The role of heat pumps in the transformation of national energy systems - Example Germany

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Abstract

The aim to limit climate change is the major driver for the transformation of energy systems globally. Renewable energies and high efficiency energy conversion on the whole chain from primary energy to net energy in all end-use sectors are key elements of highly decarbonized energy systems. Electric heat pumps in combination with highly decarbonized electricity or gas heat pumps in combination with decarbonized methane (biomass, power-to-gas) can cover a large share of the low temperature heat demand in various end-use sectors such as buildings (space heating, hot water) and the tertiary sector. Decentralized solutions in single buildings and large scale solutions in combination with district heating networks can both contribute to an efficient low temperature heat supply. In the paper results of a powerful simulation-based optimization of the transformation of the German energy system are presented and the role of heat pumps in the heat sector is be particularly highlighted. Cost-optimization clearly shows the dominant role that heat pumps must play in the heat sector under energy scenarios that lead to highly decarbonized overall energy systems. Furthermore the impact of electrical heat pumps on the residual load and thus on the total system infrastructure is investigated.

1. Introduction

During the past decade, Germany has taken a leading position in the market introduction of renewable energy technologies that was instrumental in bringing down their cost dramatically. The driving force of the energy transformation in Germany is the political goal of drastically reduced greenhouse gas emissions in order to limit the anthropogenic climate change and thus the danger of drastic influences on nature and the conditions of human life and economy. The declared goal of the German Government is to decrease the greenhouse gas (GHG) emissions of Germany by 2050 by at least 80 % [1] and wherever possible by 95 %, below 1990 levels [2, 3]. This objective is supported by a wide social consensus in Germany. The total amount of GHG emissions in the reference year 1990 amounted to 1,215 million tons of CO_2 equivalent (for this purpose, all greenhouse-relevant effects are converted into the climate-changing effect of CO_2). This value includes the CO_2 lowering in agriculture and forestry. For the years prior to 2050, reduction target values are defined as well: a reduction by 40 % by 2020, by 55 % by 2030, and by 70 % by 2040.

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The amount of the German GHG emissions in the past is presented in Figure 1, together with the target values intended for the period up to 2050.
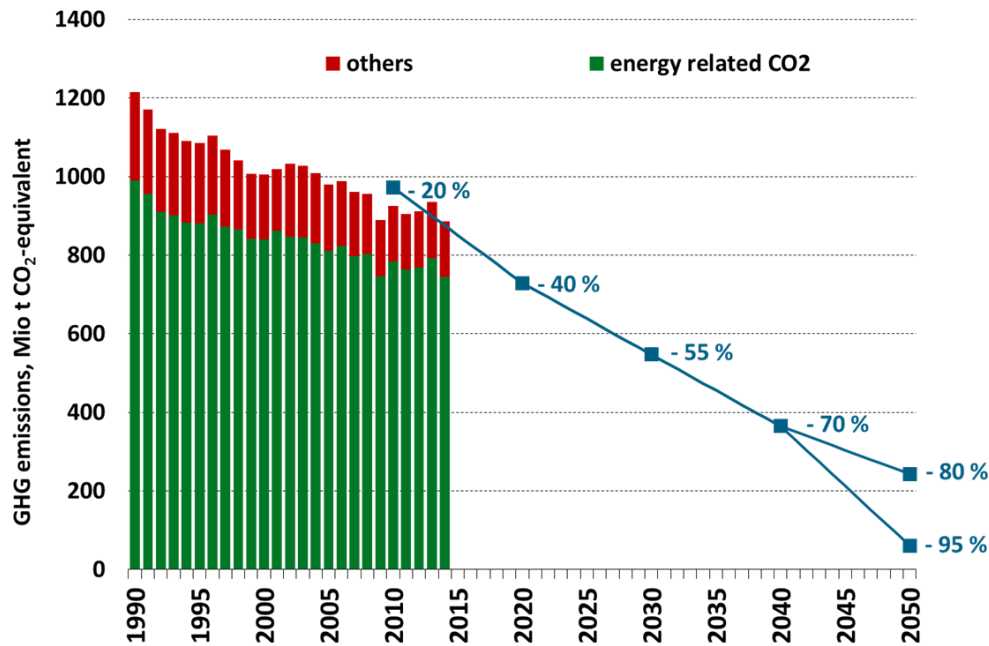

Figure 1: Greenhouse gas (GHG) emissions in Germany from 1990 till 2013, and target values up to 2050 (blue dots). Green bars represent energy-related CO_2 emissions, red bars other GHG emissions. Percentage reductions refer to the 1990 value

The largest share of GHG emissions is provoked by energy-related CO_2 emissions with close to 990 million tons in 1990 and 793 million tons in 2013 (see green bars in Figure 1). Thus, energy-related CO_2 emission is allowed to be at maximum 198 million tons in 2050 in order to achieve the reduction goal of 80 % compared to the reference year 1990. Here it is assumed that energy-related CO_2 emissions are reduced to the same extent as all other greenhouse gas emissions.

