gas demand is much more seasonal than power demand, due to ambient temperature-dependent space heating demand plus seasonal variations in industrial activity. The electricity system will have to take over the function of the gas system with its seasonality, as illustrated in Figure 3, and beyond that it will also have to take over the functions of oil in the heating and transportation sectors.

These ambitious plans will have to be coordinated and meet their deadlines, to a large extent, by 2037, and avoid delays in roll out, permitting, technology development or economics. The resulting all-electric system will have to cope with all major intermittence of renewables on the input side and with major seasonality and year on year variations of demand.

The calculations in OIES paper ET 13[33] demonstrate that the rollout speed of renewables as foreseen in the coalition agreement – which underlies the scenario framework – will fall short of meeting the net zero target by 2045, even more so in view of the modest roll out of onshore and offshore wind seen recently. While the targets in the Coalition Agreement translate into an annual addition of 41 TWh/a until 2030, the average addition was 10.9 TWh/a from 2011 to 2020, 7.6 TWh/a in 2021 and 12.7 TWh/a in 2022. Preliminary figures for 2023 suggest an addition of circa 21 TWh/a, mainly due to a doubling of the PV capacity installed in 2023 to 14 GW. [34]

How is temperature dependence reflected in the scenario framework?

Total heat demand of a given year or month is proportionate to the degree days.[35] This applies also with better insulation, only that the gradient is getting steeper. However, the Scenario Framework of the 2023 NEP approved by the BNetzA does not discuss temperature dependence of space heating demand supplied by HPs and its impact on demand for power capacity. The approval document on page 50 refers only to the weather in 2012 being used for modelling. With 3,598 degree days, 2012 was colder than average but 2010 with 4,099 degree days (+ 13.9%) and 2013 with 3,777 degree days (+ 5.0%) were much colder.

Importantly, the most critical situation - a cold 'Dunkelflaute' [36] (a situation usually in winter, when the wind is not blowing and the sun not shining, often occurring under cold continental weather conditions) - is not addressed. In this situation there is no PV nor wind-generated power while heat demand is high. For reliable power grid operation this is a trivial situation, but for reliable power supply it absolutely matters.

Heating demand is temperature dependent and therefore has strong seasonal variations. Based on steady supplies of gas and oil these seasonal variations are covered in Germany by a gas storage volume of about 280 TWh th and by six million oil tanks in buildings heated by oil corresponding to circa 80 TWh th. Box 1 illustrates the discrepancy, by order of magnitude, between these seasonal energy volumes and the electric storage volumes included in the NEP 2023, which claims to cover secure heating by HPs and renewable power at all temperatures.

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[31] Übertragungsnetzbetreiber (2023, July 27)
[32] Bundesnetzagentur (2023, December) page 1
[33] Dickel, R. (2022, June), see pages 9 ff
[34] Bundesnetzagentur (2024, January 5)
[35] The sum of the difference of 16°C -minus daily average temperatures, zero for temperatures above 16°C over a given time period
[36] Dickel, R. (2022, June) p. 11

Box 1: Storage needed to handle seasonal heating demand variations

Demand for seasonal energy storage

Today's gas storage capacity is around 280 TWh th, to which 6 million private residential oil tanks, equivalent to 80 TWh th can be added, making a total of 360 TWh th. This storage has reliably covered seasonal variations in heat demand over recent decades, although in the case of the prolonged 2018 winter there was little working gas left.

By comparison, the scenario framework 2023 envisages for 2045 electric storage of about 100 GW el through PV batteries and some 55 GW el of large battery storage (plus a slight increase of pumped storage of 40 GWh el). Assuming 2 kWh/kW both for PV batteries and for large scale batteries[37] this gives a storage volume of 310 GWh el in addition to pump storage volumes in Germany (40 GWh el) or under contract abroad (20 GWh el) of 60 GWh. In total, this is **370 GWh el** in 2045, compared with almost **280 TWh th** working gas storage in Germany today. [38]

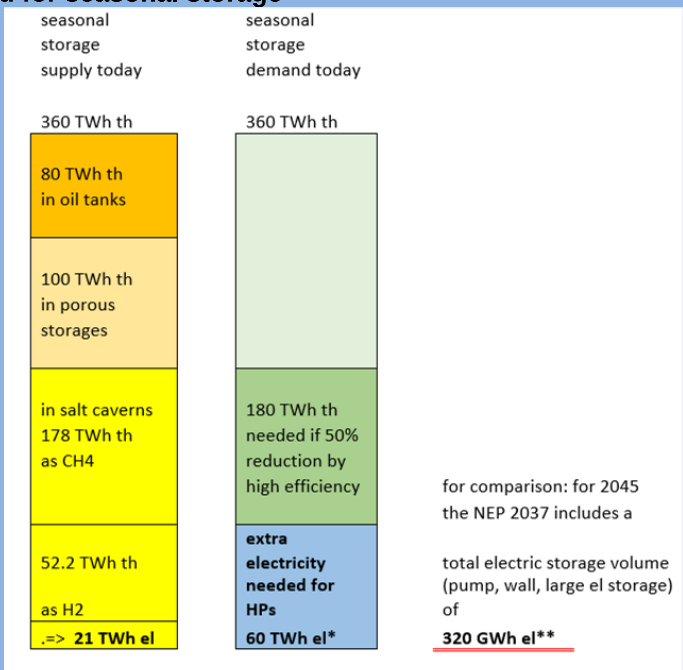
Even with different systems for the supply of heating demand (HP, etc.), seasonality of final energy demand (space heating and industrial seasonal demand) will remain. Even assuming energy saving of 50 per cent due to better insulation for all buildings and an efficiency of heat pumps of 3 kWh th per kWh el, the actual 360 TWh of fossil fuel storage (280 TWh gas storage and 80 TWh oil storage) will still need to be replaced by seasonal electric volumes of 60 TWh el by 2045.[39]

Present seasonal storage

Today Germany has 14.8 Bcm of gas storage in salt caverns, which can most likely be retrofitted to store hydrogen and 8.5 Bcm working gas in porous storage (untested to store 100% hydrogen).

When only hydrogen is stored the thermal storage capacity is reduced from 360 TWh th to 52.5 TWh th (no oil tanks, no porous storage and only one third of the methane storage capacity in energy terms). Using hydrogen-fired generation would produce 21 TWh el, falling short of the 60 TWh el needed for back up for HPs, as illustrated in Figure 9.

Figure 9: Supply and demand for seasonal storage



Source: Author

Note: *assuming 3 kWh th / kWh el for mix heat pumps. ** The double line at the bottom exaggerates the electric storage volume

[37] Wille-Haussmann, B., Biener, W., Brandes, J., Jülch, V., Wittwer, C. (2022, May 2)

[38] LBEG (2023, October 27)p. 35

[39] 360 TWh divided by two to account for hypothetical improved building insulation and other efficiency and then by three to account for the efficiency of heat pumps

Converting existing salt caverns from methane to hydrogen looks possible (a pilot to convert two caverns at Etzel is underway) but the energy content stored will shrink by two thirds due to the lesser specific energy content of hydrogen compared to methane.

