ANNEX
57

FLEXIBILITY BY IMPLEMENTATION OF HEAT PUMPS IN MULTI_VECTOR ENERGY SYSTEMS AND THERMAL NETWORKS

IEA Heat Pumping Technologies Annex 57

FLEXIBILITY BY IMPLEMENTATION OF HEAT PUMPS IN MULTI-VECTOR ENERGY SYSTEMS AND THERMAL NETWORKS

Task 1 summary report

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Executive Summary

The IEA World Energy Outlook 2022 and 2023 show an increase in the electrical consumption and productions towards 2030 and 2050. An increase in the electrical consumption is also the trend shown in the different country reports. Most of the increase in the demand for electricity is caused by the transition away from fossil fuels, mainly in the industry but also in the transport sector and in the production of PtX fuels. PtX fuels like hydrogen is creating an extra demand which is a factor 3 higher than today.

In the Net Zero by 2050 Scenario, district heating and cooling (DHC) is expected to cover 20 % of the global space heating needs by 2030, a rise from 15 % in 2020. 350 million building units connected to district energy networks by 2030 are going to provide about 20 % of the space heating needs.

District heating in general and heat pumps connected to the grids in particular are predicted to play a key role in the energy grid and the energy supply for the future. With the implementation of district heating, it is possible to cover up to 50 % of the heating demand in Europe, and heat pumps can deliver around 25 % of the energy to the district heating grid. The Heat Roadmap Europe 4 scenarios with a larger share of district heating in the energy system show that CO_2 emissions can be reduced with more than 70 % compared to the current situation.

The simulations show that heat pumps in district heating grids can cover between 16 % and 38 % of the district heating production in Europe.

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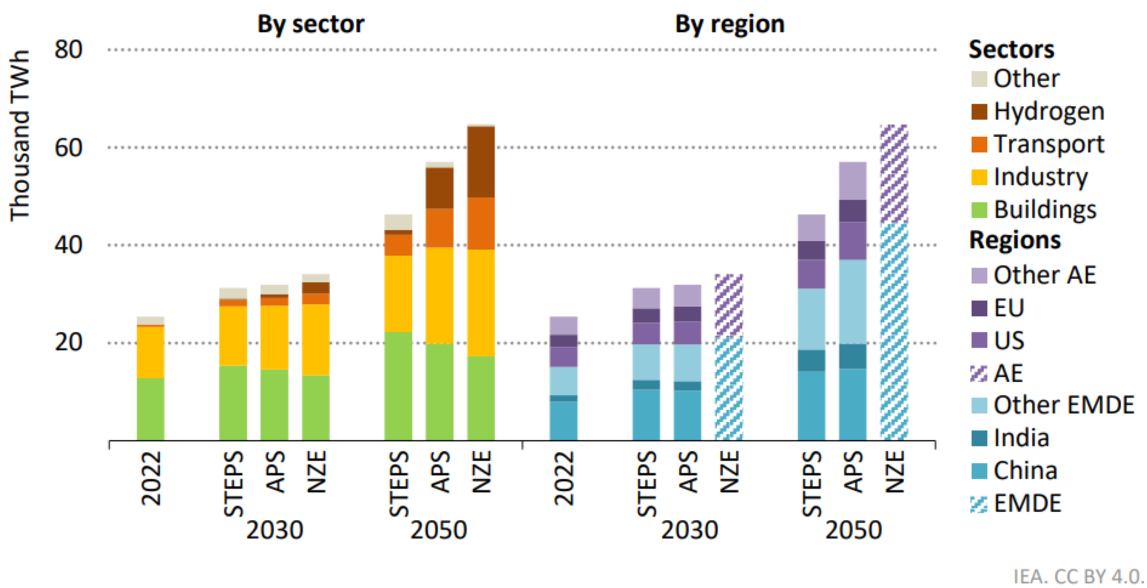
1. Introduction

The IEA World Energy Outlook 2022 and 2023 show an increase in the electrical consumption and productions towards 2030 and 2050. Most of the increase in the demand for electricity is caused by the transition away from fossil fuels, mainly in the industry but also in the transport sector and in the production of PtX fuels. PtX fuels like hydrogen is creating an extra demand which is a factor 3 higher than today.

The Announced Pledges Scenario (APS) shows how the future would be different if all countries were to hit their aspirational targets, including national and regional net zero emissions pledges, on time and in full.

In the updated Net Zero Emissions by 2050 (NZE) Scenario, district heating and cooling (DHC) is expected to cover 20 % of the global space heating needs by 2030, a rise from 15 % in 2020.

All the projections show an increase in the electrical consumption and the productions towards 2030 and 2050.

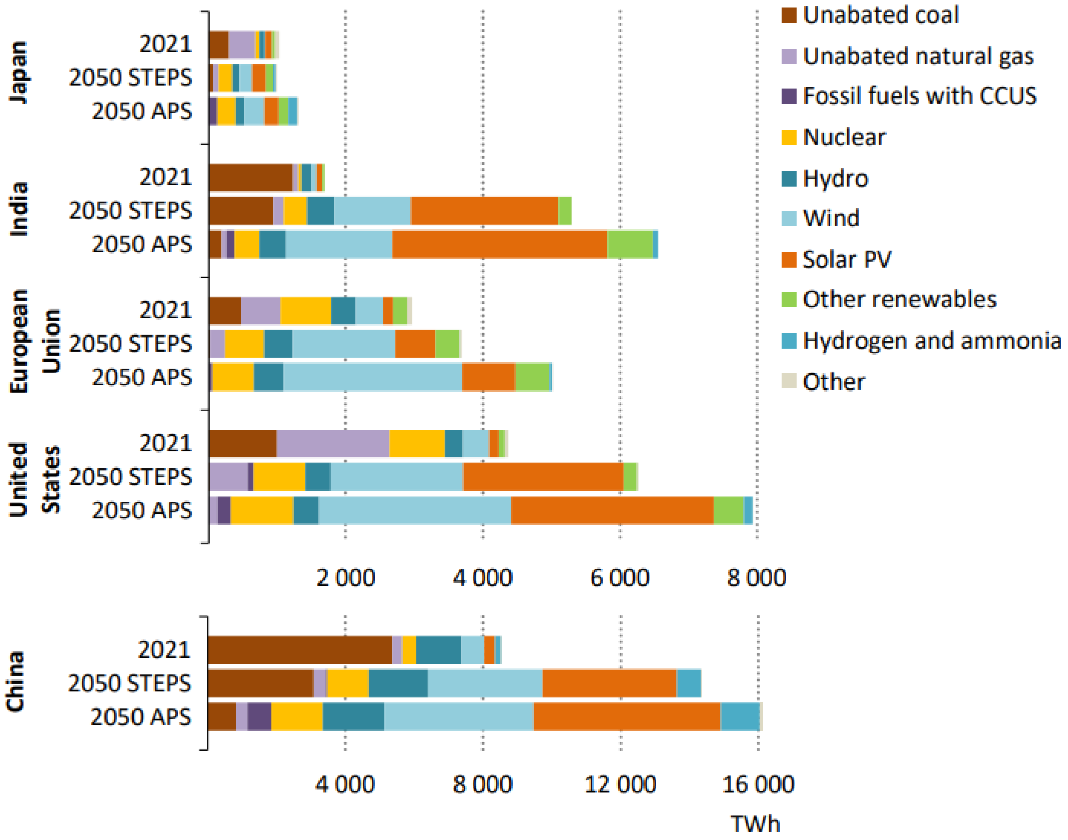


Emerging economies see robust electricity demand growth reflecting population growth and rising incomes; EVs and hydrogen production add to electricity demand growth

Note: EMDE = emerging market and developing economies; AE = advanced economies; US = United States; EU = European Union.

Figure 1 Electricity demand by sector and region, and by scenario. (IEA Outlook 2023)

The capacity of renewables expands 2.4-fold in the STEPS scenario by 2030, 2.7-fold in the APS scenario, and triples in the NZE Scenario. Almost 95 % of this growth are in the form of solar PV and wind. The share of wind and solar PV in total generation is set to rise from 12 % to about 30 % by 2030.

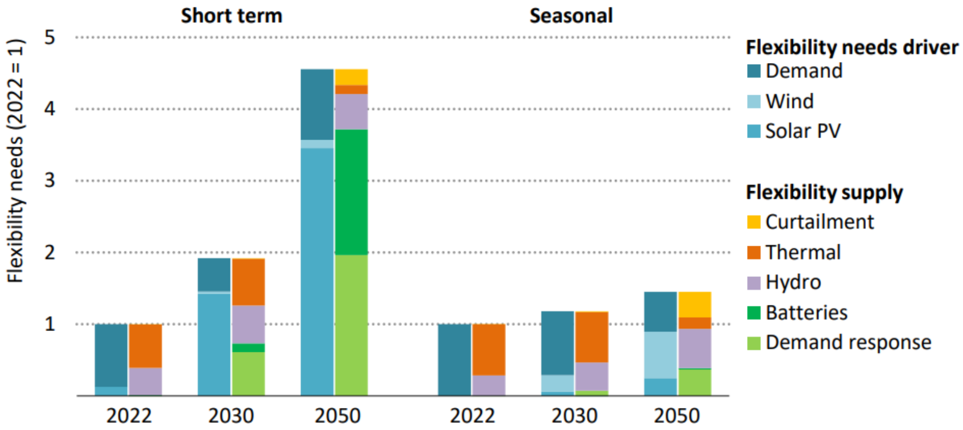


Electricity supply is set to shift away from unabated fossil fuels in all major markets, as renewables, nuclear, hydrogen, ammonia and carbon capture scale up

Note: Other renewables includes bioenergy and renewable wastes, concentrating solar power and marine power. Other includes non-renewable waste and other sources.

Figure 2 Electricity generation by source, key region, and scenario, 2021 and 2050. (IEA Outlook 2023)

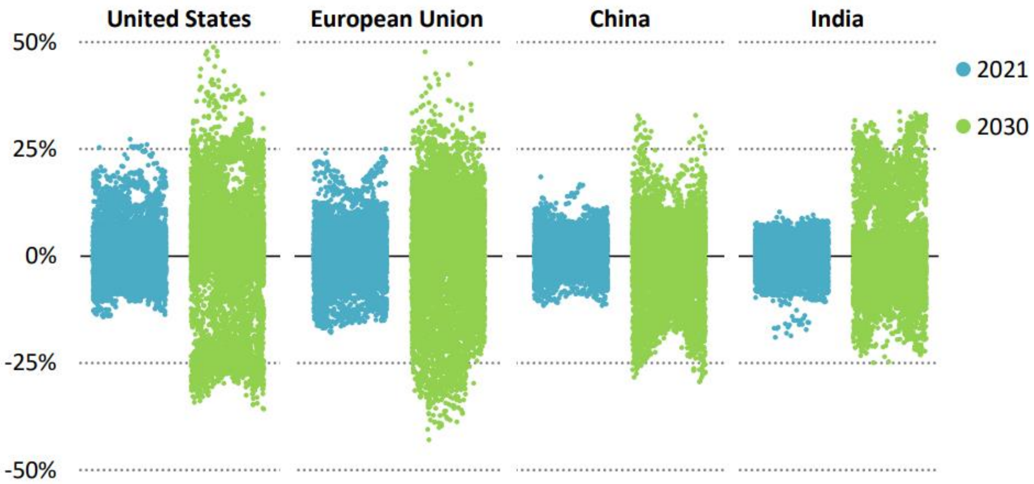
In the STEPS scenario, short-term power system flexibility needs to more than tripled globally by 2050 relative to today. Global needs for seasonal flexibility increase less sharply: they rise by nearly 20 % towards 2030 and 45 % towards 2050 in the APS. The fast-rising share of solar PV emerges as the key factor increasing short-term flexibility needs: wind is less variable in the short term, but it can vary significantly across weeks or seasons. Moreover, it becomes an important driver of seasonal flexibility needs as its share increases in power systems across the world. Patterns of wind and solar output can be complementary to variations in electricity demand, but their rising share tends to increase overall system flexibility needs.



Short-term needs increase significantly, mainly due to solar PV, with batteries and demand response emerging as crucial suppliers of flexibility; seasonal needs rise less sharply

Notes: Flexibility needs are computed for 2030 and 2050 taking into account changes in electricity supply and demand and weather variability over 30 historical years. Demand response includes the flexible operation of electrolysers.

Figure 3 Global power system flexibility needs and supply in the APS. (IEA Outlook 2023)



Hour-to-hour flexibility needs rise significantly by 2030 in major markets, driven by increasing shares of variable renewables and changes in demand patterns

Note: Flexibility needs are represented by the hour-to-hour ramping requirements after removing hourly wind and solar PV production from hourly electricity demand, divided by the average hourly demand for the year.

Figure 4 Hour-to-hour flexibility needs in the United States, European Union, China, and India in the APS, 2021 and 2030. (IEA Outlook 2023)

1.1. District Heating Potential

In the Net Zero by 2050 Scenario, district heating and cooling (DHC) is expected to cover 20 % of the global space heating needs by 2030, a rise from 15 % in 2020. 350 million building units connected to district energy networks by 2030 are going to provide about 20 % of the space heating needs.

Nearly 90 % of district heat globally was produced from fossil fuels in 2021. To fully play its role in the transition, the DHC system requires significant efforts to improve the energy efficiency of existing networks rapidly, integrate renewable heat sources (such as bioenergy, solar thermal, heat pumps, and geothermal), integrate secondary heat sources (such as waste heat from industrial installations and data centres), and to develop high-efficiency infrastructure in areas with dense heat demand.

Today, district heating meets about 12 % of the final energy use for space and water heating for households as well as service and industry sectors. District heating in general and heat pumps connected to the grids in particular are predicted to play a key role in the energy grid and the energy supply for the future.

With the implementation of district heating, it is possible to cover up to 50 % of the heating demand in Europe, and heat pumps can deliver around 25 % of the energy to the district heating grid.

The Heat Roadmap Europe 4 scenarios with a larger share of district heating in the energy system show that CO_2 emissions can be reduced with more than 70 % compared to the current situation.