In 2013 the largest individual portion of energy-related CO_2 emissions with close to 45 % is caused by electricity generation. Although electricity amounts to around 20 % of the final energy, its portion in CO_2 emissions is significantly larger due to high losses and own consumption in the power plant sector. Mobility is responsible for around 20 % of the energy-related CO_2 emissions with street traffic representing the largest portion. Around 18 % are caused by business, public sector, and households. Here, fuels for space heating and hot water play the largest role. Additional 16 % are caused by the manufacturing and construction industry. With these numbers in mind and under the assumption that climate protection targets will be met it becomes clear that the investigation of national energy systems needs to be done considering all sectors together.

To investigate how a national energy system in line with the mentioned political goals could look like in 2050 we developed an energy system model called Regenerative Energy Model: REMod [3–8]. As far as known, among all existent energy system models, no other model considers all relevant consumption sectors and conversion techniques in the energy system and simultaneously optimizes the transformation path on an hourly resolution from today to the year 2050. With Germany as example, in this paper we focus on the relevance and the influence of heating technologies – particularly electrical heat pumps – in the context of decarbonizing the German energy system.

2. Model Methodology

The basic functionality of the REMod model is founded on a cost-based optimisation of a German energy supply system under the boundary condition that energy-related CO_2 emissions do not exceed the target values show in Figure 1. The optimisation target is to dimension all generators, converters, and consumers at minimum cost, such

that the energy balance of the overall system is met at every hour. Conventional power plants with lignite and hard coal as fuel, nuclear power plants, oil-fired power plants, gas turbines, CHP plants, and gas-fired and steam power plants are implemented as generators. Renewable energy can be supplied in the model using wind turbines onshore and offshore, photovoltaic systems and hydropower plants.

Biomass can be used in different ways either directly or after conversion into a secondary energy carrier. For example, wood can be used in boilers, in order to provide process heat for industrial applications and for the generation of low-temperature heat in the building sector. Biogas systems, gasification systems with subsequent synthetisation into hydrogen, methane, or liquid fuels and biodiesel systems are implemented as possible systems for the conversion of biomass. Electrical energy storage systems in the form of stationary and mobile (in vehicles) batteries or pumped-storage power plants are used as storage systems. Hydrogen storage systems and thermal hot water storage systems in different orders of magnitudes are considered as well. With respect to methane storage system, the simplified assumption is made that currently already existing storage capacities (including grid, approx. 210 TWh in Germany [9]) will also be available to the system in the future. They are not subject of the optimisation. [5]
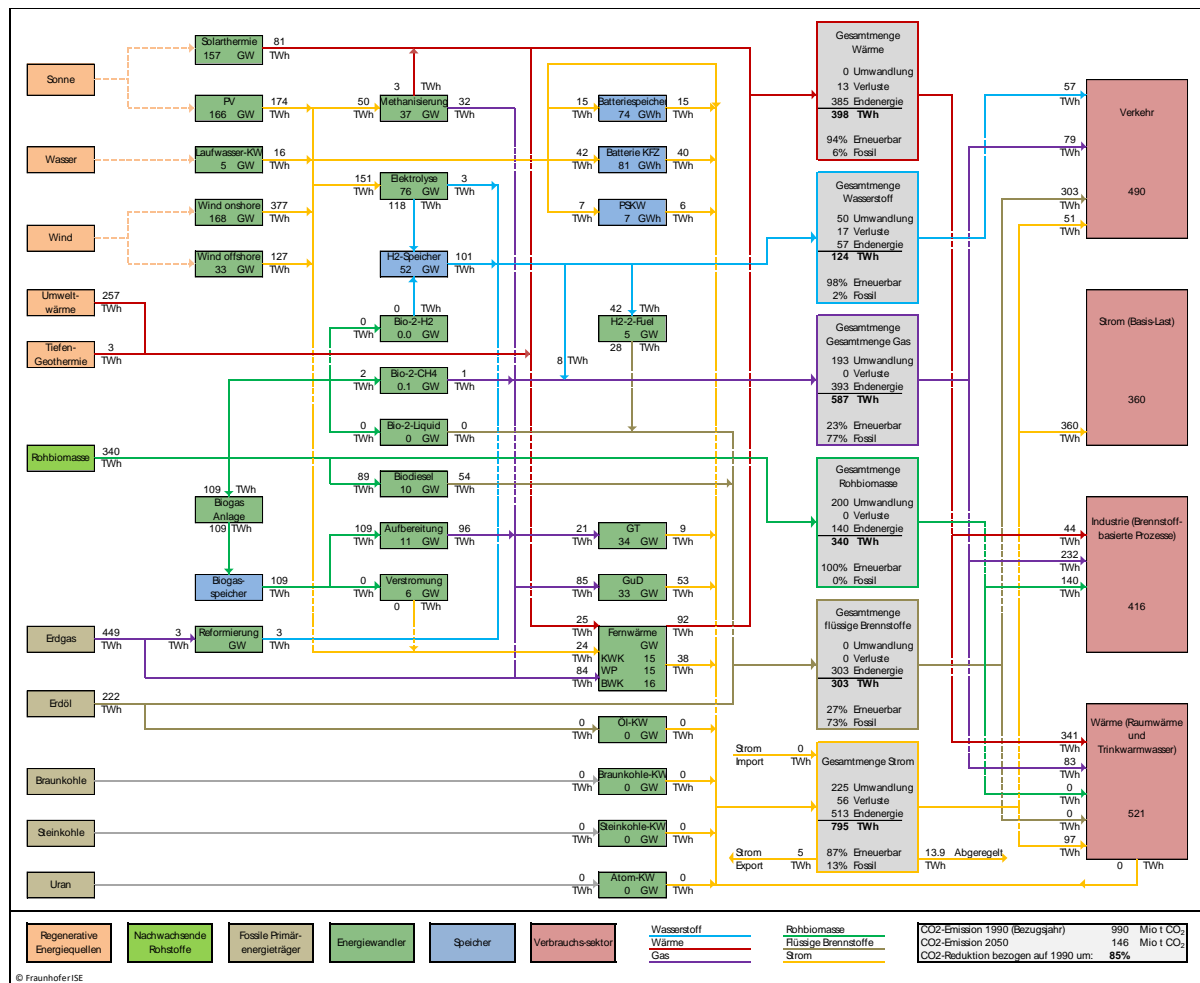
Figure 2: Schematic of the energy system as presented in the REMod simulation model. The illustration shows all conversion pathways of fossil primary energy and/or renewable energies up to the end-use sectors. (Values are examples for a scenario with a reduction of energy-related CO₂ emissions by 85 % [5].