The building of additional salt caverns for hydrogen storage could also be considered: northern Germany could develop at least 100 caverns, each with a working gas volume of 50 – 100 million m^3. However, a major bottleneck is leaching since the disposal of salt water is tightly controlled.[40]

In conclusion

- The seasonal variations of heat demand are orders of magnitude above electric storage potential.
- Even when using electricity converted to hydrogen the storage volumes potentially convertible to hydrogen are too low to cover seasonal variations for heating demand, even assuming substantial improvement in building insulation.
- Using existing natural gas storages seems to be the best option to cover primary energy supply needed for seasonal variations of heating.

(ii) Deployment of 15 million HPs with decarbonized power as back up

While an HP system underpinned by fully renewable power generation is unrealistic by 2045, replacing part of the renewable primary energy supply with gas-fired power with CCS as back up for 15 million heat pumps looks more feasible as shown in Box 2. This would mitigate the slow roll out of renewables and the absence of sufficient storage.

Box 2: Gas and CO_2 sequestration volumes needed to back up 15 million HPs

Assuming heating demand of 20 kW th/building with a 50 per cent simultaneous factor of power demand from HPs and an average efficiency of 3 kW th/kW el of the HPs installed, the system would require a back-up power capacity of 50 GW el as shown by the calculation below.

15 million buildings * 20 kW th/building * 0.5 simultaneous factor*1 kW el/3 kW th = 50 GW el.

If built as gas turbines with an efficiency of 33 per cent (accounting for degradation for decarbonization by the energy losses of amine scrubbing of the flue gases or of the energy needed for pre-combustion air splitting in an Oxyfuel process), a load factor of 1000 h/a (which seems a reasonable estimate for the load following needed by gas fired power) requires a gas input of 50 GW el * kW th/0.33 kW el * 1000 h/a =150 TWh th. This corresponds to 13 Bcm/a[41] of natural gas resulting in 24 Mt CO2/a to be sequestered. This looks feasible (even in the event of a colder than usual winter) using imported gas bolstered by existing storage.

In this case, back-up power generation could be built close to the power consumption of the HPs and be supplied using the existing gas pipeline system. This approach would provide a CO_2-free primary energy supply capacity at any time to run the heat pumps at all temperatures. The north-south reinforcement of the power grid would be reduced or could be dropped as the energy transport for heating on a national level would be provided by the existing natural gas system. Instead of requiring high volumes of electrolysers and a hydrogen system in the case of an all-renewable system, this approach would require 50 GW of gas turbines with CCS and the corresponding CO_2 collection system (by ships or pipelines) and CO_2 disposal systems. In this case the existing natural gas transmission and storage system would be used to ensure heating independent of renewable power generation from gas-fired power with CCS.

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[40] The salt caverns in Etzel have a special pipeline for leaching. To leach 100 more caverns each with a geometric volume of between 50,000 – 100,000m^3 with a volume of 50 million to 100 million m^3 working gas resulting in 5 to 10 Bcm additional working gas by 2045 would be a great challenge

[41] Assuming an energy content of 11.5 kWh/m3. The mass of 1 m^3 of methane is 0.67 kg, burning 1 kg of methane (mol weight of 16) results in CO_2 (mol weight 44) with a mass of 44/16 = 2.75 kg

This scenario implies that 550,000 km of gas distribution grid pipelines would become obsolete. Instead, local and regional power systems would need to be upgraded to bring additional power from gas-fired generation. The potential of cogeneration for heating demand in sync with power for HPs would not be used.[42]

2.2.2 Combining HP, DH and methane-hydrogen switching

A system of 15 million individual HPs, drawing on renewable power, if and when available, supported by regional gas or oil-fired back-up power plants with CCS looks possible.[43] The biggest challenge would be the roll-out of 15 million individual HPs plus refurbishment of buildings and the upgrade of local power grids. The approach would leave no room for other CO_2-free heating systems, thereby squandering the options to integrate various CO_2-free heating energies via the DH system and using the switch from methane to hydrogen in the existing gas distribution system as a backup. Therefore, a diversification of approaches avoiding bottlenecks which cannot be compensated in other places looks reasonable.

What combination of HPs, DH and switch from methane to hydrogen is reasonable by 2045? Each of the three options come with advantages, disadvantages and specific limitations:

a. HPs have the advantage that they can replace oil heating in 5 million buildings in locations where electricity is supplied but there is no access to gas pipelines or DH. This option requires the upgrade of power distribution plus additional back-up power generation capacity.

b. DH has the advantage of a large, collective system allowing CO_2-free energies like geothermal, large heat pumps, waste heat, CHP with CCS, possibly based on waste incineration to be tied in. DH also opens the way to use large heat storage in the soil.

   So far DH is restricted to single local municipalities. The bottleneck is the roll out speed: DH grids have a total length of 31,000 km with approximately 1 connection every 20 m of grid. A total of 619 km of new DH lines was built in 2020 corresponding to 30,000 new connections.

c. Methane to hydrogen switching: switching the distribution grids from methane to hydrogen is possible with a limited investment estimated by DVG at €30 billion and could reach all heated buildings. The main obstacle is limited availability of green hydrogen by 2045. The supply of blue hydrogen with the high capacity needed looks feasible but would either require a high capacity of autothermal reformers (ATRs) close to consumption points with a low utilization factor or ATRs combined with hydrogen storage in north Germany, which would require new storage sites and a nationwide hydrogen pipeline grid, which looks challenging in the 2045 time frame.

In more detail:

a. The role of HPs

HPs are the only heating option for the 5 million buildings with no possible link to gas distribution or a DH grid. The total capacity demand for reliable electricity to supply these houses would be 33 GW el (assuming demand capacity of 20 kW th per building and an efficiency of 3 kWh th/kWh el for heat pumps installed). About 30.24 GW el could be provided by hydrogen-fired power plants. This number comes from the sum of the peak plateau send out of all salt caverns divided by the heating value of hydrogen used in a hydrogen-fired gas plant with 40 per cent electric efficiency (21.6 million m3/h [44] * 3.5 kWh/m3 H2[45] = 75.6 GW th H2

[42] A CHP plant (with or without CCS) uses the exhaust heat of the power generation process for heating purposes often as feed in into a DH grid. The ratio between use for power generation and use as heat has some flexibility, so it can produce more electricity in summer and more heat in winter. The demand for power by HPs and for heat for DH is in sync as it is induced by the same temperature development. Using a gas fired plant with CCS only for pure power generation would waste the exhaust heat which would then just warm up the environment. Instead of using this exhaust heat for low temperature space heating this space heating would have to be provided by extra heat pumps with extra renewable and back up capacity

[43] The building of adequate CO_2 collecting systems requiring several large CO_2 trunkline systems is technically possible by 2045. For comparison: EUGAL, a twin 56” pipeline of almost 500 km length was constructed within 2.5 years. Comparison with the Cortez CO_2 pipelines in the US suggest that one 56” CO_2 pipeline might transport as much as 50 Mio tCO2/a. Under the CCS act, the construction of CO_2 pipeline is possible, just waiting for the technical standards – under work at DVGW – and the permitting procedures to be issued by the federal ministry BMWK. The retrofitting of power plants with decarbonization in 20 years looks feasible: desulfurization of coal fired powerplants also by amine scrubbing was achieved in little more than a decade

[44] LBEG (2023, October 27) p. 37

[45] The higher heating value of hydrogen is 39.39 *kWh*/kg or 3.54 *kWh*/m³.