2. Overall Summary Aalborg, Denmark

Aalborg University has within the project made an extensive market research for large-scale heat pumps to analyse where the trends are heading.

Aalborg University has also made simulations with the EnergyPlan tool of the potential of future district heating demands for several countries, The simulations show the level of heat pump capacity possible in the system as well as the share and production from heat pumps.

2.1. District Heating Demand in the Future

The table below summarizes the results of the simulation regarding large-scale heat pumps and district heating. The table shows the thermal capacities of large-scale heat pumps (LHP), annual heat production and share in district heating (DH), and both annual and average operation times within the heating season from October to April for different countries.

Tabel 1. Simulation results of large-scale heat pumps and district heating. (Aalborg University)

		AT		DE		DK		ES		FR		IT		SE	
	unit	BASE	LW	BASE	LW	BASE	LW	BASE	LW	BASE	LW	BASE	LW	BASE	LW
HP Capacity DH	MWe	450	450	3500	3500	600	600	2500	2500	3750	3750	3000	3000	900	900
HP operation	%	22%	26%	28%	34%	37%	41%	24%	28%	36%	39%	24%	26%	34%	36%
HP operation in HS	%	39%	43%	47%	54%	68%	68%	41%	45%	61%	65%	39%	49%	49%	51%
HP DH share	%	16%	19%	16%	21%	24%	27%	21%	25%	35%	38%	17%	19%	25%	27%
HP DH prod.	TWh	3.5	4.2	34.6	42.0	7.9	8.6	21.3	24.5	47.5	51.6	24.8	26.9	10.7	11.4

The district heating production is calculated for the 2030 and 2050 scenarios. In the scenario simulations, the sources are simulated. The simulations show that a share of heat pump production has increased from current time to 2030 and 2050. Moreover, fuel boilers and CHP has been phased out.

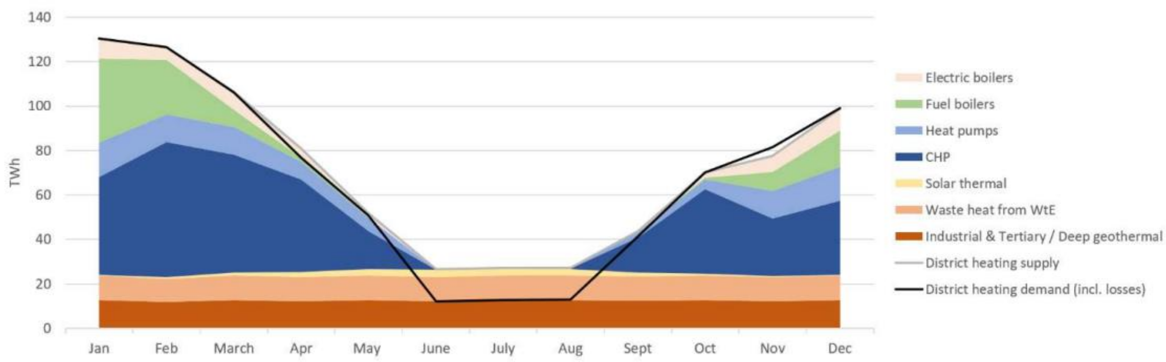


Figure 5 District heating production mix presented monthly, 2030 scenario. (Aalborg University)

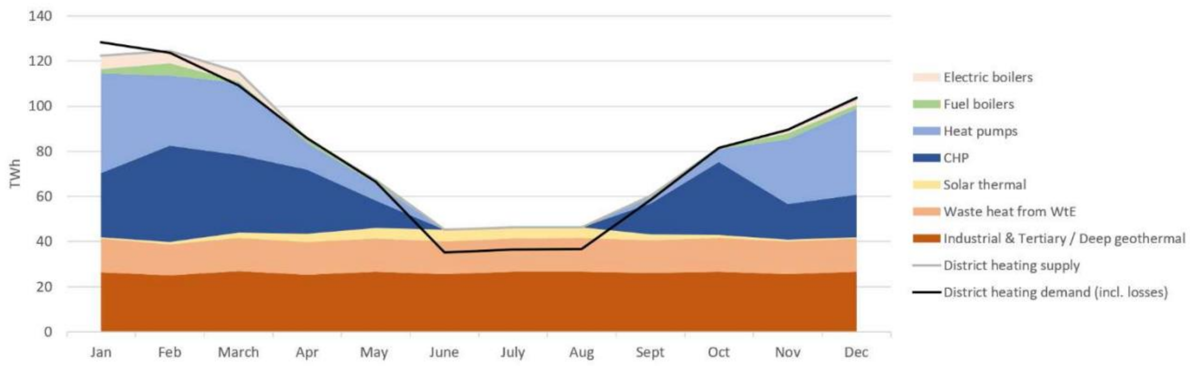


Figure 6 District heating production mix presented monthly, 2050 scenario. (Aalborg University)

The district heating level is assessed for the 27 EU countries towards 2050. The simulation shows that the extent of district heating increases in most countries.

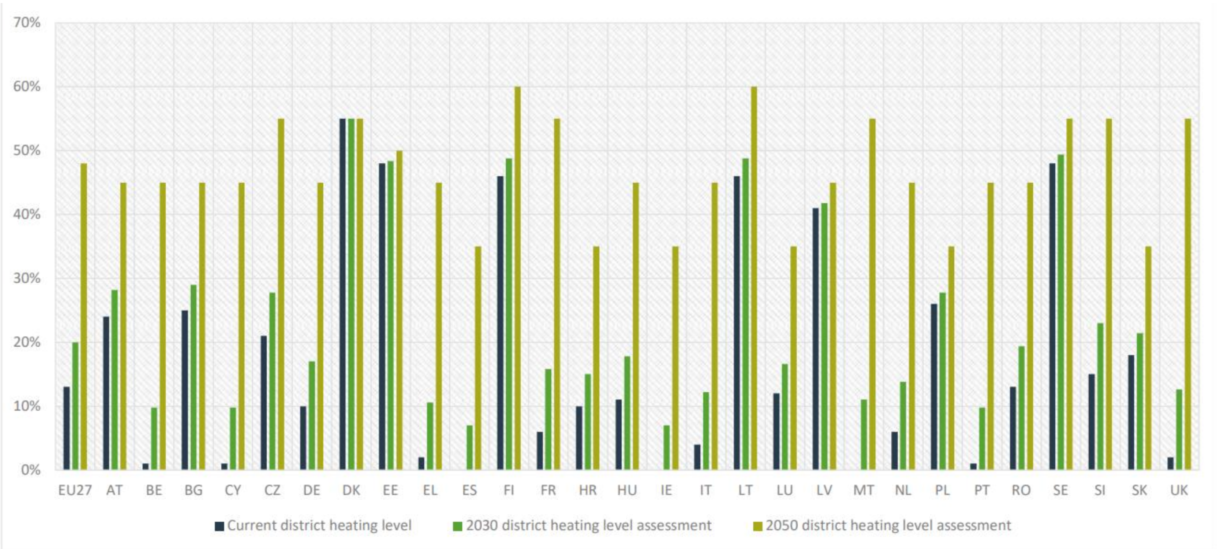


Figure 7 District heating levels towards 2023 and 2050 for heating buildings for EU27, pr. EU country and UK. (Aalborg University)

3. Summary Sweden

3.1. District Heating Demand Now and in the Future

The Swedish district heating market is mature with a market share for space heating and domestic hot water (DHW) of almost 60 %. Today, 285 of the 290 municipalities in Sweden have district heating grids (Lindahl, Wennerlund, 2018). As shown in Figure the delivered district heating in Sweden has been relatively stable during the last 15 years.

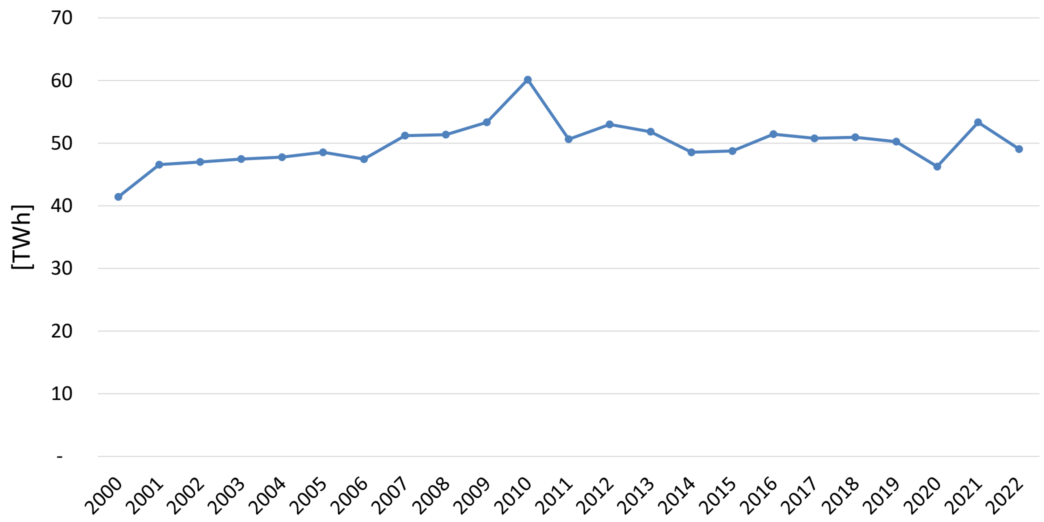


Figure 8 Delivered district heating in Sweden (Energiföretagen, 2023)

The Swedish Energy Agency report “Scenarier över Sveriges energisystem 2023” (Energimyndigheten, 2023) concludes that the production of district heating in Sweden is largely driven by the heating demand in the residential sector but also in industry. In the short term, the demand for district heating varies in terms of temperature, and in the long term, it varies in terms of population growth and how district heating competes with other heating sources.

In the 2050 scenarios, the district heating production is foreseen to slowly increase to approximately 66 TWh in 2050, with only small variations depending on different scenarios.

3.2. Electricity Demand Now and Then

The Swedish transmission system operator Svenska kraftnät has analysed and proposed scenarios for the Nordic and northern European electricity systems until 2050 (Brunge et al., 2021). The future scenarios are divided into four different categories, see Figure . The common denominator for the given scenarios is an increasing demand of electricity and a supply of electricity to enable the transition towards an energy system independent of fossil fuels.

In terms of generation (and dependent on which of the four scenarios is being observed), hydropower and thermal power are assumed to be relatively constant throughout the different analyses. Nuclear power is assumed to remain at current level or to decrease down to zero. Wind power on land and solar power are expected to grow, but only a little. The strongest variation, both in relative and absolute terms, is assumed to occur in offshore wind power. One key component in this future energy system is the sector coupling between electricity and gas, specifically hydrogen. It is stated that electricity-based production of hydrogen may play a pivotal role in the energy system, substituting fossil fuels in the transport sector and the industry sector. It is also expected to enable the expansion of intermittent renewable electricity generation with increased ability to balance the power grid. Furthermore, it is expressed that this infrastructure will be associated with the industry, and with a significant increase of the potential to introduce more flexibility to the energy system.

Some examples of new or increasing electricity demands are that the mining and minerals company LKAB together with the steel company SSAB and the energy company Vattenfall have the ambition to manufacture steel using hydrogen instead of coal and coke, using the HYBRIT technology.

Another example is the increasing demands of data centres, which is included as a unique label in Figure 9, and according to citing's by Koronen et al. (2020), the share of global electricity demands for data centres is estimated to about 1 %. Furthermore, the electrification of the transport sector is assumed to generate an increased demand as well, this is also specifically estimated in Figure . Not only electric vehicles are considered in this context but also the option to manufacture liquid fuel such as methanol in bio-refineries.

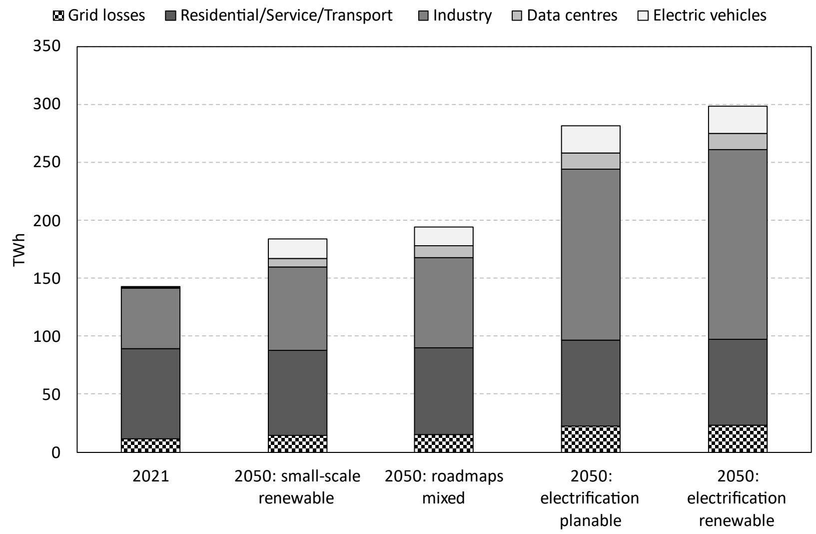


Figure 9 Electricity demand projections for Sweden in four different scenarios, according to (Brunge et al., 2021). Graphical representation based on supplementary spreadsheet file to the cited report.

3.3. Perspectives on the Power Grid

When discussing the energy markets in Sweden, it is relevant to mention the Swedish power grid, particularly since the focus is on the power-to-heat sector coupling. Oftentimes, electricity receives a relatively large focus in the public discourse about energy in general, allocating smaller relative shares to other components of the energy system. Even if a strong emphasis is put on electricity in the energy system discourse, it may not be a large concern since the electricity component of the energy system consists of many interesting layers of complexity. Some of which are discussed a bit further in the following chapters. In this regard, general information about the capacity situation is given in the section "The capacity situation", while the section "Capacity markets" provides general information about the capacity markets in Sweden.