The energy demand side is divided into four groups, according to the different fields of use: Mobility, intrinsic electricity applications, heat for buildings (residential, non-residential, and industrial buildings), and process heat in the industry. The mobility sector is mapped in detail concerning passenger cars and trucks, with seven vehicle concepts each. The energy demand of aviation, shipping, and fuel-based railway traffic is considered in the balance, however, without temporal resolution. The basic electricity load is mapped using load profiles based on

the data of European transmission grid operators that was reduced by the current load for heating systems. This load is calculated model-endogenously and is not included in the basic load. [5]

The building sector is implemented with 18 possible heat supply technologies. Each of these heating technologies can be optionally supplemented with a heat storage device or solar thermal energy system. Figure 3 shows an example of the »electrical brine heat pump« system, hence, a brine-water heat pump with the ground as heat source. The possible energy flows between the individual system components are shown. Thermal storage devices can be charged through solar thermal energy, as well as through heat from excess power (directly or via the heat pump). The latter option allows the flexible use of power in the case of a negative residual load. Vice versa, the heat pump can be switched off and the heat storage discharged in the case of a positive residual load and simultaneous heat requirement.
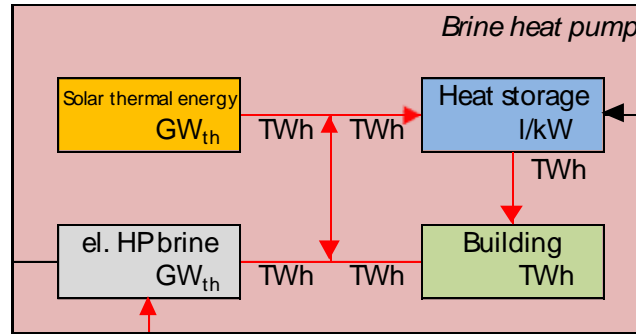

Figure 3: Schematic design of heating systems based on the example of a ground-coupled, electrical heat pump (HP) (red lines = heat, black line = power) [10]