* 0.4 = 30.24 GW el). However, it would be better to use gas (otherwise used in producing blue hydrogen) directly in power plants with CCS.

Green hydrogen would run into the limited roll out of renewable power capacity already needed for the power system and imply 25 per cent conversion losses in electrolysers and need enormous electrolyser capacity.

A roll out of 5 million HPs by 2045 corresponds to 225,000 per year in line with 236,000 installed during 2022 under special circumstances. Regarding reliable power capacity, the best approach seems to use CHPs with CCS feeding heat into urban DH systems while supplying electricity in sync to the HP in the surrounding countryside. 33 GW el from CHPs with CCS could co-produce 66 GW thermal, enough to heat 3.3 million buildings by DH. Bringing the energy as gas to CHPs close to consumption will de-stress the power grid at the transmission level and the regional/local level while using the existing gas grid. It comes with the need to build a new CO_2 collection system.

Individual HPs should be avoided in areas suitable for DH to avoid cannibalizing DH economics. The 10 million buildings remaining to decarbonize are linked to a gas distribution grid of 550,000 km in length.

b. Feed in of zero CO_2 energy into DH grids

DH grids offer a large potential to tie in various forms of CO_2-free heat depending on their availability and subject to their technological development.

With little or no electricity input: geothermal heating [46]

This would require a small amount of electricity for pumping. It needs a DH system so that the high costs of the deep drilling (2,000-3,000m) required can be spread, but it is a reliable heat supply at any time and ambient temperature. To the extent geothermal heat is produced in the south of Germany it reduces the need for reinforcement of the north-south power grid connection which deploying heat pumps in the south would require.

The potential of geothermal in Germany is estimated by 2030 at 100 TWh th per year/24 GW th and for 2040+ at 300 TWh th per year/72 GW th.[47] With an estimated 20 kW th peak demand per building, this translates into 1.2 million buildings by 2030 and 3.6 million buildings by 2040+. Geothermal is already used in Munich,[48] but further drilling and pilot projects should be undertaken to get a better understanding of the potential and costs.

With electricity input: large heat pumps

Large HPs can use heat from wastewater, from industrial and IT processes but also from geothermal layers close to the surface or from lakes and rivers, which are not accessible for individual HPs. Large heat pumps have been operated at 180 MW th in Stockholm based on sea water; in Vienna (Simmern) a project with 110 MW th based on wastewater is close to start up. In Cologne a project based on the water from the river Rhine of 150 MW th is being planned.[49]

At the beginning of 2023, at least 30 large HP with a total 60 MW th were in operation in Germany, with another 30 large HP projects worth 600 MW th under construction or being planned.[50] While large HPs have so far been individually designed, standardization to save cost is now being addressed.

From CHP with CCS co-generating reliable power for heat pumps

Power coproduced from CHPs with CCS can be used to supply power to run the heat pumps as HP power demand and heating demand for DH are both driven by ambient temperature. Heat coproduced by CHPs in summer could be stored in subsurface geological formations and retrieved

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[46] Bracke, R., Huenges, E. (2022, Feburary) p. 25
[47] Bracke, R., Huenges, E. (2022, Feburary) p. 36
[48] Stadtwerke München GmbH (2023, March 8)
[49] In Stuttgart under construction: Berse, A. (2023, May 22)
In Vienna: 2 x 55 MW to be finished in 2023: Ringel, A. (2022, July 6)
In Cologne: In planning heat pumps from the Rhine river 150 MW plus some smaller HPs: RheinEnergie AG (2023, June 15)
In operation Stockholm 180 MWth: Friotherm AG (n.d.)
[50] Agora Energiewende, Fraunhofer IEG (2023, July) p. 25

in winter with 70-80 per cent of the heat recovered.[51] This technology is still in early development. Geological storage is being trialled at the DeepStor project in Switzerland at the KIT-CH.[52]

Surface heat storage has been successfully deployed at a large tank in Berlin with a volume of 56,000 m^3, a water temperature of 98°C and a capacity of 200 MW th which can be discharged for 13 hours.[53]

CO_2-free CHP can be provided by one of the following options:

- *CHPs run by zero carbon hydrogen* either green, blue or turquoise hydrogen.[54] However, availability of green hydrogen is uncertain, as the limited volumes produced will be prioritised for industrial process heat. In addition, the use of hydrogen in turbines or power plants (hydrogen ready) has not yet been tested at scale due to insufficient feedstock. Hydrogen burns at a much higher temperature than methane, requiring heat-resistant turbine blades and creating a problem with NOx formation. At temperatures above 1000°C the nitrogen of ambient air reacts with the oxygen to form Nitrogen oxide which would exceed the NOx emission limits.
- *Use of fossil fuels or biomass with CCS*[55]
    - CO_2 capture from power plants is known at TRL 9 (Technical Readiness Level; 9 is the highest level, proven at industrial scale) by amine scrubbing (pilot projects at industrial scale are Boulder Dam in Saskatchewan and Petra Nova in Texas)[56] which extracts CO_2 from the exhaust stream of a lignite power plant, in a process similar to desulfurization.
    - The same process can be applied to waste incineration, as at the Oslo Warme pilot project.[57] Usually 50 per cent of the power from waste incineration is attributed to biological waste, so its capture and sequestration is regarded as a net saving on CO_2 emissions. Germany has some 90 waste incineration plants[58] with a total capacity of 20 million tons of waste, usually run as CHP, with a ratio of 1t waste producing 1.1t of CO_2.[59]
    - Another approach is to use pure oxygen instead of ambient air so that only CO_2 is produced or if burning gas, CO_2 plus water vapor. This process has been tested to TRL 8 in Jänschwalde at a scale of 30 MW th.[60]
    - NET Power has announced an industrial scale project in Texas of 300 MW el using gas and oxygen[61] capturing circa 860,000 t CO_2/year to start operation in 2026. This is based on its experience at the 50 MW th test facility at La Porte, Texas.[62]