3.4. The Capacity Situation

The expansion of power grids is associated with a processing time in the size of up to a decade. Hence, a capacity challenge emerges as society is changing quickly. Some examples of changes include (1) the energy transition towards sustainability, (2) changes in composition of electricity demand, with new electricity demand within the transport and industry sectors for instance, (3) increasing population, (4) greater degree of people living in urban areas, and (5) an aging infrastructure of the existing power grid. The combined factors have resulted in growing pains for several regions in Sweden regarding economic growth since a tendency to deny connection of new demand and to deny increase from existing demand have occurred due to the lack of capacity. This acts as an inhibitor for economic growth and to some degree the transition into a more sustainable society.

The Swedish Energy Markets Inspectorate was commissioned by the Swedish government to assess the capacity situation. The outcome of this work is documented by Axberg et al. (2020), and this section briefly summarises the results of the report.

The content of the report focuses among others on the extent of capacity limitations and the demand to changes in regulations. The report suggests a set of actions deemed necessary to alleviate the capacity issues. These actions include:

- Improved planning and coordination in connection with electric grid development
- Improved connection processes
- A more cost-effective operational reliability
- Increased use of flexibility services for more efficient electric grid utilization
- Efficient pricing to counteract large margins in capacity demands of existing consumers in the electric grid.

When reviewing the plans for investments into the transmission grid (220/400 kV), the regional grid (70-130 kV), and the local grids (<20 kV, 400/230 V), an extensive expansion is anticipated during 2020-2040. The expansion should meet demand but uncertainties for demand exist, e.g., technology development, digitalisation, urbanisation, and electrification of society. The capacity issue has activated other solutions beyond power grid expansion such as varying options for increased flexibility. It is clarified that the distribution system operators and the transmission system operator are obliged to care for the system responsibility, which means an obligation to expand and ensure that electricity is sufficiently supplied. In current regulation, it is specified that grid operators may deny access for new and expanded electricity demands with reference to lack of capacity. However, the regulation is not clear as to how to determine available capacity. The grid operator has an absolute responsibility to supply existing customers as it is not possible to lower the capacity to a customer after an agreement has been made. Options to manage the lack of capacity revolve around (1) potential to limit transmission capacities between countries, (2) design of flexibility market mechanisms, and (3) contracting and use of network capacity reserve (Axberg et al., 2020).

In an analysis, Axelsson et al. (2018) assess the impact of increased use of heat pumps related to the capacity scarcity in the electric power grid. It is estimated that the current use of electric heating in Sweden corresponds to 6-9 GW during the coldest periods. It is also estimated that with an increased market share and performance improvements, the electric power demand for heating may decrease by 20 % to 40 % by the year 2030. It is reasoned that the major variation in total power demand between winter and summer is caused by electric heating.

Currently, there are ongoing discussions about increasing electricity demands in Sweden. Such discussions are combined with different projections of future demand. One of these projections are described in Figure 10. For the time series in Figure 10, this increased demand is not yet clearly observed. Instead, when observing the average value, it seems that there is a weak tendency for lower electricity demands to occur with time. The spread of data is quite large, indicating the variation between summer and winter. The cause of the large spread is not known, but it is presumed that electric heating contributes to a large degree during cold periods.

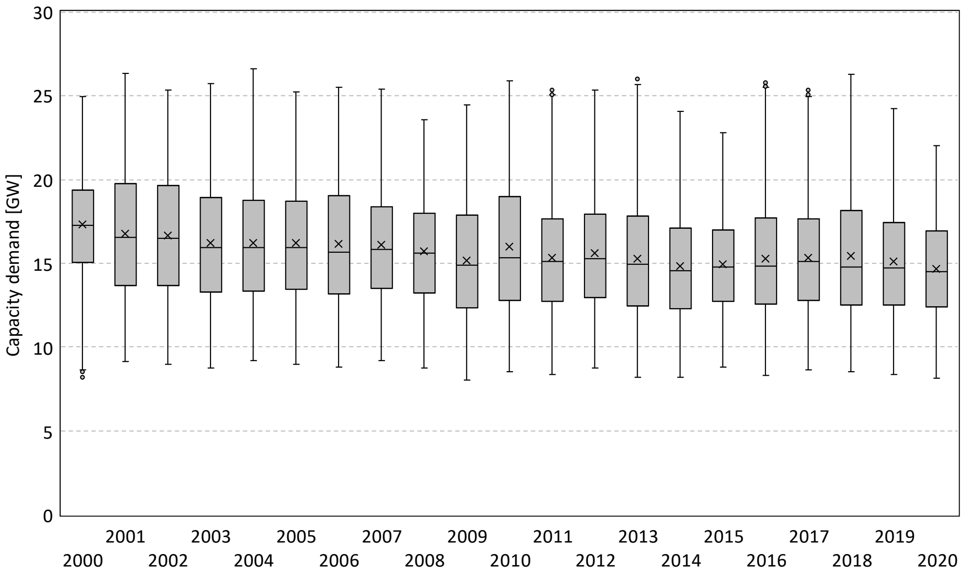


Figure 10 The capacity demand in the Swedish power system between 2000 and 2020. Power as hourly averages. (Svenska kraftnät)

The net balance of the electricity grid in Sweden is presented in Figure 11, where it is seen that for a large majority of the hours during a year, the total generation exceeds the capacity demand for electric power. This indicates that a surplus situation in terms of energy as a total volume is present during a large part of the year. It is still necessary to differentiate between total available volume of energy and the potential possibility to transfer capacity to all the nodes of the network without experiencing bottlenecks as could be the case in an expanding urban area.

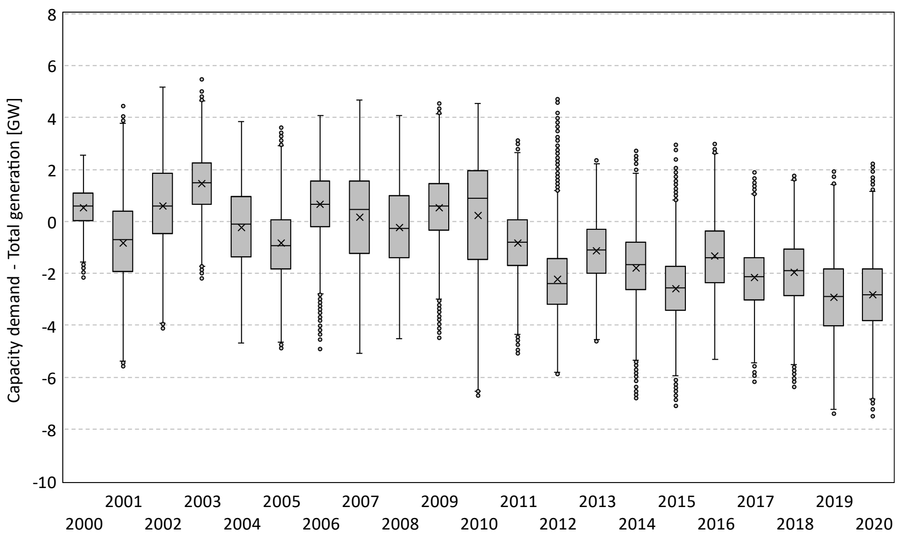


Figure 11 The Swedish power system total balance of import/export. Power as hourly averages. (Svenska kraftnät)

3.5. Capacity Markets

Capacity markets are employed to assist in grid stability, and they are currently also part of becoming a component to obtain greater degrees of flexibility within the power grid. Information about the support services for capacity markets are provided by Svenska kraftnät and summarised in Table .

Table 2 Overview of requirements for support services within the power system. Accompanying this summary of support services is more detailed information about balance responsibility agreement and associated rule documents. (Svenska kraftnät)

Designation	**Minimum bid size [MW]**	**Activation method**	**Activation time**	**Volume requirements [MW]**	**Minimum time duration**
FFR (Fast Frequency Reserve)	0.1	Automatically at frequency changes at low level of rotational energy[1]	Three options for 100%: -0.7 sec (at 49.5 Hz) -1.0 sec (at 49.6 Hz) -1.3 sec (at 49.7 Hz)	~100	- 30 sec alternatively 5 sec - Repeatability: Ready for activation within 15 minutes
FCR-N (Frequency Containment Reserve-Normal)	0.1	Automatically at frequency deviation within 49.90-50.10 Hz	63% within 60 sec and 100% within 3 min	~240	1 hour
FCR-D, up (Frequency Containment Reserve – Disturbance)	0.1	Automatic linear activation in frequency range 49.9-49.50 Hz	50% within 5 sec and more 100% within 30 sec	~580	Minimum 20 min
FCR-D, down (downward Frequency Containment Reserve -Disturbance)	0.1	Automatic linear activation in frequency range 50.1-50.5 Hz	50% within 5 sec and more 100% within 30 sec	~560	Minimum 20 min
aFRR (automatic Frequency Restoration Reserve)	5	Automatically via frequency deviation from 50.00 Hz	100% within 120 sec	~140	1 hour
mFRR (manual Frequency Restoration Reserve)	10[2]	Manually at the request of Swedish power grid	100% within 15 min	None	1 hour

[1] The amount of kinetic energy available in large generators.
[2] In price region SE4, the minimum bid size is lowered to 5 MW.

4. Summary Austria

4.1. Energy Market Analysis

In this section, the potential for efficient heating and cooling in Austria is discussed under the assumption of reaching climate neutrality 2050 in the building sector. To achieve this goal, extensive efforts in building renovation, the decarbonization of electricity generation, and the integration of waste heat into district heating systems are crucial.

District heating has been increasing since 1970. As of today, around 25 % of primary residences are supplied by district heating in Austria (around 20 TWh final energy use for heating). Within district heating, the share of biomass has been steadily increasing since 2005, and it is now providing around 50 % of the final energy use in district heating systems. Especially in rural areas, biomass combined heat and power plants or biomass boilers are used whereas district heating is provided by fossil fuels, waste incineration plants, and heat pumps in larger cities. In some cases, waste heat is utilized in Austria to feed district heating networks (between 0.8 and 1.8 TWh per year). The potential of geothermal energy is limited, and currently 12 plants (total of about 70MW_{th}) using geothermal energy are operating, mainly to feed district heating networks. The waste heat potential is differentiated between high (>100°C) and low (<100°C) temperature. In total, Austria has a potential to use waste heat from industrial processes of around 10.3 TWh of which 7.7 TWh are in the temperature range below 100°C. The paper industry (in total 5.4 TWh of which 5 TWh are low heat potential) has by far the largest potential. For low heat, the chemical industry has a potential of around 1.4 TWh, the steel mills 0.3 TWh, and the mineral oil processing 0.7 TWh.

To estimate the energy market for the building sector, two scenarios are taken into consideration. The first scenario (WEM) assumes existing measures to stay in place and no additional efforts are made to decarbonize the building sector. This scenario results in a possible reduction of residential heating and hot water demand by around 30 % until 2050. In this scenario, decarbonization of the sector in 2050 is not reached.

The second scenario (Transition) enforces a decarbonized building sector by 2050 by enforcing higher building renovation rates and change in heating systems away from fossil fuels. In this scenario, hot water and heating demands are reduced by approx. 50 % until 2050. In both scenarios, district heating as a high economic potential in 2050 takes the availability of different sources for district heat generation into account.

Scenario results show that in 2050, district heating would be economical to supply between 20 % and 50 % of all heat demand (Figure). This result highly depends on the allowed costs for connection, overall energy prices, connection rates of the grid to the buildings within reach, and interest rates. Especially high energy prices make district heating a viable option compared to decentralized solutions. The reason for this is that energy prices affect decentralized solutions directly while a relevant share of the costs for district heating is due to the distribution network. A higher connection rate of the heating grid to buildings has a very strong impact on the economic viability of district heating as well, which also increases the relevance of large-scale heat pumps significantly while the costs for expanding the heating network seem to have a linear impact.

In all scenarios, heat pumps play a vital role, both for the centralized and decentralized generation of heat. The results in Figure indicate that scenarios with a greater proportion of district heating require an increase in energy input, which is attributable distribution losses in the district heating systems. Nonetheless, this increased energy requirement does not translate to reduced energy efficiency. In fact, it leads to improved overall heat supply efficiency because it often allows for the utilization of a larger portion of available sources like waste heat, geothermal, or river-based heat pumps.

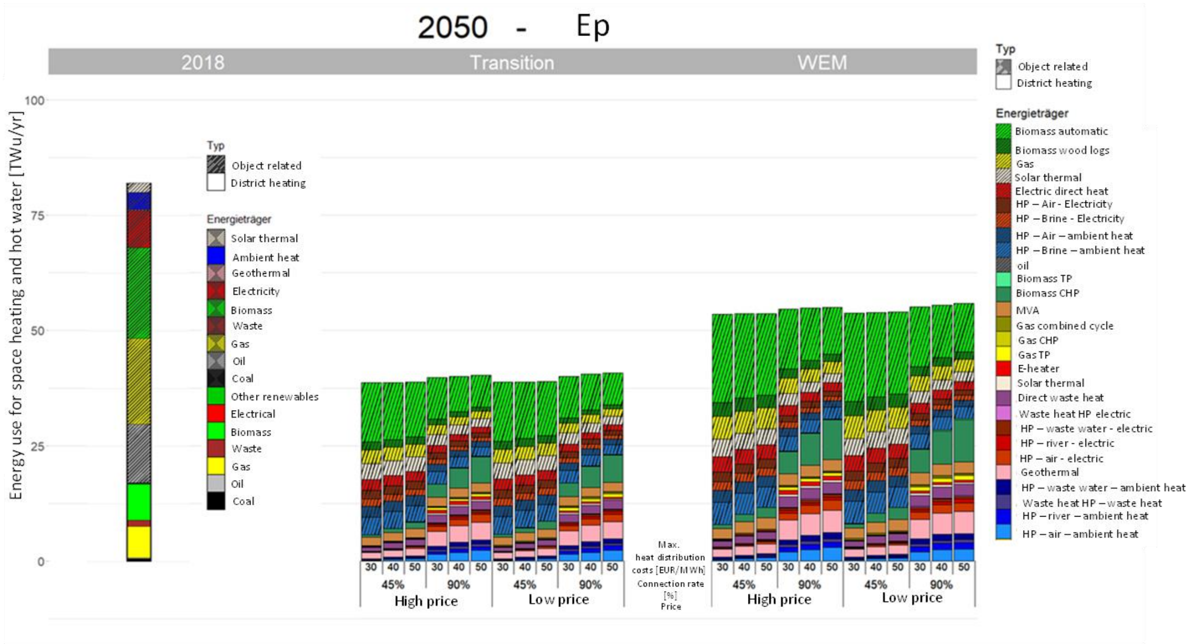


Figure 12 Use of energy sources for space heating and hot water in different scenarios in 2050 in Austria from an economic perspective. (AIT)

The scenarios show that renewable gases are not a cost-effective option for decarbonizing the building sector. A high uptake in the electrification of heating systems, centralized (district heating) and decentralized together with the use of biomass will play a major role. The use of large thermal storage systems contributes significantly to an economical operation of the heating networks. At the same time, there are significant uncertainties regarding the associated costs.