2.1. Modelling of heat pumps

Hybrid heat pumps and gas driven heat pumps in REMod are represented as air-to-water systems. The temporal dependency of these heat pumps is described by characteristic performance curves. This means that the relation between the heat delivery and the necessary operating power is represented as a function of the difference between the source and the sink temperature. The source temperature for air-to-water heat pumps depends on the outside ambient temperature where for brine heat pumps the ground temperature is assumed to be constant at 10°C [11]. Figure 4 shows the coefficient of performance as a function of the temperature difference between the source and sink for the described systems.
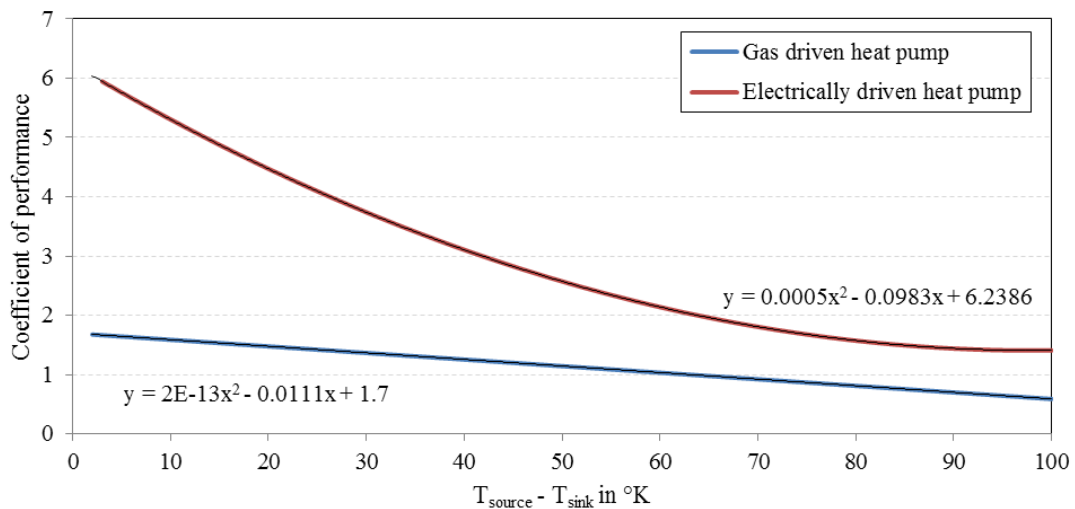

Figure 4: Function of the coefficient of performance for electrically driven and gas driven heat pumps. Illustration based on [5]

The sink temperature depends from the respective time step. For each time step the hourly inlet temperature is calculated from the weighted average heating and hot water demand. The data shown in Figure 4 is obtained from measurement campaigns, conducted at Fraunhofer ISE ([12–14]). Gas driven heat pumps are still considered to be at the research stage which is why the available data is currently unsatisfactory. Nevertheless with the help of an expert survey an approximated curve for the coefficient of performance has been drawn. [5]

3. Results

As shown in a preliminary study [10] the declared CO_2 reduction targets on the pathway from 2015 to 2050 heavily influence the composition of the heating supply technologies. While for a CO_2 reduction of 80 % (referred to 1990) a considerable part of the heat supply technologies relies on gas as energy carrier, a shift to electricity based systems becomes more evident once the CO_2 emissions are further decreased (cf. Figure 5). Concretely, in the target year 2050 the resulting share of electric heating supply technologies amounts to approximately 35 % for the -80 % CO_2 emission target, 65 % for the -85 % CO_2 emission target and more than 85 % for the -90 % CO_2 emissions target.
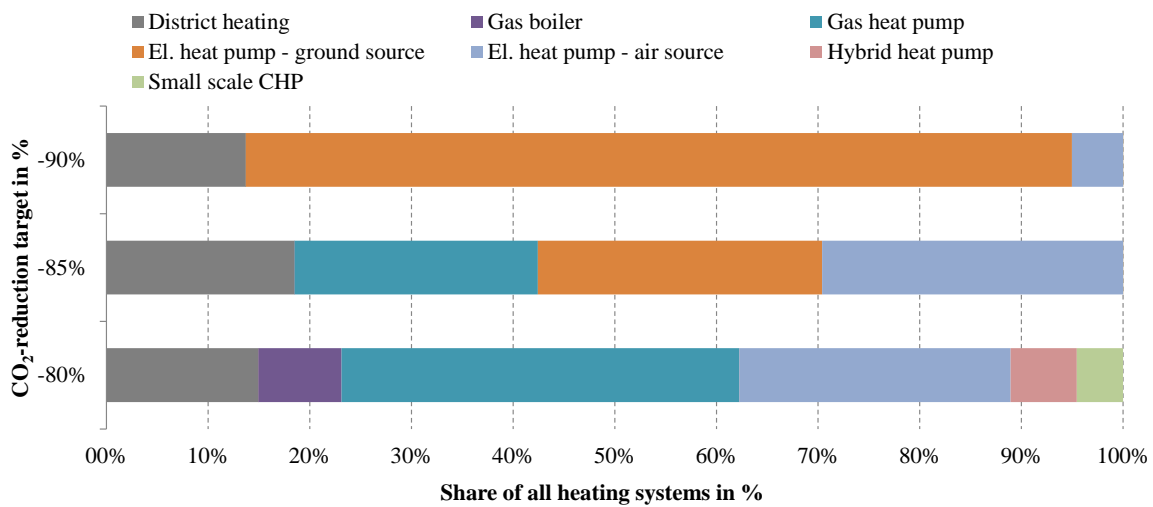

Figure 5: Share of all heating systems in 2050 for three different CO_2 -reduction targets. Own illustration based on [10]