By 2045 5 million buildings could be heated by DH based on the inputs described, composed as follows:[63]

-	from geothermal	1.2 million buildings
-	from large heat pumps	0.5 million buildings
-	from cogeneration with CCS:	3.3 million buildings
	in total	5.0 million buildings

[51] Bracke, R., Huenges, E. (2022, February) p. 21
[52] KIT (2023, April 27)
[53] Vattenfall Wärme Berlin AG (2022, August 8)
[54] green hydrogen results from electrolysis run by renewable power, blue hydrogen from steam reforming with CCS and turquoise hydrogen from splitting methane by pyrolysis into carbon and hydrogen.
[55] See Dickel, R. (2022, June) p. 28
[56] See Dickel, R. (2022, June) p. 28
[57] Dickel, R., Fattouh, B., Muslemani, H. (2022, September) p. 9
[58] Wikipedia (2023, November 7)
[59] Arnold K., Scholz A., Taubitz A., Wilts H. (2022) p. 10
[60] See Dickel, R. (2022, June) p. 28
[61] NET Power Inc. (2022, November 7)
[62] NET Power Inc. (n.d.)
[63] 1.2 million buildings as the potential mentioned above for 2030 as a modest estimate for 2045, 3.3 million buildings from CHPs with the capacity to back 5 million HPs with a ratio of one to two use for heat/power in the CHPs and the rest using the potential of large HPs

The feed-in potential of CO_2-free energy offers multiple options. More challenging is the expansion of DH grids, which now extend for 31,000 km. In 2020, 619 km of additional lines were built (while 196 km were removed).[64] At 20m per connection, a 100,000 km grid expansion would be needed to link 5 million more buildings to the DH grid, or about 4,800 km grid expansion per year, eight times more than is being built at present (not counting necessary replacement). The DH grid expansion might be substantially reduced with a mandatory linking to the DH grids when replacing gas fired heating which in many areas is so far in parallel to DH systems.

c. *Switching from methane to hydrogen*

Using the existing gas distribution grid but switching to hydrogen from methane has the advantage that no additional distribution infrastructure needs to be built and the changes needed within the building are limited to the boiler. The switch would occur at a point upstream from the respective distribution grids in large scale units producing hydrogen, mainly from natural gas by ATRs. The gas grid can serve customers that cannot be reached through the expansion of DH grids.

Switching the grid from methane to hydrogen

Switching the German gas grid to 100 per cent hydrogen is possible according to recent investigations by the DVGW which show that at least 95 per cent of the distribution pipelines are H_2-ready and that a switch from methane to hydrogen of the existing gas grid would cost no more than €30 billion.[65] Producers of gas boilers announced that H_2-ready gas boilers would be available from 2024. Switching from methane to hydrogen district by district will not be an easy task, requiring two separate systems for gas and for H_2, at least for a period of time.

The main obstacle, however, is availability of green hydrogen, which is insufficient to match present gas supply. For instance, supplying 5 million buildings at 20 kW th with hydrogen at a load of 1500 h/a would require 150 TWh th/a.[66] Furthermore, storage to handle that amount of hydrogen is also insufficient.

If produced in ATRs close to customers, ATRs would be run with a poor load factor reflecting the poor load factor of heating demand. Conversion at the landing point of base load volumes of natural gas would require converting all volumes to hydrogen and the (summer) surplus being stored in salt caverns, needing a geometrical volume in excess of present salt caverns. It would also need a national hydrogen transport system. Some combination of conversion plus storage for customers close to salt caverns in the north and east plus conversion close to the customer in the south might be a reasonable solution.

In any case, a system of CO_2 collection by ship or pipeline and CO_2 sequestration is necessary. These elements have been operated for a long time at industrial scale in the US, Canada and Norway.

Using HPs for the 5 million oil heated buildings outside built-up areas looks inevitable, but without much potential for individual HPs to go beyond that for the reasons explained in this paper. For the remaining 10 million buildings now supplied by natural gas, the dividing line will be between areas of high concentration of heat demand in the inner cities which are best supplied by DH with a various mix of feed in and switching the gas system to hydrogen from ATRs with CCS or green hydrogen to the extent available (more in the industrial and commercial areas plus the suburbs of cities). The balancing point depends on the roll out speed of the DH grid and the balance of costs for roll out of DH vs the conversion costs of methane to hydrogen by capital intense ATRs with a poor demand structure.

2.3 Primary energy supply chains needed to deliver reliable and CO_2-free energy

Figure 10 illustrates the supply chains and their elements from primary energy to reliable CO_2-free energy and on to provide CO_2-free heat. The chart illustrates different kinds of restrictions in different colours.

While it is evident that decarbonization will imply extra costs not covered by the market, all measures marked in yellow will be able to contribute with adequate funding to meet the net zero target by 2045. Technologies subject to funding are: ATR with CCS used for switching distribution from methane to hydrogen for hydrogen-ready boilers; renewable power generation combined with thermal power with CCS for direct

[64] Agora Energiewende, Fraunhofer IEG (2023, July) p. 22
[65] DVGW (2023, March 28) p. 2
[66] This corresponds to a dedicated wind capacity of 115 GW el running at 2000 h/a and 0.65 efficiency of the chain of electrolysers plus H_2 grid and storage: 115 GW * 2000 h/a *0.65 = 150 TWh/a

electric heating and heat pumps within the limits of local power grids (which can be overcome by 2045); the use of decarbonized CHPs for DH; the use of decarbonized thermal power for large heat pumps for DH; and geothermal for DH. DH grids will also need expansion by 2045.

Oxyfuel,[67] as an alternative way to decarbonize power plants, should be further developed through pilot projects to elevate the technology to TRL9. This could develop as an alternative to amine scrubbing of exhaust streams. The oxyfuel process - splitting air into oxygen and nitrogen before combustion - might be less sensitive to load as oxygen can be stored. It is not absolutely necessary but should diversify technologies and contribute to reducing costs.