4.2. Sources for Waste Heat

The following section discusses various conventional and unconventional sources of waste heat.

4.2.1. Conventional Sources

4.2.1.1. Industrial Waste Heat

Marina et al. found the overall waste heat potential from the sectors described above in the EU28 to be close to 1200 PJ per year, with the majority being low temperature waste heat up to 100°C. Figure shows the share of waste heat of each sector and the respective waste heat temperature. The refinery sector has the largest share of waste heat with a greater variety of waste heat temperatures as well.

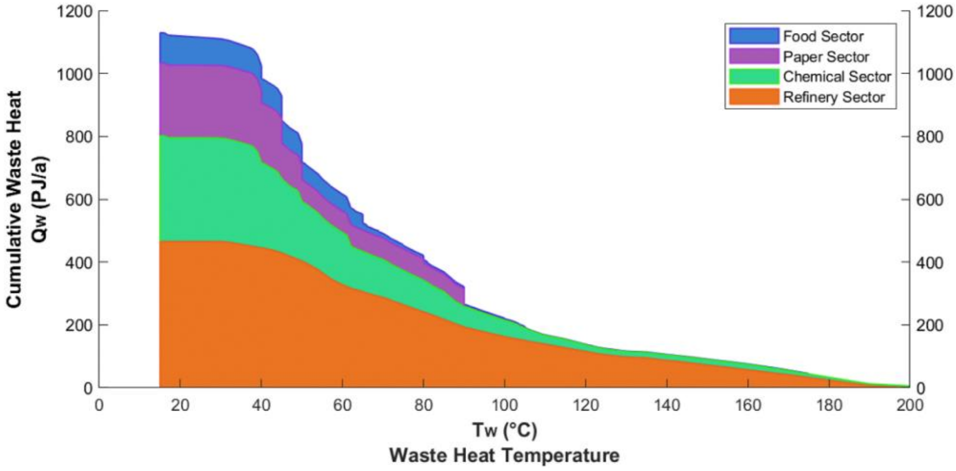


Figure 13 Cumulative waste heat <200°C in EU28 identified in processes which make up the heat pump market study. (AIT)

4.2.1.2. Wastewater Heat Recovery

Wastewater heat recovery is a mature technology. The first publications, patents, and implemented projects date back to the mid-1970s. Throughout the year, graywater flows through the wastewater pipes at a temperature of between 10°C and 20°C. The annual performance factor of a wastewater heat pump is around five for new buildings and four for existing buildings.

4.2.1.3. Flue Gas Condensation

Flue gas is a mixture of combustion exhaust gases. Many companies regard it as a waste product and discharge it unused into the environment. Valuable heat energy is lost in this way. With a flue gas heat recovery system, the waste heat can be utilized. The system is usually installed in the chimney. In general, a flue gas heat recovery system can reduce the cost and consumption of heat. Less energy is required for the same temperature and heat effect, and, moreover, it does not cause any changes in the production operation time.

4.2.1.4. Thermal Use of Lakes and Rivers

Heat pumps are used to utilize the low-temperature heat of lakes and rivers. The lake/river water circulates in a primary circuit, and a secondary circuit brings the heat transfer fluid to the user. After the heat is released, the cooled water is returned to the water body.

4.2.2. Unconventional Sources

Due to the decarbonization of the entire energy system, it is to be expected that new waste heat sources for heat pumps will emerge.

4.2.2.1. Waste Heat from Tunnels

The idea of using waste heat from tunnels revolves around the water which drains through the man-made hole in the mountain. Rain penetrates the mountain and seeps downward. With increasing depth, the rock temperature increases. The approximate gradient is 3°C/100m. An example in this field is the Brenner base tunnel, which should be finished by 2030. Above the tunnel are 1800 meters of mountain leading to water with temperatures around 35°C to 40°C, which is collected by drainage pipes. Due to a gradient, the water then runs towards Innsbruck.

4.2.2.2. Waste Heat from Converter Stations

Typically, large transformer stations have very high efficiencies, often above 99 %. Nevertheless, losses of as little as 0.5 % can provide a significant amount of waste heat from large systems. A collaboration by a Danish (Energinet) and a Dutch (TenneT) transmission system operator implemented the COBRA cable for energy transmission between their countries. The HVDC converter station in the Danish town of Endrup provides excess heat to the local district heating network. The converter station has a voltage of 320 kV and a transmission capacity of 720 MW. The surplus heat generated by the converter station, which has a full load capacity of 3150 kW, will reach around 35°C. Heat pumps are used to reach the temperatures of the district heating network.

4.2.2.3. Data Centers

The energy consumption associated with data centers was 200-250 TWh in 2020, corresponding to approx. one percent of the global electricity demand. A different source states a consumption of 350 TWh for the year 2017. Data centers are designed for continuous operation and can, therefore, provide constant heat. Typical, specific power densities are in the range of 250 to 1,500 W/m² IT area, resulting in high power requirements for larger data centers. On average, European data center has an area of 2,616 m², which means an electricity demand for the IT hardware of about 17.2 GWh/a when assuming a power density of 750 W/m² and continuous operation. Since the electricity used is completely converted into waste heat, this heat must be cooled away.

4.2.2.4. Electrolysers

The production of hydrogen from water and renewable electricity with electrolysers is the preferred production path in the future. There is a multitude of different technologies available at varying technology readiness levels. However, three electrolyser types are the most promising: Alkaline electrolysis (AEL), polymer electrolyte membrane electrolysis (PEM-EL), and solid oxide electrolysis (SOEL). An overview of the key parameters for the technologies is given in Table .

Table 3 KPIs of electrolysis technologies

	AEL	PEM-EL	SOEL
TRL	9	8 - 9	6 - 7
Operating temperature [°C]	60 - 90	50 - 80	650 - 900
Electric efficiency (LHV)	50 - 71	50 - 68	75 - 85
Recoverable waste heat (% of electricity input)	16 - 30	20 - 30	-

5. Summary the Netherlands

5.1. District Heating Networks in the Netherlands

In the Netherlands, the district heating sector does not have a large market share due to an extensive natural gas infrastructure, which is the most common heat source for buildings. Around 490,000 homes are connected to a district heating network, which is equivalent to approximately 6.4 % of homes in the Netherlands. Since 2010, the number of connections has grown by 4.6 %, mainly due to new construction projects. This percentage is relatively low, and some measures must be considered to increase the expansion, also in the existing building stock. Various industrial complexes also make use of a heat grid for steam production, usually from a CHP. In total, this amounted to 35 PJ in 2017, which is more than all district heating combined (22 PJ).

The Netherlands is characterised by two different kinds of networks, the large-scale networks and the small-scale networks. Large networks consist of more than 150 TJ of heat delivery, and the main heat sources are usually power plants, waste incinerators, industry, and refineries. However, there are thousands of small-scale heat distribution networks. According to 2022 figures, there were approximately 41,000 connections connected to a small-scale network (less than 500 connections per network), and 55,000 connected to a network between a small-scale network and a large-scale network. Most of the small-scale networks count less than 50 connected consumers and those networks are owned by small firms, association of homeowners, and other parties. The networks between the large and small-scale networks are mostly owned by energy suppliers, which use cogenerations unit, waste heat, heat pumps or biomass plants as a source.

5.2. District Heating in the Future

District heating in the future is aimed to cover around 1/3 of the energy supply. Another 1/3 will be covered by electrical heat pumps, and the last 1/3 will be covered by hybrid heat pumps that runs on renewable gas. Supporting policies will help to achieve the goals below. For example, the government opened a new subsidy scheme to reduce the CAPEX investment of new district heading grid projects in 2023.

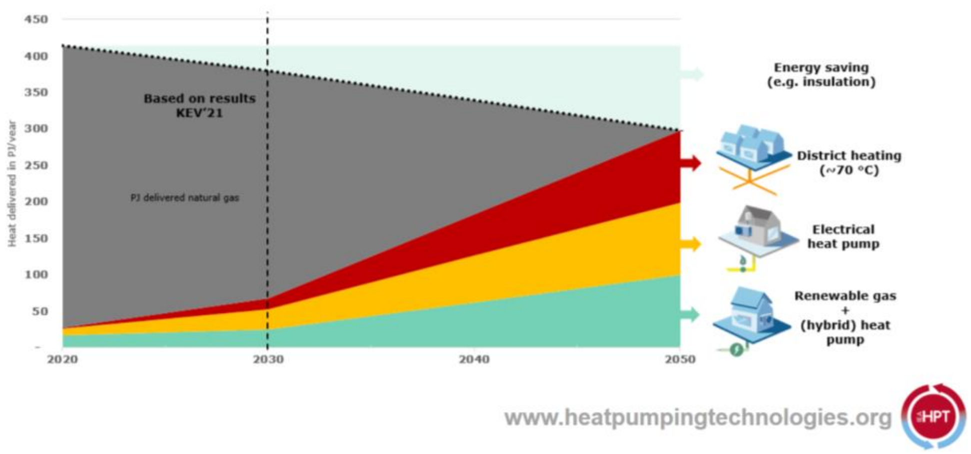


Figure 14 Policy Transition in The Netherlands (IEA 2023)

5.3. Electricity Demand Now and Then

5.3.1. Heat Pumps

The total number of heat pumps installed in the Netherlands might rise to more than 568,000 units (167,000 units in 2023). The Dutch association of national-regional electricity and gas network operators, Netbeheer Nederland, has introduced a plan to deploy up to 2 million (hybrid) heat pumps by 2030, especially in existing building stock. The plan is supported by a subsidy scheme provided by the government which enables the installation of at least 100,000 heat pumps per year from 2024, which is already reached in 2023. However, the quality of installation must be improved. Manufacturers, installers, and the government have answered by starting the first 200 homes hybrid heat pump monitoring pilot program (https://www.demoprojecthybride.nl) and 500 installations a day acceleration program with installers.

To enface the electrification of the energy system, the power grid must be enforced. The acceleration of hybrid heat pumps is seen as a transition technology from gas boiler to electrification in the building environment.

5.3.2. The Capacity Situation

The ever-increasing rate at which additional transmission capacity is required exceeds the speed at which grid operators can expand the electricity grid. Although work on the grid is in full swing in all regions, the billions of euros invested, and the additional measures are unfortunately not enough. The grid operators signal that the Netherlands is entering the next phase in which access to the electricity grid will come under further pressure. Without these drastic measures, housing construction, economic growth, and sustainability in the Netherlands will slow down.

In more and more places, a new connection or reinforcement for a company or home is no longer self-evident. This calls for a serious acceleration of the expansion of the electricity grid. In addition, grid operators and the government are taking additional measures to keep the electricity grid accessible and reliable. Examples of this are the mandatory use of smart charging stations, controllable heat pumps, and the mandatory relieving of the power grid at peak times. The changing energy system also requires different behaviour, by using the grid mainly when the supply of energy is large.

5.3.2.1. The Netherlands is switching en masse to electricity

There are currently more than 105 GW (comparable to more than 150 times the capacity of Amsterdam) in applications for reinforcements or new connections for electricity consumption. These are, for example, applications for large-scale batteries (75 GW) and industry, companies, data centres, hydrogen plants, and new residential areas. All these developments add up much faster than grid expansions can be realized. Rising energy prices and increasing climate ambitions are accelerating this considerably. Users are switching to electricity en masse.

5.3.2.2. Full Nets in all Regions

A study recently published by TenneT shows that there is no space available on the electricity grid for entrepreneurs in some regions. This means that they have to take long waiting times into account. In addition, the maximum capacity of the electricity grid has also been reached in North Holland for companies that want a connection or reinforcement. Nationally, the trend is that the limits of capacity are coming into focus in more regions. The grid operators also note that the electrification of businesses and households is also making the electricity grid in the district busier. Unfortunately, this means that small businesses and consumers will also have to wait longer for a connection or an increase.

5.3.2.3. Changing Energy System Requires Different Behaviour

The joint grid operators indicate that the electricity supply is under pressure, especially at peak times when the maximum limits are reached. This entails risks of slowing down housing construction, economic growth, and making the Netherlands more sustainable. This is an uncomfortable truth that must be dealt with in this transition. The energy infrastructure is the foundation of our society. Keeping the energy grid as accessible as possible requires not only substantial investments in the energy grid but also a change in behaviour from all users. Electricity is no longer available indefinitely.

5.3.2.4. Flexibility for Businesses and Households

The new energy system requires different behaviour from all users, with electricity mainly being used when there is a lot of sustainable generation of wind or sun, and less electricity is used during peak hours. The grid operators are confident that the measures announced by the government at present time will be implemented quickly, including the accelerated application of grid-aware charging of vehicles, and ensuring that smart controllable devices become the norm. The grid operators also consider it a positive development that the government is making 166 million EUR available for an Energy Hubs Incentive Programme. In doing so, companies coordinate their electricity supply and demand locally so that less space is needed on the power grid. In addition, the government and the grid operators want to proactively start flex tenders from next year that allow companies such as a battery operator to offer more than 1 GW of space on the power grid at strategic locations during periods of time.

5.3.2.5. Smarter Use of the Grid

The main focus for grid operators is to accelerate the realisation of the infrastructure. However, an enlargement alone is not enough. The sector is committed to smarter use of the grid, for example by making *rush hour avoidance* more financially attractive and less non-committal and by increasing the load on the grid where this is safely possible. To this end, interest groups, governments, ACM and system operators are also working together through the National Action Programme for Network Congestion (LAN). With measures announced by the government, grid operators expect to be able to relieve the electricity grid more and make better use of it so that they can connect more customers to limit delays for housing construction and the impact on economic growth as well as the sustainability of the Netherlands.