If the overall system costs and the achieved reduction of energy related CO_2 emissions are both taken into account, the scenario with the reduction target of -85 % (cf. Figure 5) seems the most reasonable [10]. Therefore this setup is analysed in more detail.
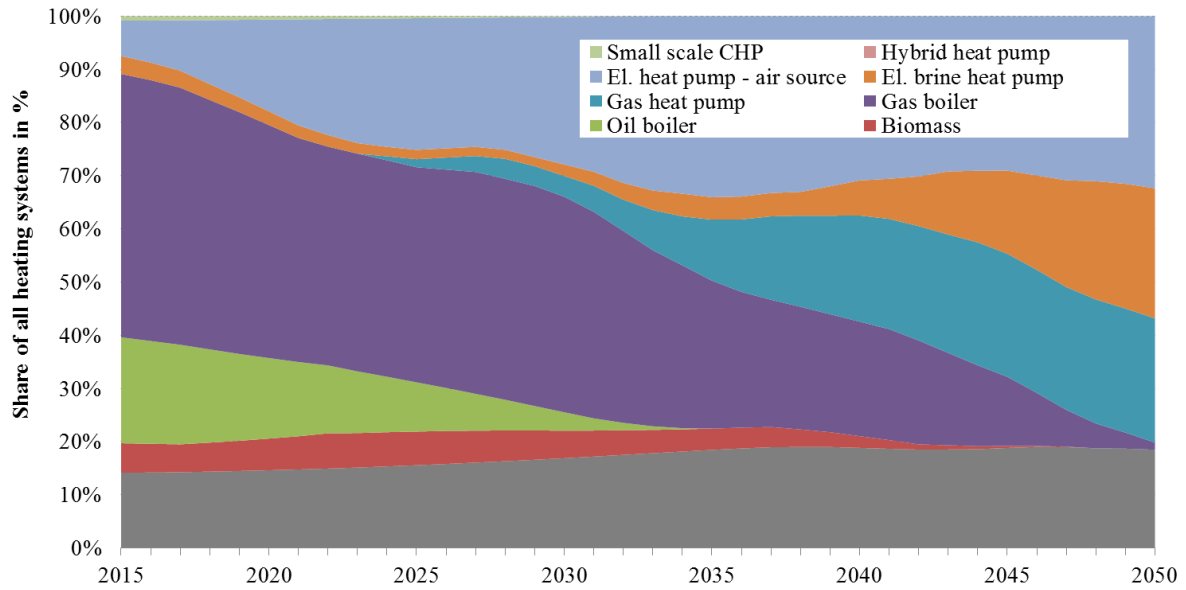
3.1. Scenario analysis: -85 % CO₂ emission target

Figure 6: Development of heat supply technologies in buildings for energy related CO_2 emission reduction of 85 %

Figure 6 shows the composition of heat supply technologies on the pathway from 2015 to 2050. The chart highlights that oil boilers expire first, followed by biomass and gas boilers. The number of district heat connections increases slightly only and is at approx. 20 % at the end of the investigated period. The figure shows clearly that - under the assumed boundary conditions – heat pumps will become the dominating heating technology. Their share over all heating systems increases continuously and reaches more than 80 % by 2050. Approximately one quarter of all decentralized heat pumps is gas driven, while the remaining 75 % are electrical air- and brine heat pumps. Hybrid heat pump systems, which integrate an air heat pump with a condensing gas boiler, under given boundary conditions don't play any role. This means that a substantial part of the total heat demand (excluding process heat) is supplied by electric heating systems. The associated increasing electricity demand for heating purposes can have a significant impact on the residual load.
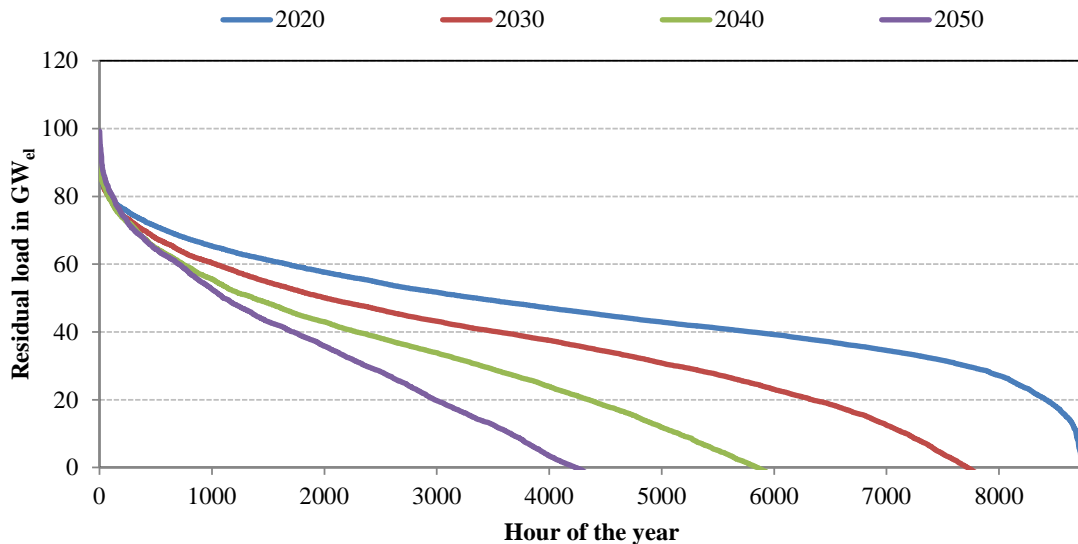