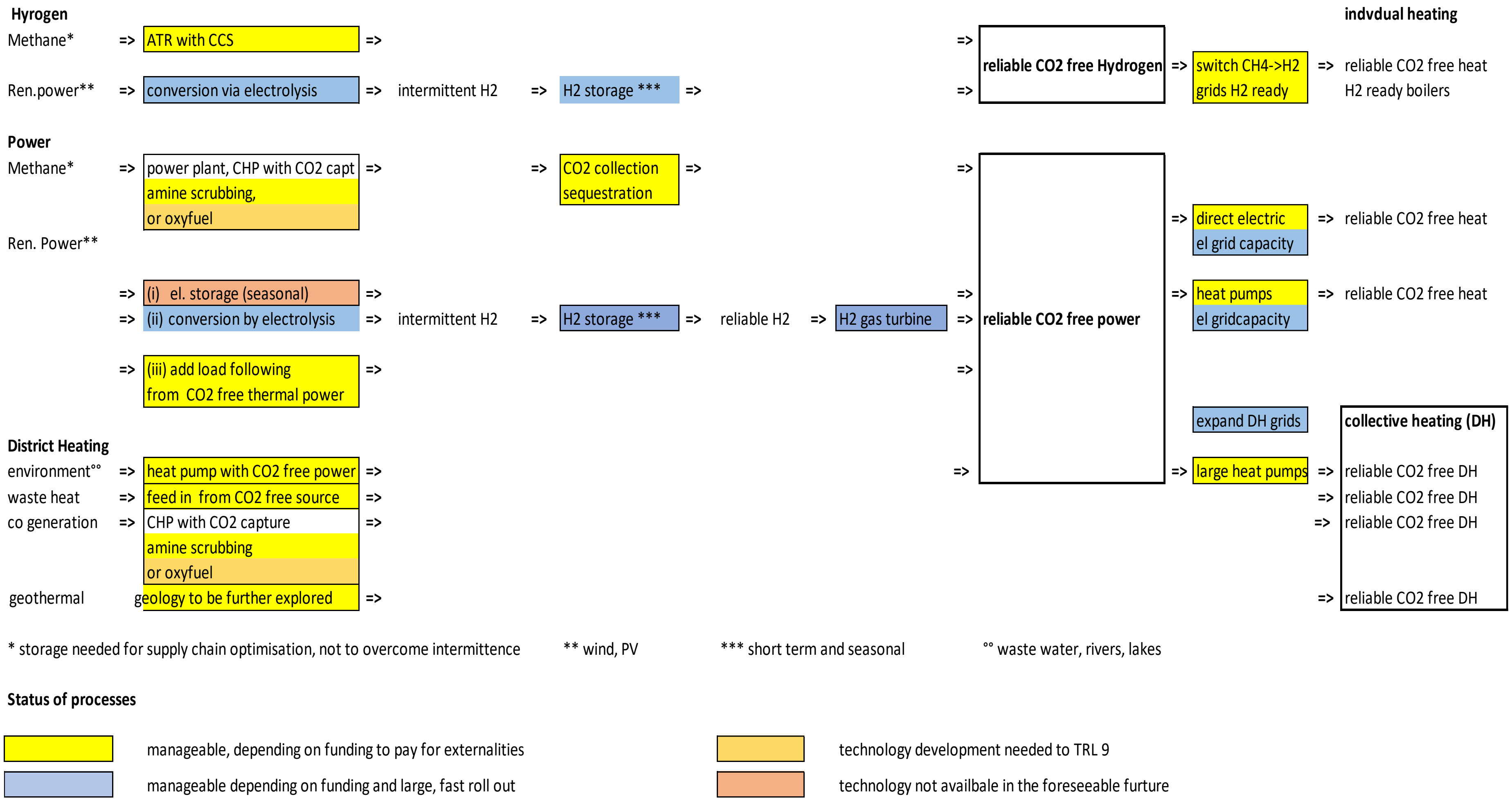
While research on direct storage of electricity continues and has led to remarkable progress in batteries, they are far away from the size needed to cover seasonal variations at scale and should not be relied on as a solution by 2045.

The use of renewables which need conversion to hydrogen (green hydrogen) is hampered by rollout restrictions, constraints on electrolysers (so far globally only 2 GW, although electrolyser giga factories which reportedly have a total manufacturing capacity of more than 30 GW/a could change that) and for producing power in hydrogen-ready power plants (the first 100% hydrogen-fired turbine with 12 MW el started operation in October 2023).

While as many avenues as possible should be pursued to achieve net zero, focussing on any single avenue with many unresolved issues is unlikely to be successful. Following the most advanced technologies and diversifying with an equal split of the CO_2-free heating of the 15 million buildings to HPs, DH and switching from methane to hydrogen seems to be the most reasonable and robust way to achieve net zero for heating in the residential and commercial sectors.

[67] Oxy-fuel combustion is the process of combusting hydrocarbon fuel in a nearly pure oxygen environment, as opposed to using ambient air

Figure 10: Supply chains for reliable, CO2 free heating



Source: author

2.4 Impact on demand for gas as primary energy and for CO2 disposal

With this approach, half of the 10 million buildings supplied with gas today would be supplied by hydrogen with some losses from conversion from methane to hydrogen compensated by better house insulation.

Five million buildings would be heated by HPs using electricity from renewables and backed up by CHPs, which would also be used for DH to the extent not supplied by geothermal and large HPs. The heat produced by the CHPs would be used in 3 – 4 million buildings and the electricity generated would go to HPs not supplied by renewable power. This solution would consume some 20 – 30 per cent less gas than the present direct gas heating for the buildings which switched to DH. Some gas will also be needed for the power supply of HPs not provided by renewables.

Overall, this leads to an estimated gas supply of 25 Bcm/a and 45Mio t CO_2/a to be collected and sequestered.

The main change is that oil heating will be replaced by higher efficiency environmental heat by HPs. Gas will no longer be used as final energy in heating but will be used in CHPs with CCS to provide reliable power for HPs with waste heat feeding into the DH systems and to produce hydrogen in ATRs to replace methane as final energy.

3. Transition challenges

Chapter 2 demonstrated that a robust and reliable pathway to net zero by 2045 would involve replacing oil heating in 5 million rural buildings with HPs, using DH for around half of the remaining 10 million buildings with the rest switching from methane to hydrogen. Using that framework, we now discuss the organisational, economic and financing elements of that transition.

3.1 Individual vs. collective action, markets vs planning

Individual HPs are the obvious and de facto only option in rural areas but their deployment will be restricted by the speed of expansion of power grid capacity on all levels (local, regional and federal). Vice versa, as the final status of power supply needed for heat pumps can be reasonably anticipated, the expansion of local and regional power systems can be planned on this basis. As explained before, input of CO_2-free power could be from CHPs with CCS feeding DHs in neighbouring urban centres or alternatively from renewables requiring a massive north-south expansion of the national grid.

The pathway to net zero heating is complex and requires the use of collective infrastructure such as DH and using the gas distribution grid converted to hydrogen (even HPs depend on the power grid and on reliable power supply). Net zero in heating and in general is overall an exercise in internalizing the externalities of climate change. Externalities are, by definition, not covered by markets but can eventually be internalized by public institutions.

In Germany there is certainly enough competition to provide heat pumps but there are bottlenecks caused by the size of the available skilled installation workforce.