Actual capacity figures from grid operators (grid lower than 110 kV) can be found on the following website:

https://capaciteitskaart.netbeheernederland.nl/

The actual situation in the high-voltage grid (110 kW and higher) can be found below or in the following viewer:

https://www.tennet.eu/nl/de-elektriciteitsmarkt/connecting-dutch-high-voltage-grid/netcapaciteitskaart

5.3.3. Policies

The energy transition is accelerating and the demand for renewable electricity has exploded. The grid operators currently invest 3.9 billion EUR annually in the electricity grid. However, this is not enough to keep up with the pace of the transition, and the electricity grid is reaching its limits. To achieve climate goals, companies and industry are investing in sustainability, but they are hampered by a shortage of transport capacity. Priority one remains to expand the electricity grid as quickly as possible so that more and faster grid capacity becomes available, but more is needed. The National Action Programme for Grid Congestion, which is drawn up and endorsed by a broad representation of stakeholders, focuses on four main goals:

1. Faster construction and faster realisation of grid expansions

2. Stronger efforts to make better use of the grid

3. Increasing flexible capacity: public-private actions for smart solutions

4. Smart EV charging and smart sustainable homes.

The actions are not only aimed at tackling grid congestion, but they also necessarily follow from the changing energy system.

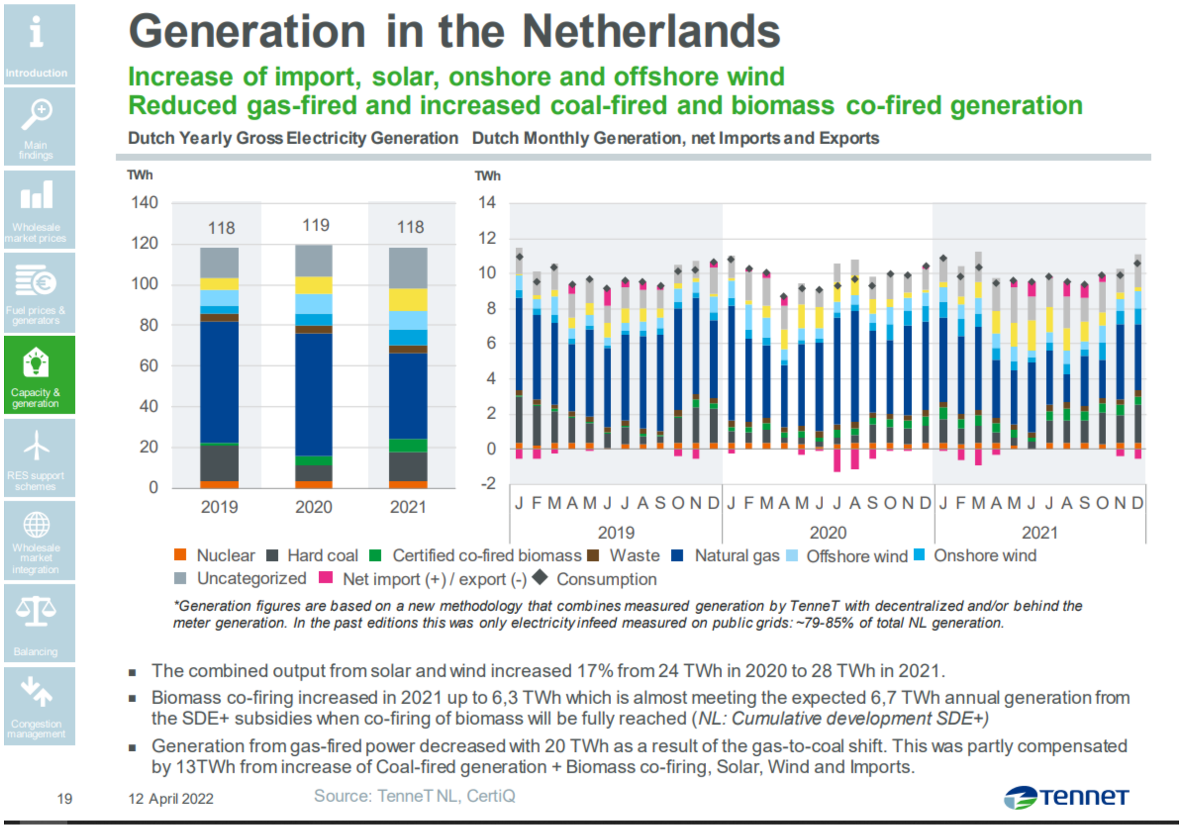


Figure 15 Generation in the Netherlands. (TenneT)

5.4. The Capacity Situation

https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2022-07/Annual_Market_Update_2021_0.pdf

Generation from wind and solar in the Netherlands has increased with 17 % to 28 TWh. As a consequence of gas-to-coal switching, generation based on natural gas significantly decreased and generation based on coal significantly increased. Additionally, around 6.3 TWh of biomass co-firing in coal-fired power plants was certified, meaning that the share of total generation in coal-fired power plants can be attributed to biomass co-firing.

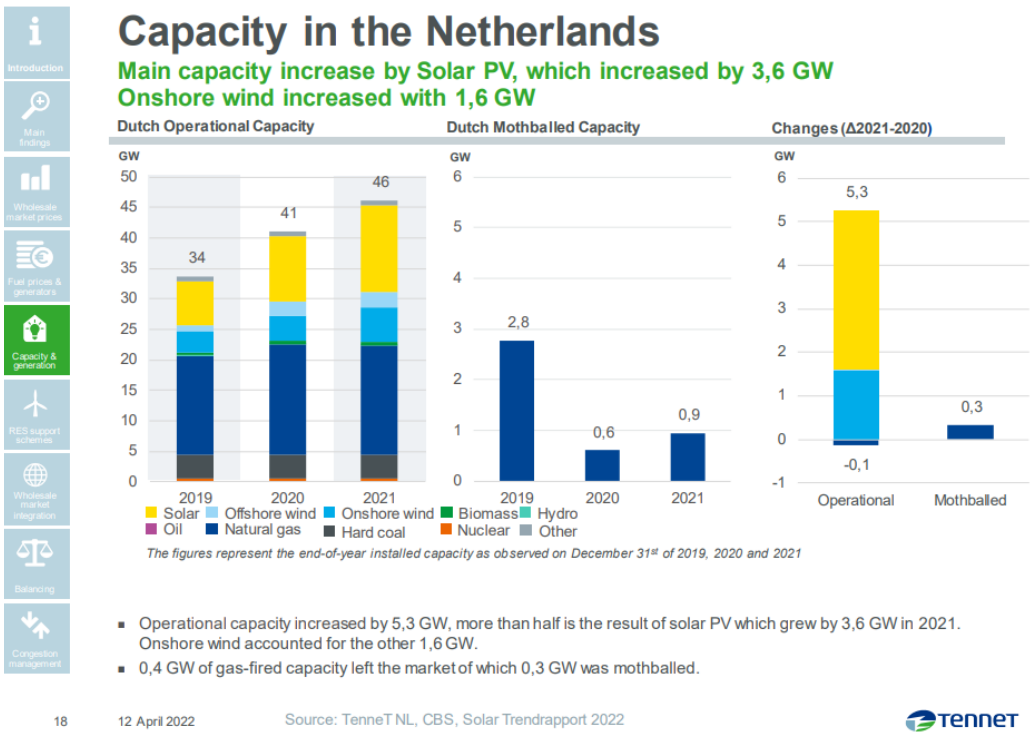


Figure 16 Capacity in the Netherlands. (TenneT)

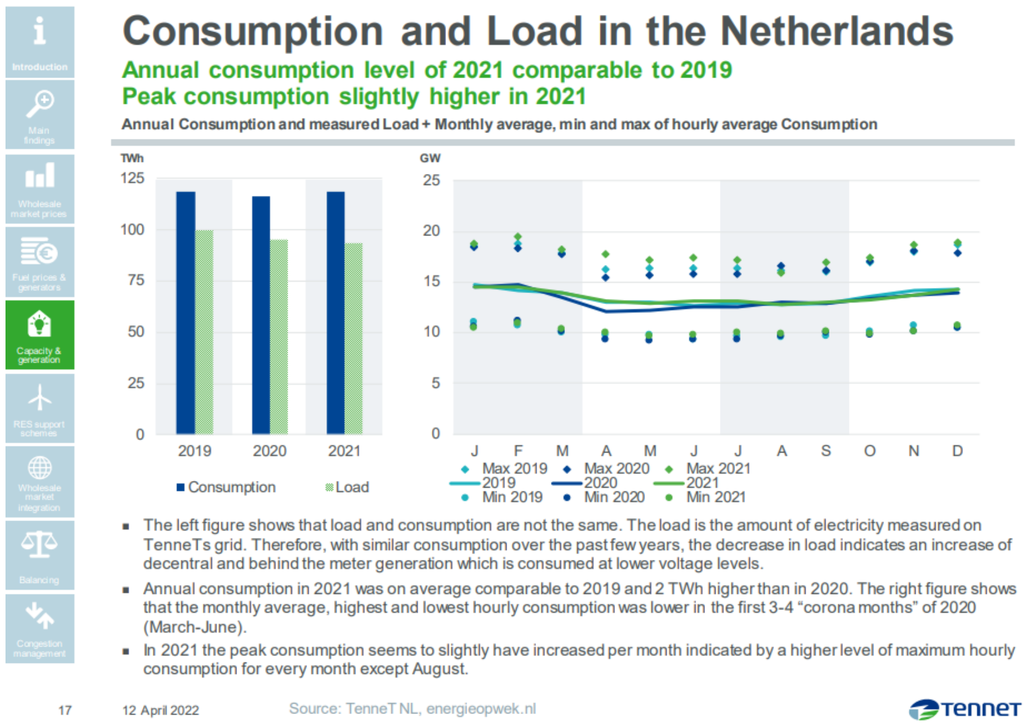
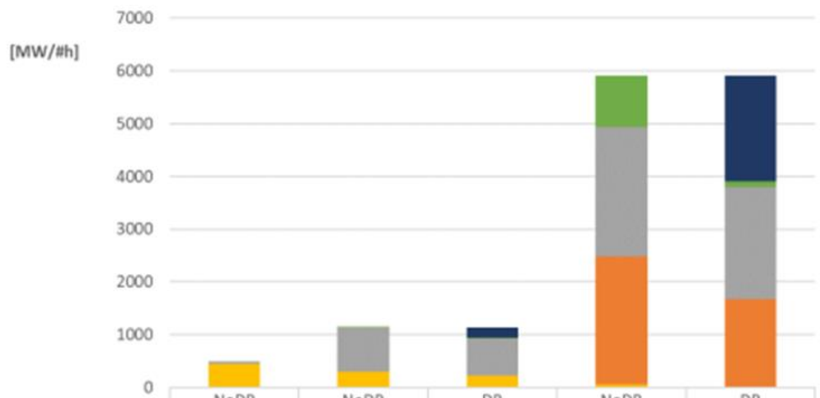


Figure 17 Consumption and load in the Netherlands. (TenneT)

5.4.1. Potential for Demand Response from Heat Pump in Single-Family House / District Heating Grids

Figure 18 describes the summary of major results regarding the impact of demand response (DR) on the mix of options to meet the total annual demand for flexibility in the scenario years CA2030 and NM2050 with and without DR (DR versus NoDR), including the reference scenario year 2015 (R2015) see: https://publications.tno.nl/publication/34639481/emVYyq/TNO-2022-P10131.pdf



	NoDR	NoDR	DR	NoDR	DR
	R2015	CA2030		NM2050	
Demand response	0	0	186	0	2002
Storage	0	0	12	975	105
Trade	46	827	712	2446	2131
VRE curtailment	0	6	4	2425	1663
Non-VRE generation	457	299	220	64	7

Figure 18 Mix of supply options to meet the average hourly demand for flexibility in R2015, CA2030 and NM2050 with and without demand response (DR versus NoDR). (TenneT)

6. Summary Denmark

6.1. District Heating Demand Now and in the Future

The opening of the electricity market and the green transition have significantly changed the incentives for establishing and maintaining thermal electricity production capacity in Denmark. Since the opening of the electricity market in 1999 and 2000, a significant part of the thermal electricity production capacity has been taken out of operation.

The Danish District Heating Association has made an analysis and forecast of the electrical production and district heating production in the future. The scenario shows that district heating in the future will be produced mainly by electrical heat pumps and excess heat. Waste incineration and biomass will be phased out as a heating source.