Figure 7: Sorted profile of the positive residual load for target years 2020, 2030, 2040 and 2050 (-85 % CO₂ reduction target)

Figure 7 portrays the sorted positive residual load profile for the target years 2020, 2030, 2040 and 2050. The residual load is here defined as the total electric load minus the production from non-dispatchable renewable energy sources, i.e. solar PV and wind power plants.

Although the system in 2050 is dominated by electric heat supply technologies (Figure 6) the number of hours per year for which the residual load is positive decreases from 8740 hours/year in 2020 to approximately 4240 hours in 2050. On the other hand the peak value of the residual load only slightly increases over the course of the years, ranging from 90 GW_{el} in 2020 up to 100 GW_{el} in 2050 (+12 %). This power can be covered by discharge of short term storage (pumped hydro, batteries) or by residual dispatchable power generation capacity (e.g. thermal power plants).

To quantify to what extent the electric heat pumps are responsible for the increase of the residual load a further analysis has been carried out. It is shown that electric heat pumps mainly operate in times where power deficiency in the energy system occurs and thereby contribute to further increase the residual load of the overall system. In 2050 almost 97 % of the electricity demand by electric heat pumps occurs when the residual load is already positive. This corresponds approximately to 107 TWh_{el}.
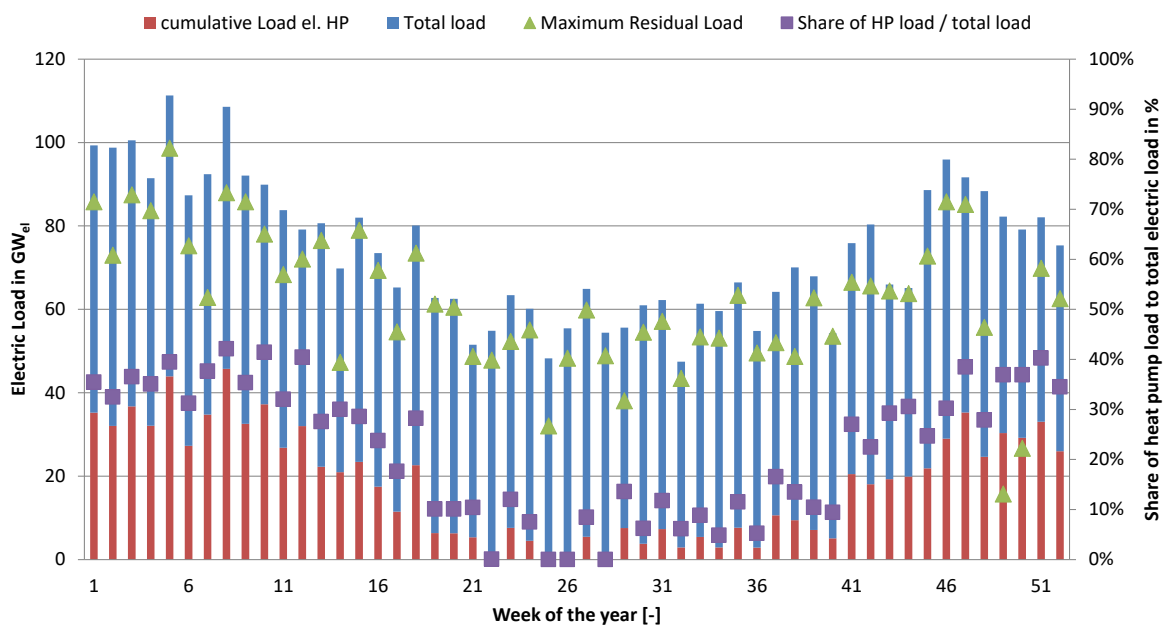

Figure 8: Maximum residual load and electric load of heat pumps in 2050 (CO_2 -reduction target -85 %)

Figure 8 shows the maximum value of the residual load for each week of the year as well as the total electric load and the cumulative electric load of heat pump systems in the respective hour (primary axis). On the secondary axis the share of the electrical heat pumps on the total electric load is displayed.

According to Figure 8 the values for the maximum residual load over the year range from approximately 15 GW_{el} to 100 GW_{el}. On average the maximum residual load in summer amounts to 50 GW_{el}, while in winter it increases by almost 30 GW_{el}.