Within the three avenues, only the components of HPs and H_2-ready boilers are individual components, but the HPs heavily depend on available power capacity. DH and the switch from CH_4 to H_2 have limited individual elements (heat exchanger for DH and devices to switch to H_2 from CH_4) but they depend on collective actions at the municipal level (all local distribution uses municipal streets) or at the national level, in particular transmission infrastructure and CO_2 collection and disposal, incentivizing or otherwise fostering the decarbonizing of methane (by internalizing the costs of decarbonization and establishing technical rules). Markets for CO_2-free hydrogen (in future) need an infrastructure for transport and storage as well as certification.

Planning instruments at federal and municipal levels are needed, maybe derived from the planning processes for gas and power infrastructure but driven by the net zero target and coordinated with economic instruments to provide CO_2-free heating. Implementing coordination and regulation still need further discussion. Leaving it to the market will not work in view of the many infrastructure decisions involved and the character of decarbonization as a public good.

3.2 Early action priorities

The CO_2 budget requires early action. These should be guided by the final goal of net zero by 2045 and not timidly looking at marginal cost advantages nor trying to postpone decisions waiting for cost reductions and technology breakthroughs.

Decarbonizing the heating system comes with substantial costs, which have to be paid for by the users of heat or by the public. Early decarbonization reduces pressure on the CO_2 budget and helps meet the net zero target. With only 22 years left from a CO_2 budget point of view, it rarely makes sense to split necessary action into two stages, given the necessary preparations for each stage (planning, permitting, mobilizing of work forces). Postponing action would only save on costs if substantial saving developments in the future from new technology or by learning by doing can reliably be anticipated. Delaying action will only increase the cost of the complex actions needed as the time pressure of meeting net zero by 2045 increases. Other major uncertainties include how interest rates and inflation will develop.

As Germany has obliged itself to achieving net zero by 2045, the requirement for corresponding decarbonization measures is clear. If not organised and paid by single customers, actions must be delivered by organizations and costs passed on to the customers in line with the CO_2-free heating service provided. This should allow for low-risk business models.

It is the federal government which has rightly imposed decarbonization on the country and it is the federal government which should organize it in the most economical way. Part of the solution is to use the high federal credit rating of Germany for financing, for example by creating a credit facility to finance decarbonization measures, individual or collective (more details in section 3.3). Upfront financing for the early establishment of the final infrastructure capacity with saving due to economies of scale could be financed, for instance, by municipal companies and later recovered from customers. Similar measures could be taken at the federal level, such as installing CCS. As customers cannot escape decarbonization, demand is secured.

In many cases actions for the decarbonization of the heating system start with preparatory work such as legislation and regulation, planning, and technology development. These are a modest portion of the cost but will avoid delays, bottlenecks and time pressures later.

3.2.1 At the municipal level

Municipalities are major actors in the provision of infrastructure ready for decarbonization. While individual situations differ, some guiding principles apply to municipal actions:

- Early delineation of areas which will not be reached by gas/hydrogen nor DH. Here the early roll out of HPs to replace oil heating (5 million buildings) should be fostered and all the necessary power grid reinforcement must be addressed early.
- In areas with high density of heat demand, upgrade and expansion of DH grids should be planned and implemented early (and with an obligation to link to DH by 2045 in order not to undermine the economics of DH).
- DH should use CO_2 -free heating such as geothermal, large HPs, and waste heat from industry.
- Establish the potential of CHP with CCS as a reliable heat supply supported, where possible, by heat storage and plan for the electricity supply of HPs in the surrounding areas by power from CHPs.
- Between DH and the HPs in rural areas, the remaining 550,000 km of gas distribution pipelines can be switched from methane to hydrogen for space heating and used in commercial and industrial sectors. Little action is needed in the gas distribution grid. However, an early announcement where and when the switch from methane to hydrogen will happen is needed so that older boilers can be switched to H_2-ready boilers in good time or to make sure that existing boilers can be retrofitted to H_2.

3.2.2 At the federal level

Certain issues have to be dealt with at the federal level:

- Back up for reliable power capacity, frequency and voltage management. This will be done by the NEP (planning process of the power transmission grid) and by organizing a national reserve capacity to bridge deficiencies of renewables (by administrative acts or by organizing a market for back-up power).
- As decarbonized hydrocarbons are needed to bridge intermittent renewables, a CCS scheme has to be established early at the national level, including the economic basis for decarbonization (CO_2 taxes, subsidies) and building a CO_2 collection system and dealing with sequestration.
- Also, the design of gas and hydrogen systems including placement of ATRs and use of storage for methane or hydrogen should now be discussed.
- Technology demonstration by further pilot projects for decarbonizing fossil power to diversify technology approaches (not betting on hydrogen-based thermal power generation only).
- More drilling to explore the geothermal potential in the south and southwest of Germany which, if successful, would ease the need for north-south expansion of the power grid.

3.2.3 Lead by the federal level

Many decarbonization options for heating depend on action at the federal level, such as providing enough reliable backup power capacity available for HPs and early availability of a CO_2 collection system for early abatement of CO_2. As these elements are compulsory, they should be a priority for action at the federal level to be ready for the municipal level, which depends on them.

3.3 Financing

The German parliament, government and constitutional court have imposed on Germany and its citizens an obligation to achieve net zero by 2045. While in the end this will impose costs of decarbonization on its citizens, it is fair to expect that the government will make every effort to keep costs low, for instance by using Germany's high credit rating to ease and reduce the costs of borrowing, as mentioned earlier. Using the creditworthiness of the Federal Republic through a special fund (Sondervermögen) or guarantees to support early investment in decarbonization should not be a problem as the companies or municipalities could use the income from selling CO_2 free energy as collateral. This borrowing would be backed by assets and future income from decarbonization measures to be paid by their customers. This contrasts with the Klima- und Transformationsfond/KTF) of €177 billion which is federal debt. By its ruling of 15 November 2023, the constitutional court declared the rededication of €60 billion credit authorisation left from fighting the COVID crisis to the KFT to be unconstitutional.

As most of the measures are on a collective level (except for installation of HPs and H_2-ready boilers) investment will be organized by private or municipal companies which will pass the costs on to the heating customer:

- For power infrastructure by tariffs (charged for the installation of HPs or cross-subsidised by everyone) supervised by BNetzA (the Federal Network Agency).
- For power by market prices for CO_2-free electricity or by including the costs of decarbonization.
- For DH
  - for infrastructure: it will be included in the capacity charge of the tariff.
  - for the heat: the costs of CO_2-free heat will be reflected in the commodity charge.

The tariffs will be supervised by BNetzA and the Federal Cartel Office to prevent abuse of local monopoly power.

- For hydrogen instead of CH_4 by the market price for CO_2-free hydrogen (if there is any market) otherwise by the market price for methane or for electricity plus conversion costs.

- For the CO_2 collection and disposal system the costs will be borne by its users which can pass them on via the price of decarbonized energy to the heating customers.