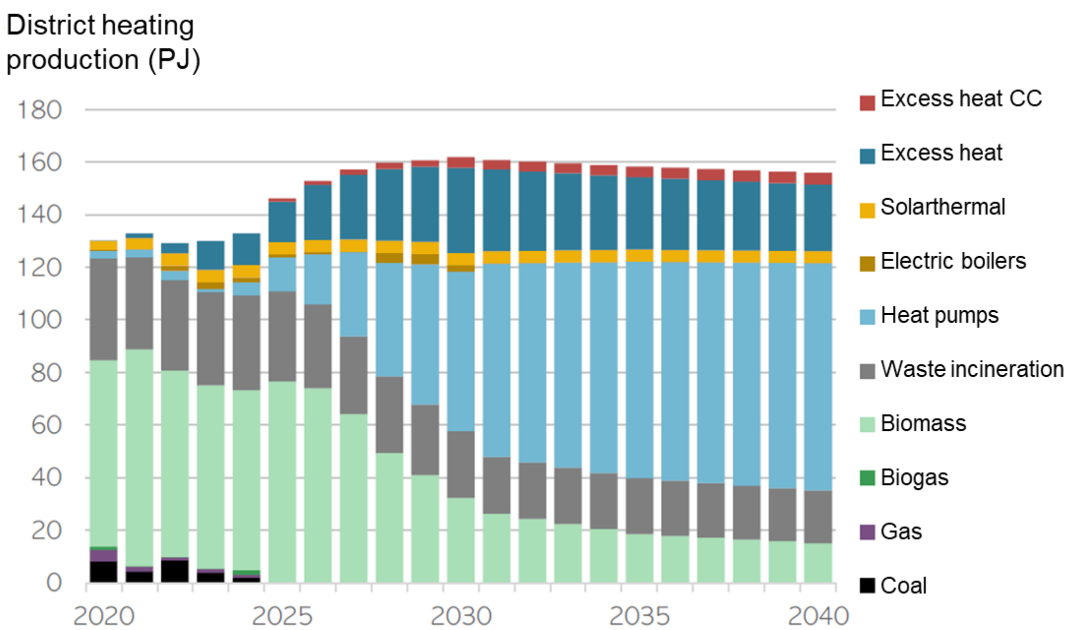


Figure 19 Scenario for the development in district heating production until 2040. (Danish District Heating Association)

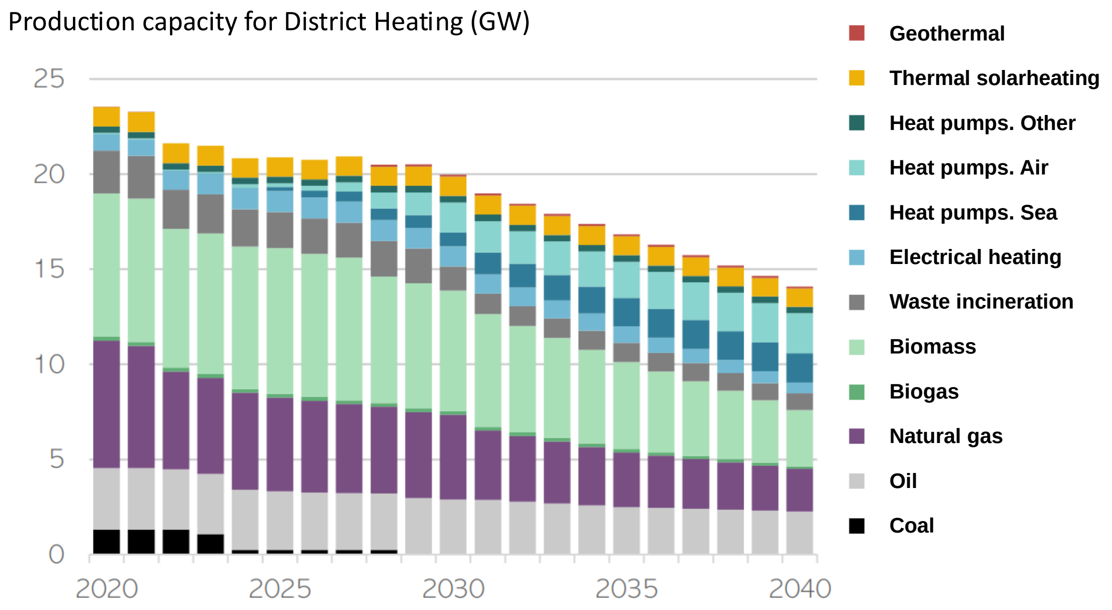


Figure 20 Scenario for the development in district heating production capacity until 2040 (DDHA)

A decrease in capacity is seen despite of an increase in district heating production. This is because excess heat covers part of the heating requirement. The activation ratio of the thermal heating plants is very low, and they are used primarily as a backup.

6.2. Electricity Demand Now and Then

The primary reason for the decrease in the capacity of the thermal plants is that electricity production will be outcompeted by large amounts of wind and sun produced electricity. Coal and gas in electricity production will already be phased out in the first half of the 2020s. Lead gas is a mixed product of natural gas and synthetic natural gas. Towards 2040, the proportion of fossil gas in pipeline gas will decrease.

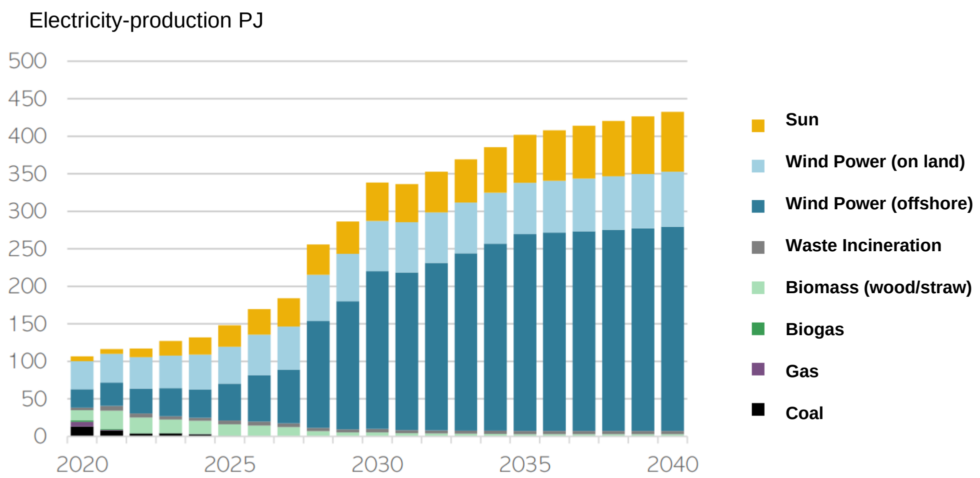


Figure 21 Scenario for the development in electricity production until 2040. (Danish District Heating Association)

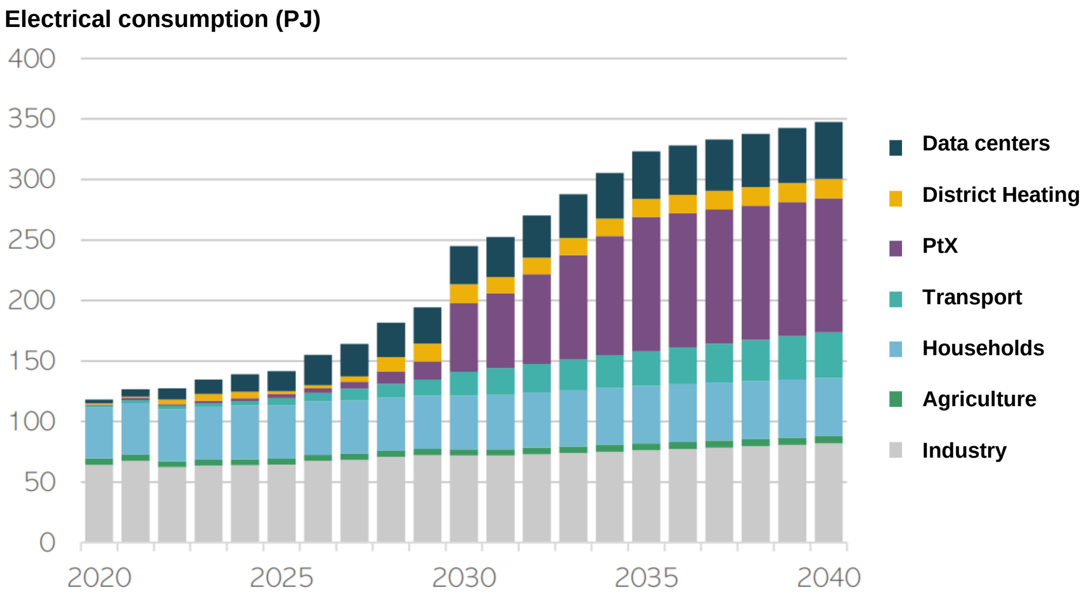


Figure 22 Scenario for the development in electricity production until 2040. (Danish District Heating Association)

The increase in demand for electricity comes primarily from PtX plants and secondary from the electrification of land transport. PtX includes both the production of hydrogen and derived fuels. District heating includes electric heaters and large heat pumps in the district heating sector.

6.3. Perspectives on the Power Grid

To produce electricity for the growing consumption, a large expansion of renewable energy technologies is taking place. Electricity production capacity is strongly dominated by wind power, especially offshore wind in 2040 and 2050. Depending on the scenario, 22-26 GW of wind power is seen in 2050. In the ambitious scenario, a greater influx of solar energy is seen with approx. 8 GW capacity from 2030.

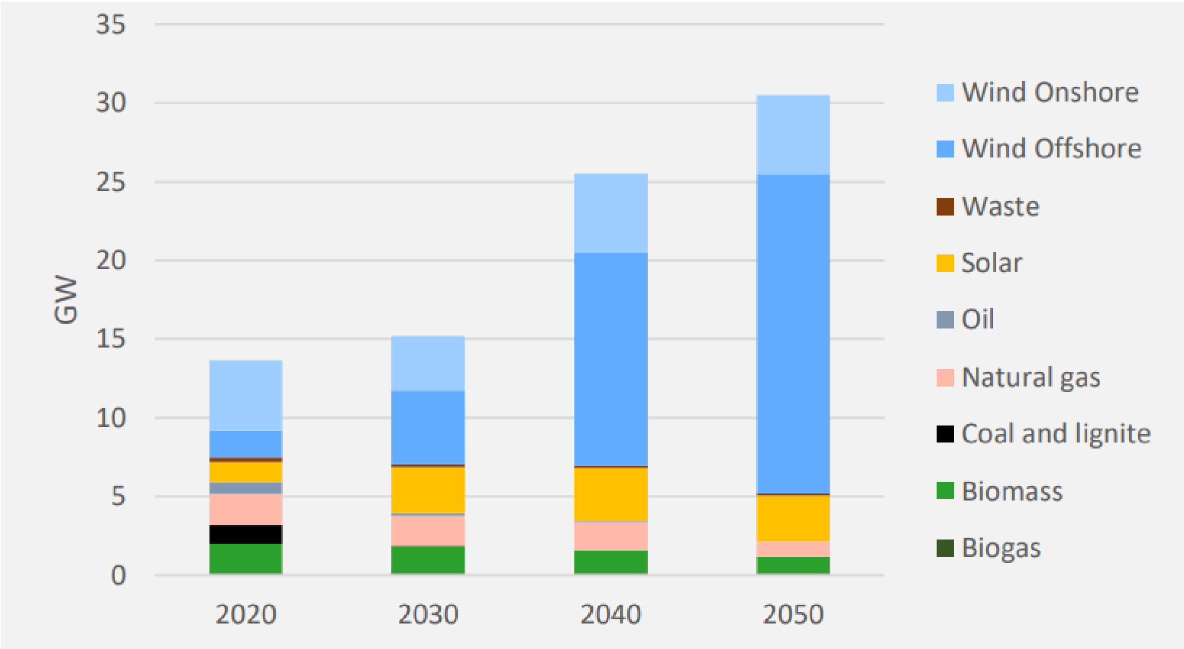


Figure 23 Scenario for the development in electrical production capacity. (EnergiNet)

6.4. The Capacity Situation

The Danish TSO, Energinet, has made an analysis of the energy system. The purpose of these system perspective analyses is to analyse possible long-term development processes for the energy system as a unified system and to provide input based on this to the long-term planning of electricity and gas infrastructure as well as the broad system development which is necessary to handle the significant transformation that the energy system is facing.

The annual balances are shown in the scenarios. In the 35 GW scenario, Denmark has enough renewable energy resources to export electricity and hydrogen and for new electricity consuming industry.

In the scenario with 35 GW offshore wind power in the Danish North Sea region, electricity generation from thermal power stations is very limited compared to wind and solar power generation. The demand-side response from PtX, heat pumps, electric vehicles, and batteries represents a significant dispatchable resource. Most of the time, there is high wind and solar power generation as shown in figure 24.

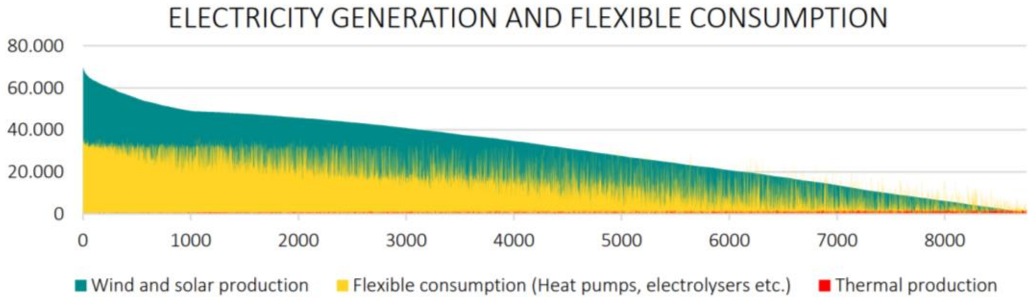


Figure 24 Hourly data for thermal production capacity, generation from wind turbines and solar cells as well as flexible consumption, for the 35 GW offshore wind scenario. (Energinet)

6.5. Capacity Markets

The model calculations show that flexible electricity consumption is increasingly taking over the supply of regulation reserves and ancillary services. The model optimizes both the capacity market, where the necessary regulation capacity is secured, and the activation market where the up and down regulation itself is delivered.

In the reference scenario, a large share of the capacity market is overtaken by electrically driven heat pumps and boilers as well as PtX while foreign trade and downregulation of wind and solar power also contribute to the activation market. The development is caused by the very significant growth in flexible electricity consumption primarily from heat pumps and PtX systems. The model establishes a total capacity of approx. 10 GW within these categories towards 2040.