The share of electric heat pumps to the total electric load varies strongly over the year. While their contribution to the cumulated load is negligible during summer (e.g. zero in weeks 22, 25, 26, 28 despite the hot water preparation), in the winter period it amounts to approximately 36 %. This corresponds to a mean enhancement of the electric load by 35 GW_{el} due to electric heat pumps only. The peak residual load in 2050 occurs during week 5 and amounts almost 100 GW_{el}. At this moment the electric load of heat pumps is about 44 GW_{el} and therefor accounts for 39 % of the cumulative load. To analyse this week in more detail it is visualized in Figure 9.
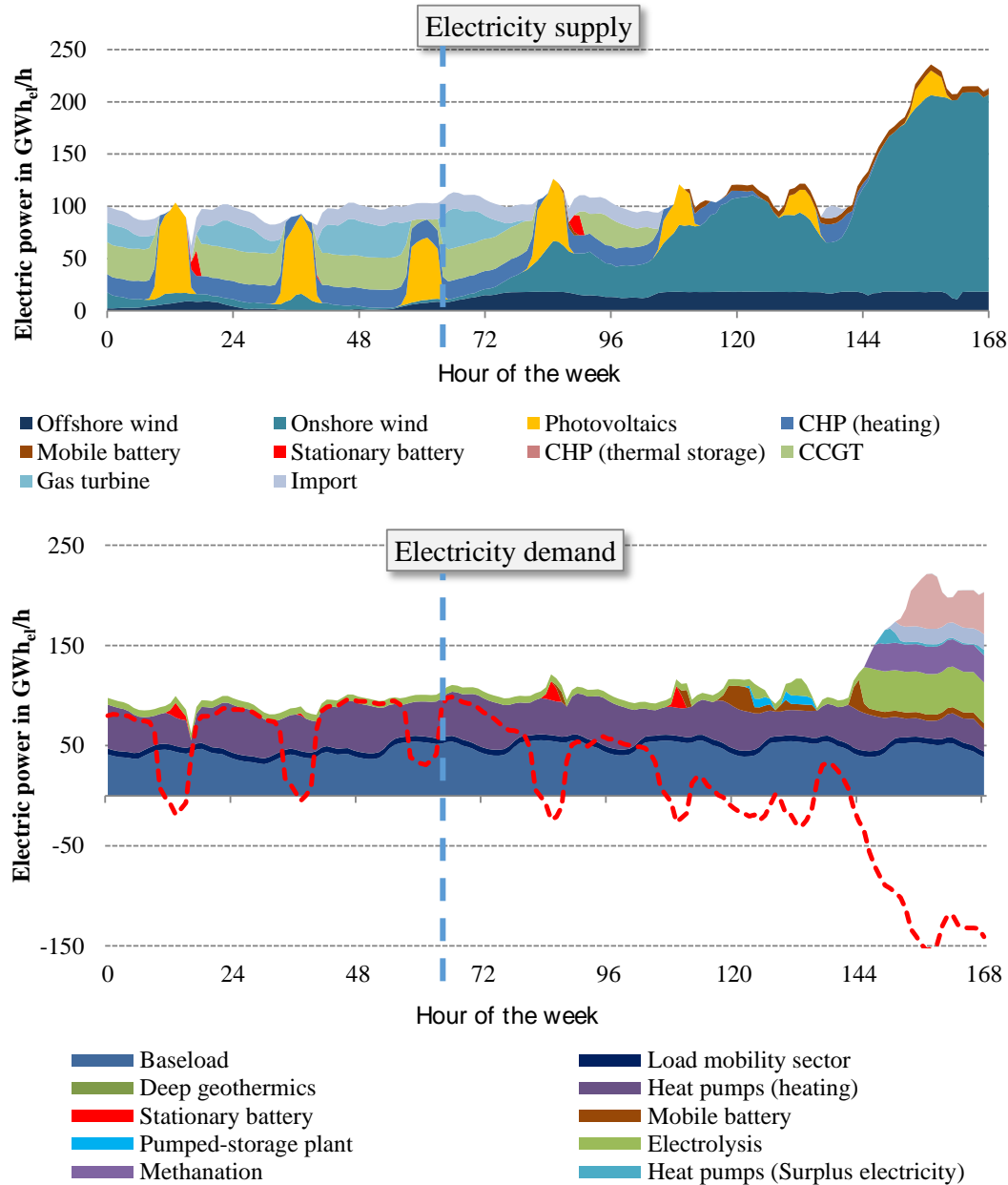
Figure 9: Electricity supply (top) and demand (bottom) for week 5 (CO_2 reduction target: -85 %). Maximum residual load during the week is highlighted in blue (hour 67)

Figure 9 displays the electricity supply (top) and demand (bottom) for the fifth week of the target year 2050. A dashed line highlights hour 67 (day 3 of the fifth week, 7 pm), which is when the maximum residual load during the week and year occurs. At this time the heat demand slightly increases due to the drop of both, the outside temperature and the solar heat gains, while the feed-in from solar energy systems stops, leaving only a modest power generation from wind energy (13 GW_{el}). This hour of the year significantly influences the dimensioning of the electricity supply components. As a result the energy demand is covered by mainly three options: import of electricity (15 GW_{el}) and highly flexible gas turbines (38 GW_{el}) as well as combined cycle gas turbine plants (31 GW_{el}).