In any case, companies organising CO_2-free heating can pass on their delivery costs, and their customers have little choice, so it looks like a sound business model with low risks.

In general, municipal or private companies will have more bargaining power for financing, to acquire equipment and skilled labour than individual heating customers, for example, for HPs. Financing is easier for aggregators of demand as individual risks are cancelled out.

3.4 Measures to ensure robustness

Robustness is needed both in terms of the pathway to net zero by 2045 as well as for the functioning of the new heating system. We look first at diversification and use of existing investment as contributions to robustness to achieve the target 2045 and then offer thoughts on the robustness of the heating system achieved by 2045.

3.4.1 Diversification on the way to net zero

Fast parallel roll-out of infrastructure multiplies possible reduction of CO_2 emissions. A monolithic approach, based on one technology alone, would create an uncertain pathway, where underperformance and deficiencies would have to be carried forward and resolved later. Following three parallel approaches to decarbonizing heating offers basic diversification, as each approach draws on different factors reducing demand compared to a non-diversified approach. (i) HPs require manufacture, skilled labour for installation plus enlargement of the power grids in rural areas together with back-up power. (ii) DH requires the laying of pipelines in urban centres plus skilled labour to install heat exchangers; on the input side DH needs diversified inputs such as large heat pumps, drilling for geothermal and CO_2-free CHPs run on hydrogen or methane plus decarbonization by oxyfuel or amine scrubbing. (iii) Methane to hydrogen switching requires the production of H_2-ready boilers. Substantial additions to ATRs and salt caverns for storage of hydrogen are needed upstream from end users.

This sort of diversification will increase robustness as it will allow further diversification within each individual approach, such as promoting various ways of decarbonizing power production. If any of the pathways fails, it can be compensated by accelerating other more successful ones.

3.4.2 Use of existing investment

Using as much existing investment as possible makes sense for economic reasons but also enhances the chances of success. Any additional investment comes with coordination, permitting, construction and operational risks, which can be reduced by using existing investment. Maintaining existing infrastructure investment can also serve as a reference point amidst many simultaneous changes.

What existing investment can be used?

- There is little or no alternative to using the existing gas storage facilities filled with methane until 2045 to provide primary energy to cover seasonal and temperature-induced heat demand. The system has worked well over decades and there is no reason to jeopardize this out of paradigmatic opposition to natural gas.

- Keep the gas transmission and storage system for reliability and security of supply reasons to bring enough primary energy to the points of conversion into CO_2- free electricity or hydrogen. This will reduce investment in the power grid to overcome north-south power bottlenecks and is an alternative to a national hydrogen transmission system (with high compression needs[68]) and a complicated build up. This implies conversion from methane to hydrogen close to the point of consumption.

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[68] To transport the same energy as Hydrogen instead of as Methane – everything else being equal – needs ca 3.5 times the compression capacity and energy. In addition, hydrogen – at present – would need piston compression instead of radial compression for methane.

- Keeping the existing gas distribution system is a 'no brainer', as the system needs very little maintenance, most of it being plastic pipelines. This may serve as a backup if DH roll-out is slower than anticipated.
- Use existing power plants (or essential parts thereof like boilers, turbines, generators, high voltage equipment) but adding decarbonization equipment like amine scrubbing of the exhaust stream of fossil power plants or for oxyfuel using oxygen instead of ambient air for combustion. This method needs boilers for coal fired plants or a new turbine design for gas turbines but keeps the electric and other local equipment and the connection into the fuel supply and power delivery infrastructure. Promoting pilot projects in Germany on decarbonizing power plants is essential for net zero by 2045 in Germany but also offers potential for technology export.
- While energetic refurbishment of the building stock is unavoidable, switching older gas-heated buildings to hydrogen or using DH addresses the necessary CO_2 reduction and allows for taking energy saving measures at a later more convenient time.

3.4.3 Robustness of the heating system

Security of gas supply - beyond supply from the global market - to the point of combustion or conversion with CCS can be secured through methane storage and the continued working of the gas transmission system.

Except possibly for the switch from methane to hydrogen (depending on the location of the ATRs) all supply of decarbonized energy for heating is on a regional/local level with little spillover to the national level in case of interruptions. Reliability of power supply can be achieved by power from local/regional CHP plants feeding heat into local DH systems and providing reliable power for heat pumps in the surrounding area. The gas switch is secured by existing large gas storage and a working transmission system. Installation of large enough ATR capacity ensures reliable supply of the converted methane. Reducing the number of heat pumps to those needed and otherwise sourcing local decarbonized energy supply avoids the power system alone handling accumulated risks.

4. Policy debate on decarbonizing heating[69]

Germany's governing 'traffic light'[70] coalition has put the implementation of the CPA at the heart of its policy agenda. It has been engaged in this area with acts passed on the amendment of the Building Energy Act (GEG), an act on municipal heat planning and a draft amendment of the CPA and measures to implement the CPA in 2023. However, this legislation is focussed on renewables and heat pumps without an overall concept nor any assessment about whether the enacted and proposed measures will meet the CPA objectives.

Discussion of the GEG

When the draft amendment of the GEG became public[71], it drew public criticism, which was also voiced in the first reading of the bill in the Bundestag on 15 June 2023. A major element in the draft was the obligation on households to install a heat pump when replacing existing heating systems from 2024. Also, the sequencing of considering legislation on heating in buildings before planning municipal heating was considered wrong. In its final version adopted by the Bundestag on 08.09.2023 and by the Bundesrat on 29.09 2023, the obligation to install heat pumps when replacing the heating for existing buildings was postponed until after municipal heating plans have been issued (these plans are due by 30 June 2026/2028 for large/small towns).[72] The new version offers some rather theoretical exceptions to installing a heat pump and a wide range of support, linked to social criteria. This postponement took the immediate heat out of the GEG discussion.

[69] This section reflects the debates in parliament up to January 2024
[70] Red = Social Democrats, yellow = liberals, plus green party
[71] BMWK (2023, May 17)
[72] Schiller, K. (2023, September 29)

The municipal heat planning act

On 16 August 2023, the Cabinet approved the draft act on municipal heat planning[73] stipulating that municipalities with more than 100,000 inhabitants would have to issue a heating plan by 30 June 2026 and municipalities with between 20,000 and 100,000 inhabitants by 30 June 2028. After discussion at the Bundesrat on 29 September 2023, a slightly modified draft dated 6 October 2023[74] was submitted to the Bundestag for first reading on 9 October 2023, which was then transferred to the committee for housing, urban development, construction and municipalities. At its public hearing on 16 October 2023, experts criticised the draft for its lack of making the municipal heat planning binding but forcing municipalities to acquire excessive data for the heat planning. According to the draft, areas for exclusive application of heat pumps must be defined (§14) but without obligation to use a specific kind of heating (§18,2). Several utilities saw a need to triple or quadruple the capacity of local power grids to accommodate increased demand by HPs. At the final reading on 17 November 2023, the conservative opposition (Christian Democrats) requested that the government withdraw the draft act and replace it with a realistic, open-technology heat planning act. The government's majority in parliament rejected this demand and adopted the act on municipal heat planning.