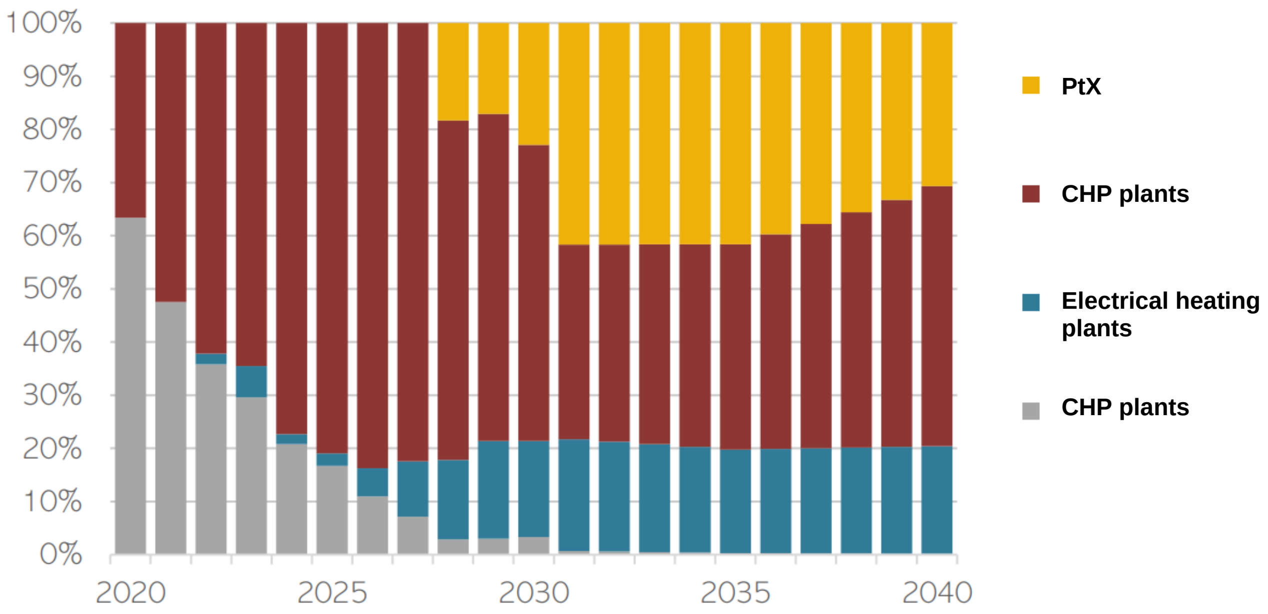


Figure 25 Technology mix which delivers to the capacity market for ancillary services. (Energinet)

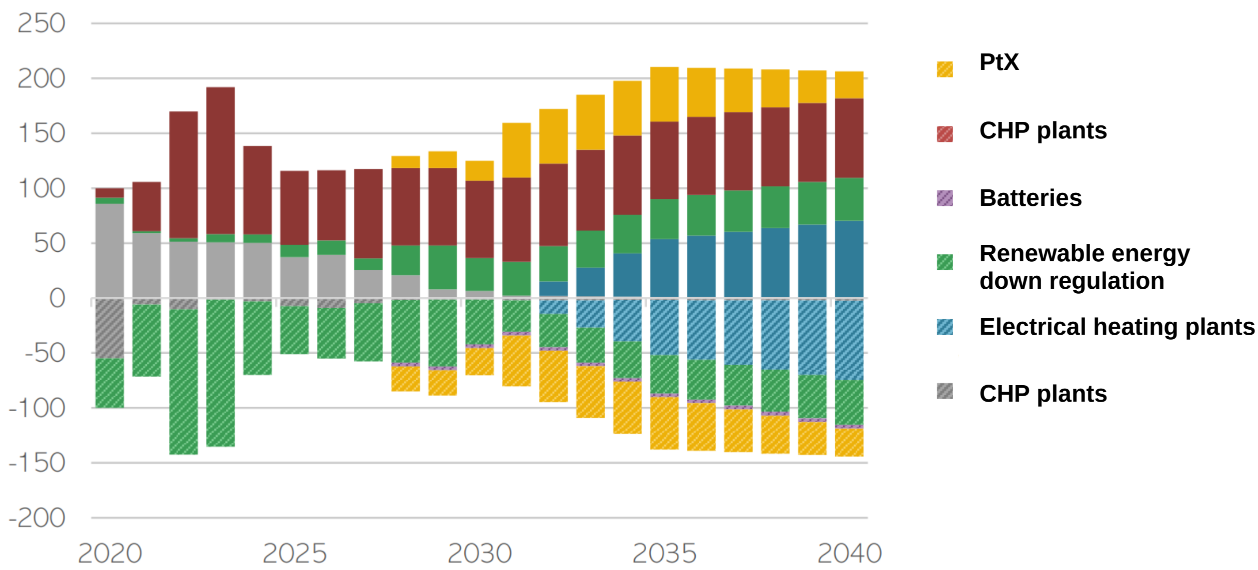


Figure 26 Technology mix which delivers to the capacity market for ancillary services. (Energinet)

7. Summary Germany

The Federal Climate Change Act (KSG) of Germany has taken effect on 31August 2021. Thereby, Germany declared its transition and certain targets over time to a green-house gas balanced system until 2045. The transition is essentially developed and accompanied by the long-term scenarios of DENA-Leitstudie [1], Agora - Klimaneutrales Deutschland 2045 [2], the German Industry Association (BDI) - Klimapfade 2.0 [3], “Langfristszenarien” of Federal Ministry for Economic Affairs and Climate Action (BMWK) [4], and the research of „Ariadne“ [5]. The former Federal Ministry of Economics (BMWi) proposed in the “Dialog Klimaneutrale Wärme 2045” [6] the essential parts for the transition of the heating sector. The total sector emissions of greenhouse gas equivalents (GHG) and its designated reduction path are shown in Figure .

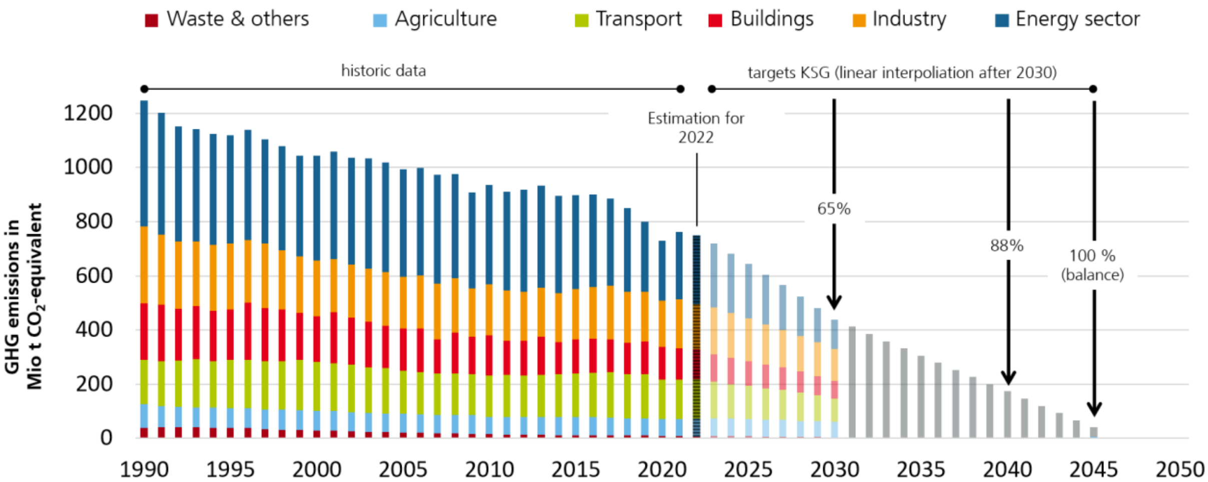


Figure 27 Total green-house-gas (GHG) equivalent emissions since the year of 1990 for Germany and its reduction path until 2045. (Umwelt Bundesamt)

7.1. District Heating Demand Now and in the Future

The annual, final energy demand supplied by district-heating (DH) systems is estimated based on [8] to 73 TWh/a for so-called low-temperature heat covering the residential as well as the trade and commerce sector, including 58 TWh/a for residential household supply. Additional 43 TWh/a account for process heat in the industrial sector in 2021 [8]. Heat losses of distribution network need to be considered and might be estimated to an additional 17 TWh. Thus, 134 TWh of heat accounting about 10 % of total heat production in Germany might have been generated to be supplied by DHN in 2021. The generation is, thereby, based on natural gas (46 %) and coal (20 %) whereas renewables contributed 17 % as almost completely by incineration of biomass.

Regarding a model-based approach accounting a variety of resources, more than 1700 cities and communities where found to be incorporating DH systems by an annual demand of 67 TWh for space-heating and domestic hot water preparation in the residential as well as the industry sector by operating about 26.700 km of DH network [9]. It is, furthermore, shown that DH will annually supply 94 TWh in the residential sector in 2045 by means of an increase in quantities of 60 % compared to 2020. This means additional quantities to be generated annually of about 1,6 TWh.

Regarding energy efficient measures in building physics and its performance, the specific heat demand is simultaneously decreasing so that the number of buildings supplied by DH is to be increased by a factor of about 2 to 3. To realize this annually, about 130,000 to 150,000 new connection units and an additional 800 km of transmission line are annually to be constructed [9] which is about twice as much as currently being accomplished. Furthermore, the need for the industrial sector must be taken into account as well as the infrastructural impact might be larger considering on-site constructions.

In another report, an amount of about 200 TWh for DH is estimating in 2050 [10]. In this approach, the capacity for DH supply is divided in a fossil free system of about 30 GW to 40 GW of installed centralized large heat pumps and about 13 GW to 27 GW solar-thermal. Peak load is covered by gas-based vessels and CHP in a range of 5 GW to 27 GW [11]. The quantities following this system analysis in the residential sector might be divided as shown in Figure .

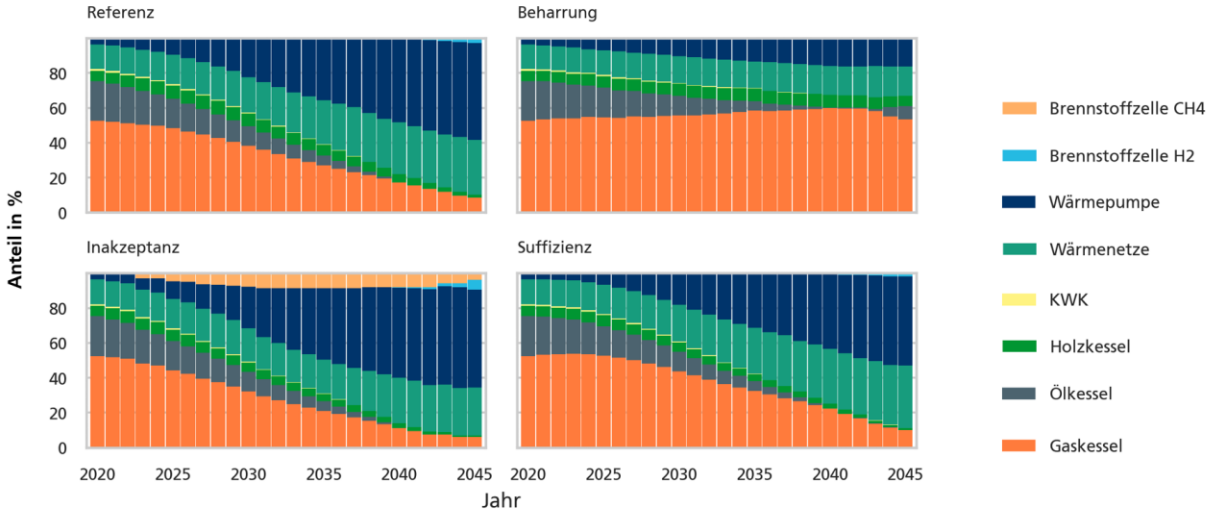


Figure 28 Share of heat supply of different technologies in certain considered scenarios. District heating is shown in green. (Brandes et al., 2021)

According to [9], operation of large heat pumps will supply about 70 % of DH related quantities in 2045, which has been developed more in detail in [12]. This means that annually about 100 TWh are supplied by large heat pumps and an additional 10 TWh of electrode boilers in 2045.

7.2. Electricity Demand Now and Then

The consumption of electric energy is shown regarding the estimation of different scenarios in [11].

It becomes clear that the current electric quantities have approximately doubled from 600 TWh to around 1,200 TWh in 2045 whereas hydrogen is by means of its quantities not supposed to play a significant role in supplying demand in the electricity sector.

7.3. Perspectives on the Power Grid

Considering the installed capacity, the German Federal Network Agency [13] takes any system connected to the grid into account. A more detailed view regarding the current market development of home storage systems (HSS), large stationary storage systems (LSS), industrial storage systems (ISS), and battery electric vehicle is undertaken in [14].

The current development and its estimated increase is shown in [11] where mobile battery systems are assigned to be used bidirectionally at a share of 10 % of the total battery based vehicles. Furthermore, a c-factor between power and capacity (GWh to GW) has been assessed to 1. Capacity might vary in 2045 in the considered scenarios in between 400 GWh to 900 GWh.

7.4. Energy Markets

7.4.1. Prices of Energy

The composition for the price of electricity is shown for a typical private household [15]. It becomes clear that taxes and cost allocation take about 50 %. Sales take about 24 %, and grid charges including metering covers the other 25 %. In the reference scenario, a specific price of 0.32 €/kWh is shown for a costumer of a private household with an annual consumption of 3,500 kWh.

In contrast, gas prices are composed regarding to [15] as well. The reference household with an annual consumption of 20 MWh is calculated to a specific fuel price of 0.07 €/kWh. In means of a comparison of gas and electricity prices [16] is to refer to. Taking the previously stated prices in the private sector for single-family-buildings into account, a ratio of electricity to gas fuel of about 4.5 occurs [15] which has been reduced to approx.. 3 after the price shock in 2022, whereas robust reference is not possible at the moment.

In the industry sector, final consumer prices are rather difficult to examine. It might be expected to find a ratio of 2 to 2.5 for Germany depending on, e.g., local infrastructural and further market criteria. Especially switching to LNG as a natural gas source has a certain impact that might intensively affect future price scenarios, indicating that references might be found in recent publications on https://ariadneprojekt.de/ and in [17]. For a robust scenario evaluation, full cost as levelized-cost of heat (LCOH) taking, e.g., CAPEX, OPEX, and subsidies over a live-cycle into account are necessary when comparing both technologies for heat generation.

7.4.2. DH Prices (LCOH)

In [18], the prices have been evaluated in comparison to typical heating technologies for a multi-family building. It becomes visible that the levelized-cost of heat (LCOH) does not vary that much in connection with different technologies. It takes around 14 to 15 ct.€/kWh for all considered technologies. Where the share of fuel cost is much lower for gas-based or electricity-based systems than for DH supply.