Todays installed cumulative capacity of gas turbines and CCGT-plants in Germany amounts to approximately 21 GW_{el}. This means that by 2050 this value has to grow by three times. At the same time it should be kept in mind that 50 GW_{el} of less flexible coal plants as well as 12 GW_{el} of nuclear power plants will be disconnected

from the power supply system. The so resulting required installed capacity of thermal power plants in 2050 is 25 GW_{el} lower than today's value (Figure 10).
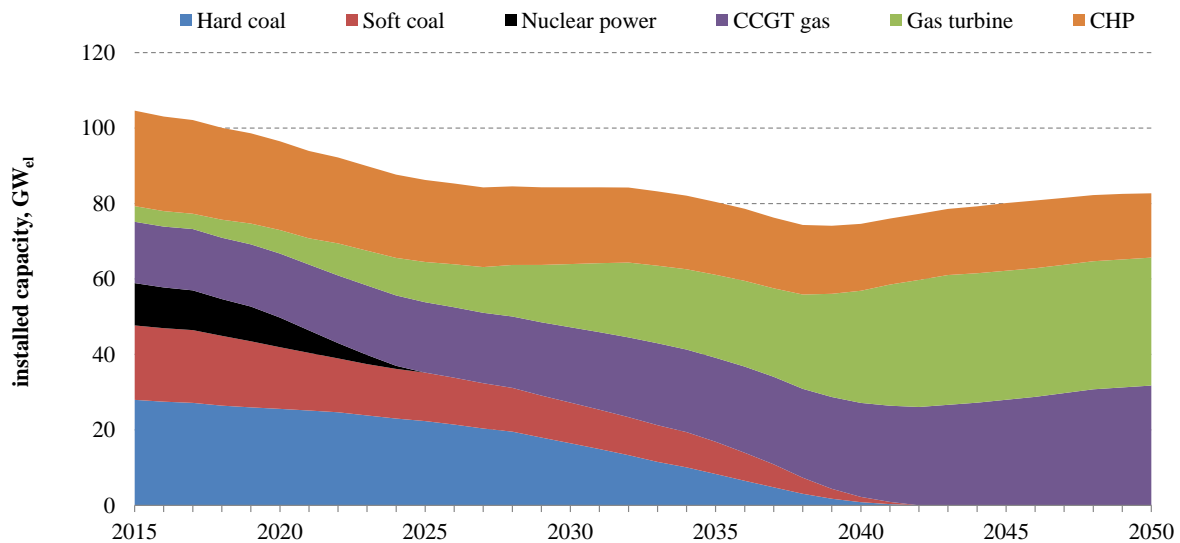

Figure 10: Profile of the installed power of thermal power plants and /or electrical power of CHP plants [10]

4. Conclusion

Our recent work shows that the predominance of purely electrically driven heat pumps increases with increasing CO_2 reduction targets. For the investigated reduction value of -85 % CO_2 in 2050 (compared to 1990 levels) the heating in buildings, which are not connected to district heating, turns out to be dominated by electrically driven heat pumps. Contemporary the total share of gas- and oil driven heating technologies significantly decreases. Although the system in 2050 is characterised by electric heating supply technologies the number of hours per year for which the residual load is positive diminishes over the course of the years. On the other hand this leads to a higher peak value of the residual load and therefor to a higher amount of required flexible backup power plants.

The contribution of electric heat pumps to the enhancement of the residual load is negligible in summer, while being most pronounced in winter during the evening hours, when outside ambient temperature and the feed-in from photovoltaic systems drop. On average the share of electric heat pumps to the weekly maximum electric load in winter amounts to 36 %, reaching peak values of 42 % (see example: fifth week in 2050). This corresponds to an increase of the residual load by 44 GW_{el} due to electric heat pumps only.

Despite the high penetration of electric heat pumps, with an appropriate expansion of flexible power plants security of supply can be achieved. Overall it turns out to be more favourable to install a higher amount of power plants to be able to operate purely electrically driven heat pumps even during cold winter periods with low electricity generation from solar and wind rather than operate hybrid heat pumps which would provide an alternative solution with a decentralized fuel switch. Further scenario studies using modified cost assumptions are under work in order to indicate under which conditions hybrid heat pumps would be able to provide a competitive solution.

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