The draft second amendment of the CPA

On 21 June 2023 the Federal Government submitted a *second draft amendment of the Climate Protection Act* (following the 13 June 2023[75] cabinet version) to parliament.[76]

The GHG reduction targets for 2030 and 2040 and the net zero GHG target for 2045 remain. The focus is less on achieving the targets set in the past but more on the total projected emissions in the future. While the sectoral targets remain until 2030, only total emissions targets are given thereafter. Responsibility of the respective ministries to keep within the annual sector limits is replaced by an overall responsibility of the cabinet to keep within the overall targets. The independent expert council for climate issues (Expertenrat für Klimafragen) is given a more important role.

As an opener to CCS, under §3b, the Federal Government is entitled to determine targets for technical sinks (for CO_2 by CCS) for the years 2035, 2040 and 2045 within the framework of unavoidable emissions, a measure apparently aimed at CO_2 emissions from the cement industry. It is unclear if this will also cover unavoidable CO_2 emissions due to the slow roll-out of renewables.

The draft act was discussed in a first reading in the Bundestag on 22 September 2023 and then referred to the committee for climate protection and energy.[77] In a public hearing on 8 November 2023, objections focused on the dilution of responsibility to the cabinet at large from respective ministers, the removal of sector specific targets after 2030, and the removal of the obligation to take corrective action triggered by missing those targets.[78]

Climate Protection Program

On 13 June 2023,[79] the Federal Government also presented its *Climate Protection Program (Klimaschhutzprogramm),* which was submitted to the Expert Council. In its report of 22 August 2023,[80] a total of 135 measures were listed (generic and cross-sector: 23/Energy: 7/Industry: 17/Buildings: 13/Traffic: 50/Agriculture: 6/LULUCF: 19). The expert council criticized the lack of a consistent and coherent approach and of an integrated action plan.[81] While the single measures proposed sound reasonable, they lacked hierarchy and several measures lacked documentation.

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[73] Press release: BMWSB (2023, August 16, i) draft text: BMWSB (2023, August 16, ii)
[74] Deutscher Bundestag (2023, October 6)
[75] Text draft amendment of the CPA: BMWK (2023, June 13, ii)
[76] Press release: Presse- und Informationsamt der Bundesregierung (2023, June 21)
[77] Deutscher Bundestag (2023, September 22)
[78] https://www.bundestag.de/dokumente/textarchiv/2023/kw45-pa-klimaschutz-klimaschutzgesetz-974134
[79] BMWK (2023, June 13, i)
[80] Expertenrat für Klimafragen (2023, August 22)
[81] Expertenrat für Klimafragen (2023, August 22)

5. Conclusions

While the CPA has set a target of net zero by 2045, it is open about how this target should be approached. The governing coalition has made the implementation of the CPA a cornerstone of its political programme. It does, however, lean heavily towards renewable power and specifically, for the heating sector to switch from oil and gas heating to heat pumps in 15 million buildings to decarbonize their heating. This approach is reflected both in recent legislation (GEG and municipal heat planning 2023) and in the binding power grid planning (NEP 2023).

While the calculations in OIES paper ET 13[82] show that an all-renewable approach will not deliver net zero by 2045, this paper shows that adding a heating system based predominantly on heat pumps will not change that assessment. In order to be effective by 2045, an all-HP system would require a substantial thermal power capacity equipped with CCS as back up for renewable power, challenging the present government's reluctance to address CCS. It would also run into the installation constraints of HP (15 million HPs to be installed in 22 years, compared to 260,000 per year now) as well as limits to local power grid upgrades, especially in cities. It would also give up the benefits of using DH with CO_2-neutral inputs and of using existing gas distribution grids for switching to hydrogen. As CCS is unavoidable to reach net zero by 2045, the approach to decarbonizing the heating sector should include CCS as part of the technology mix needed to reach net zero by 2045. Providing for about equal shares (5 million buildings each) for HPs, DH and switching from methane to hydrogen, offers a robust approach with a realistic chance of reaching net zero by 2045.

A shift in paradigm is therefore needed that moves away from a bet on renewables plus HPs and energy efficiency only to an approach which includes fossil fuels with sequestration as the third major pillar of decarbonization. The request to stop all fossil fuels ignores that renewables plus HPs and energy efficiency alone are not sufficient to cover final energy demand or heating specifically by 2045 and beyond. While fossil fuels cannot be used as final energy without abatement, which is not possible for heating in the residential and commercial sectors, fossil fuels like gas with abatement (CCS) must play a role as primary energy supply to meet short term demand peaks, seasonal variations and the foreseeable shortfall in the roll out of renewables. The earlier this is acknowledged and reflected by German policy, the better the chance that Germany reaches net zero by 2045.

[82] https://www.oxfordenergy.org/wpcms/wp-content/uploads/2022/06/Achieving-net-zero-plus-reliable-energy-supply-in-Germany-by-2045-%E2%80%93-the-essential-role-of-CO2-sequestration-ET13.pdf

List of abbreviations and acronyms

ATR	autothermal reformer
Bcm	billion cubic meters
BEV	battery electric vehicles
BNetzA	Germany's Federal Network Agency (*Bundesnetzagentur*)
CCS	carbon capture and storage/sequestration
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CPA	Germany's Climate Protection Act of 2019, amended in 2021
DAC	Direct Air Capture
DH	District Heating
DSM	Demand Side Management
DVGW	Technical association of the German gas and water industry (*Deutscher Verein des Gas – und Wasserfaches*)
el	electric
ETS	Emissions Trading System
EU	European Union
GEG	German Buildings Energy Act (*Gebäudeeenrgiegesetz*)
GHG	Green House Gas
GT	gas turbine
GW	gigawatt
GWh	gigawatt-hour
H_2	hydrogen
HH	household *(Haushalt*)
HP	heat pump
HVAC	high voltage alternating current
HVDC	high-voltage direct current
ICE	internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
km	kilometre
kWh	kilowatt-hour
LULUCF	land use, land-use change and forestry
m^3	cubic metre
mln	million
Mt	million tons

MW	megawatt
MWh	megawatt-hour
NDC	Nationally Determined Contributions
NEP	Germany's grid development plan (*Netzentwicklungsplan*)
OIES NG	Oxford Institute for Energy Studies natural gas programme
OIES	Oxford Institute for Energy Studies
PA	Paris Agreement
PJ	petajoule
PV	photovoltaic
t	ton
th	thermal
TRL	technological readiness level
TWh	terawatt-hour

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