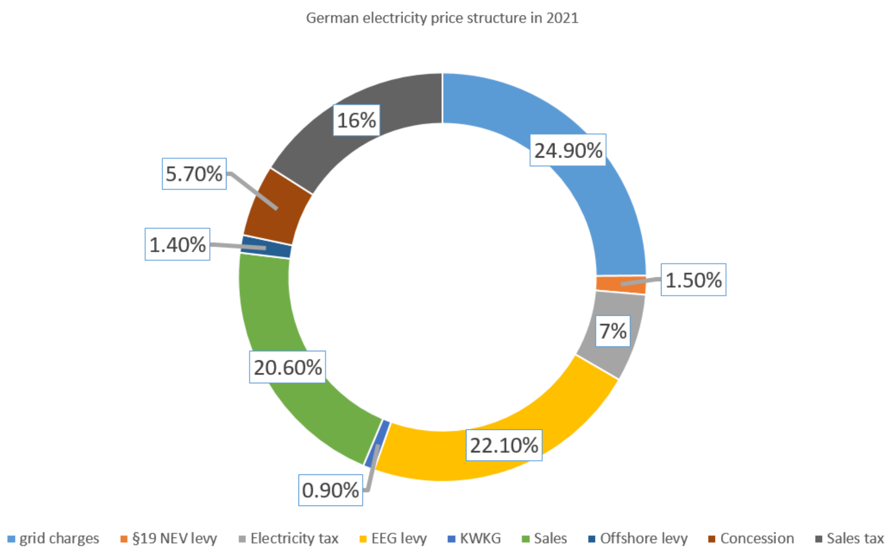


Figure 2: Structure of the German electricity price in 2021. (Verivox, 2021)

According to different sources, the current structure of the electricity price is the reason for different obstacles regarding the expansion of sector coupling technologies. As shown in Figure **2**, the amount of taxes and levies have a high share on the total price. There are currently ongoing discussions on whether the price structure could be changed in order to support the consumers. A smaller electricity price could lead to an expansion of sector coupling technologies like heat pumps or electric vehicles.

On the other hand, if part of the taxes and levies are transferred to fossil fuels, it would probably decrease the usage of these. As can be seen from Figure 30, the share of taxes is much lower compared to electricity. However, there are no concrete plans available yet on how to relieve the consumers.

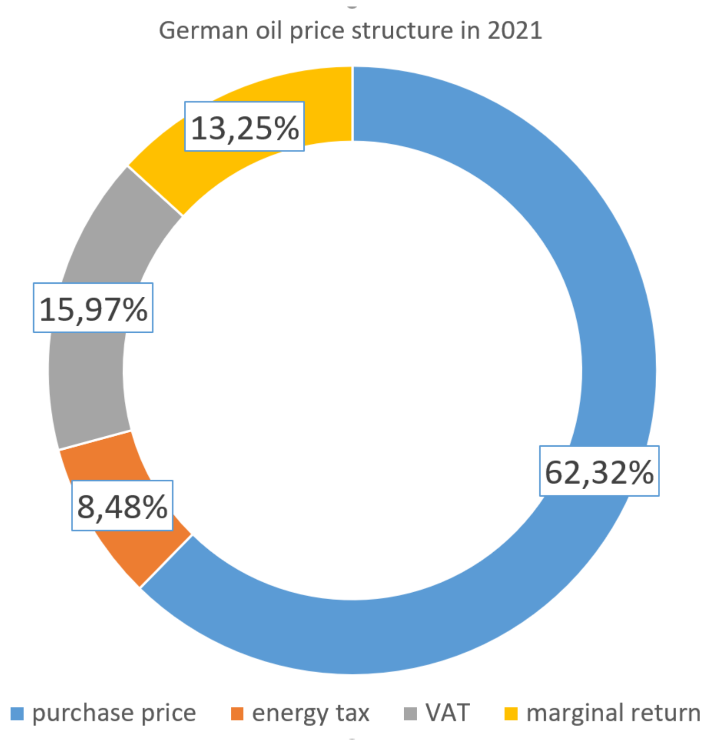


Figure 30: Structure of the German oil price in 2021. (Verivox, 2021)

7.4.3. Policies

Until the BEW Directive came into force, funding for large heat pumps in Germany was essentially only possible as part of an innovative CHP system (iKWK) according to the KWKG. Basically, the component for providing renewable heat must be dimensioned so that at least 30 % of the reference heat (total heat provided by the iKWK system) can be generated as innovative renewable heat in a calendar year. Use of waste heat is not part of it [19].

The BEW guideline came into force on September 15, 2022. It consists of four modules [20] considering:

1) Feasibility studies and transformation plans (max. 50 % or 2 million EUR)

2) Systemic promotion of heating and cooling networks – grid measures (max. 40 % or 100 million EUR; limited by economic efficiency gap to reference technology)

3) Individual measures – generating technology (max. 40 % or 100 million EUR; limited by economic efficiency gap to reference technology)

4) Operating cost support (depending on certain criteria for each technology, e.g., max. 9.2 ct€/kWh for heat pumps and further restrictions)

7.4.4. Aspects of the Flexibility Perspective

First, some considerations of an optimal dispatch in ecological and economic relations are to be pointed out. Depending on the energy market design and cost relation between electricity and gas, it has been investigated that the operation of large-scale heat pumps depends a great deal on ecological or economic aspects. Considering the operation of a district heating plant consisting of CHP units and heat pumps, the following observations have been made.

As [21] has shown, there are different methods for the allocation of CO_2 emissions in CHP systems for the produced heat and electricity. The most appropriate way is based on the Carnot-method which depends on temperature regime to be considered for each time of operation and not applied in regulatory schemes so far. Instead, quite simple and robust rules are applied which are based on constants like primary energy factor and a constant share of heat and power.

In the current energy system of Germany and its market restrictions, such a consideration leads to rather different optimal dispatch of heat pumps that are coupled electrically to a CHP system on site. Considering that most economical dispatch would lead to an operation of self-consuming electricity of the entire plant as it is favorable to consume the produced energy by the utility itself. In contrast, most ecological dispatch would incorporate renewable-based electricity which might be available through the grid, but which is too expensive due to network charges. This issue is very sensitive to the considered source of the heat pump and, therefore, its assigned COP. On rather high source temperatures, resulting on high COP-values, the issue might turn around.

The flexibility contributions of the technologies presented in this section are based on [11]. Flexibility contributions are the amounts of energy that technologies can either produce or consume when there is a shortage of electricity (electricity generation from renewables is less than the electricity load), surplus (electricity generation from renewables exceeds electricity load).

8. Conclusion

It can be stated that electricity is becoming the most important primary energy source and that flexibilization is becoming the new paradigm of grid operation. It might be put to the point that "yesterday supply follows demand", and it is stated for tomorrow "flexibilization: continuous balancing between power generation from renewable energies (wind, sun), controllable power plants, flexible loads (including electrolysers) and storage". Furthermore, there is no need for base load power generation.

Firstly, on-site energy supply solutions enable a massive reduction in regulatory complexity for integrated energy supply concepts (buildings, districts), and secondly, they enable the creation of a simple legal framework with an interface to the higher-level network (system serving).

9. References

[1] Deutsche Energie-Agentur GmbH (Hrsg.) (dena, 2021). „dena-Leitstudie Aufbruch Klimaneutralität“

[2] Prognos, Öko-Institut, Wuppertal-Institut (2021): Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann; Zusammenfassung im Auftrag von Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende

[3] Klimapfade 2.0 - Ein Wirtschaftsprogramm für Klima und Zukunft (2021), herausgegeben vom Bundesverband der Deutschen Industrie (BDI)

[4] Langfristszenarien für die Transformation des Energiesystems in Deutschland 3. Kurzbericht: 3 Hauptszenarien, Sensfuß, F., Lux, B., Bernath, C., Kiefer, C. P., Pfluger, B., Kleinschmitt, C., Franke, K., Deac, G., Brugger, H., Fleiter, T., Rehfeldt, M., Herbst, A., Manz, P., Neuwirth, M., Wietschel, M., Gnann, T., Speth, D., Krail, M., Mellwig, P., Blöhmer, S., Tersteegen, B., Maurer, C., Ladermann, A., Dröscher, T., Willemsen, S., Müller-Kirchenbauer, J., Giehl, J., Hilaire, M., Schöngart, S., Kurre, A., Hollnagel, J. u. Mikulicz-Radecki, F. von, 2021

[5] Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich, Ariadne-Report, Luderer, G., Kost, C. u. Sörgel, D., 2021

[6] Dialog Klimaneutrale Wärme 2045 - Ergebnispapier (2021) https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/dialog-klimaneutrale-waerme-ergebnispapier-publikation.pdf

[7] Vorjahreschätzung (VJS) der deutschen Treibhausgas-Emissionen für das Jahr 2022. Umweltbundesamt, 15.03.2023, https://www.umweltbundesamt.de/daten/klima/treibhausgas-emissionen-in-deutschland#treibhausgas-emissionen-nach-kategorien

[8] BMWi Energiedaten für das Jahr 2020, 27.09.2021, https://www.bmwi.de/Redaktion/DE/Binaer/Energiedaten/energiedaten-gesamt- xls.html.

[9] Mellwig, P., Lempik, J., Blömer, S. u. Pehnt, M.: Langfristszenarien für die Transformation des Energiesystems in Deutschland - Modul Gebäude. 2021

[10] Wege zu einem klimaneutralen Energiesystem. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen, Sterchele, P., Brandes, J., Heilig, J., Wrede, D., Kost, C., Schlegl, T., Bett, A. u. Henning, H.-M., 2020

[11] Wege zu einem Klimaneutralen Energiesystem. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen - Update November 2021: Klimaneutralität 2045, Brandes, J., Haun, M., Wrede, D., Jürgens, P., Kost, C. u. Henning, H.-M., 2021

[12] Agora Energiewende, Fraunhofer IEG (2023): Roll-out von Großwärmepumpen in Deutschland. Strategien für den Markthochlauf in Wärmenetzen und Industrie, 2023

[13] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation und Eisenbahnen, Marktstammdatenregister. https://www.marktstammdatenregister.de/MaStR

[14] The development of battery storage systems in Germany: A market review (status 2023), Figgener, J., Hecht, C., Haberschusz, D., Bors, J., Spreuer, K. G., Kairies, K.-P., Stenzel, P. u. Sauer, D. U., 2022

[15] Bundesverband der Energie- und Wasserwirtschaft e. V. (BDEW), Die Energieversorgung 2022, Jahresbericht - Update Mai 2023

[16] Systematische Anwendung von Großwärmepumpen in der Schweizer Industrie [online] [Zugriff am: 30. Oktober 2023]. Verfügbar unter: https://waermepumpe-izw.de/wp-content/uploads/2020/05/160510_Bfe-Bericht_WP_industr._Anwendungen.pdf, Wolf, S., Roman, F., Radgen, P. u. Blesl, M., 2017

[17] Projektionsbericht 2021 für Deutschland; Öko-Institut, Berlin; Fraunhofer ISI, Karlsruhe; IREES GmbH, Karlsruhe; Thünen-Institut, Braunschweig, Eberswalde, Hamburg [abgerufen am 08.11.2023] https://www.umweltbundesamt.de/dokument/projektionsbericht-2021-politikszenarien-x

[18] Heizungstechnologien im Gebäude: Ein Beitrag zur Bewertung der Wirtschaftlichkeit und Klimawirksamkeit, Meyer, R., Senkpiel, C., Heilig, J., Berneiser, J., Fluri, V., Gorbach, G., Herkel, S. u. Kost, C., 2021

[19] Merkblatt für innovative KWK-Systeme zur Darlegung der Zulassungsvoraussetzungen nach dem Kraft-Wärme-Kopplungsgesetz (KWKG) i. V. m. der KWK-Ausschreibungsverordnung (KWKAusV), https://www.bafa.de/SharedDocs/Downloads/DE/Energie/kwk_anlagen_mb_innovative_kwk-systeme.pdf?__blob=publicationFile&v=2, BAFA: Bundesamt für Wirtschaft und Ausfuhrkontrolle

[20] Bundesförderung für effiziente Wärmenetze: Anforderungen der Module 1 bis 4; https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/Effiziente_Waermenetze/effiziente_waermenetze_node.html, BAFA: Bundesamt für Wirtschaft und Ausfuhrkontrolle

[21] Hurst, G., Jentsch, A. u. Blesl, M.: Combination of Heat Pump with Cogeneration in District Heating Networks: Ecological Assessment and Boundary Condition for Ecologic Operation. 2023

[22] Axberg, E., Alkefjärd, T., Grahn, P., Jigvall, C., Karlsson, J., Karlsson, T., Pandur, S., Sidén, J., Nylander, C. V. & Wallnerström, C. J. 2020. Kapacitetsutmaningen i elnäten (R2020:06). Eskilstuna: Energimarknadsinspektionen.

[23] Axelsson, E., Blomqvist, P. & Unger, T. 2018. Värmepumpars påverkan på effktbalansen - Idag och i framtiden Eskilstuna: Energimyndigheten.

[24] Brunge, K., Hellström, E., Jakobsson, M. & Thornberg, E. 2021. Långsiktig marknadsanalys 2021 - Scenarier för elsystemets utveckling fram till 2050 (Svk 2019/3305 v.1.0). Sundbyberg: Svenska kraftnät.

[25] Energiföretagen, 2023, Fjärrvärmeleveranser, https://www.energiforetagen.se/statistik/fjarrvarmestatistik/fjarrvarmeleveranser/

[26] Energimyndigheten. 2023. Scenarier över Sveriges energisystem 2023. ER 2023:07. ISBN978-91-7993-112-4. https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=213739

[27] Koronen, C., Åhman, M. & Nilsson, L. J. 2020. Data centres in future European energy systems—energy efficiency, integration and policy. Energy Efficiency, 13, 129-144.

[28] Lindahl, M., Wennerlund, P. 2018. IEA Heat Pumping Technology Annex 47, Task 1: Market and energy reduction potential, Country report Sweden

[29] TenneT, 2021, https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2022-07/Annual_Market_Update_2021_0.pdf