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Power sector benefits of flexible heat pumps in 2030 scenarios

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Heat pumps play a major role in decreasing fossil fuel use in heating. They increase electricity demand, but could also foster the system integration of variable renewable energy sources. We analyze three scenarios for expanding decentralized heat pumps in Germany by 2030, focusing on the role of buffer heat storage. Using an open-source power sector model, we assess costs, capacity investments, and emissions effects. We find that investments in solar photovoltaics can cost-effectively accompany the roll-out of heat pumps in case wind power expansion potentials are limited. Results further show that short-duration heat storage substantially reduces the need for firm capacity and battery storage. Larger heat storage sizes do not substantially change the results. Increasing the number of heat pumps from 1.7 to 10 million units could annually save more than half of Germany's private and commercial natural gas consumption and around half of households' building-related CO_2 emissions.

In light of the climate crisis, heat pumps are regarded as a central technology to reduce greenhouse gas emissions in the heating sector[1]. Heat pumps can displace traditional heating technologies such as oil- and gas-fired heating and mitigate greenhouse gas emissions when powered with electricity from renewable energy sources (RES). In addition, in the European context, the Russian invasion of Ukraine has led to further political push, especially in Germany, to reduce the dependence on Russian natural gas imports. In Germany, natural gas is currently still the dominant source of residential heating. Therefore, the electrification of heating can be considered a critical measure to reduce the use of natural gas.

In Germany, policymakers are working to accelerate the implementation of decentralized heat pumps, with a declared target of 6 million heat pumps installed by 2030[2]. Given the current stock (2024) of around 1.7 million heat pumps, such a transition implies an increase in the electricity demand. So far, it is not yet fully understood how a larger heat pump stock affects the power sector in detail, considering that the electricity needs for mobility, hydrogen production, and other energy services will also rise. One common concern is that heat pumps could add to existing load peaks due to electricity load profiles coinciding with heat demand profiles, and thus increase the need for firm generation capacity or electricity storage. Therefore, the potential benefits of flexible heat pump operations are of central interest. For that reason, we explore the power sector effects of various heat pump rollout scenarios in Germany. In particular, we focus on different degrees of temporal flexibility in heat pump operations by varying the size of the heat storage assumed to be attached to heat pumps. To do so, we use the open-source capacity expansion model DIETER[3–5] to model the central European power sector for various scenarios of 2030.

Previous studies have highlighted the important role of heat pumps in the decarbonization of the heating sector. A recent study shows that deploying heat pumps is one of the fastest strategies to reduce natural gas consumption in the German heating sector[6]. Several studies investigate the potential of heat pumps to facilitate the integration of renewable energy sources in the power sector. For example, different analyses show that deploying additional heat pumps aligns well with additional investments into wind power plants[7,8]. Regarding the flexibility of heat pumps and optimal heat storage size, the picture is inconclusive. Investigating various heat storage sizes, one study finds that the optimal thermal energy capacity of heat pumps in Spain and the UK lies between 12 and 14 h of maximum heat output[9]. A previous analysis of wind power deployment in Denmark finds that the flexible operation of heat pumps provides only moderate system benefits and that even inflexible heat pumps enable a higher share of wind power energy[10]. Heat pump flexibility can also be provided by the thermal inertia of buildings[11], which can help to integrate renewable energy[12]. Another study points out that the power system cost savings from flexible electric heating with night storage in Germany are moderate because renewable availability patterns do not align well with heat demand profiles[13]. The seasonal demand pattern disadvantages flexible electric heating compared to other sector coupling options without this seasonality, such as electric vehicles. This finding is also supported by another study[14] that identifies a larger potential for load shifting in electric vehicles than in heat pumps. Another study focuses on the role of flexible, large-scale, centralized heat pumps in district heating grids[15], finding a correlation between RES expansion and the choice of heating technologies. With higher deployment of RES, large heat pumps become more competitive. Other studies focus on the competition of flexibility provided by heat pumps with electricity storage units. In power systems with a share of renewable electricity of 80% or higher, the flexible use of heat pumps reduces the investment needs for short-term electricity storage considerably[16]. The substitutional nature

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between pumped-hydro storage and thermal storage is also highlighted in the literature[7].

Our paper adds to the existing body of literature by investigating the power sector effects of decentralized heat pumps in detail, specifically accounting for different amounts of temporal flexibility facilitated via heat storage. In our analysis, we use an open-source capacity expansion model that considers the hourly variability of renewable electricity generation and heat demand over an entire year. It also accounts for additional electric load related to electric vehicles and the production of green hydrogen. We investigate how different rollout speeds of heat pumps in Germany, specifically in combination with different heat storage capacities, impact the optimal capacity investment and dispatch decisions in the power system. In addition, we also provide an ex-post calculation to measure the associated natural gas usage, cost, and emission savings. To check the robustness of our results, we further carry out numerous sensitivity analyses with alternative assumptions on relevant input parameters such as renewable availability, including an extended drought period, different natural gas prices, and a German coal phase-out. To the best of our knowledge, such an analysis has not been done so far.

We show that an ambitious rollout of decentralized heat pumps can be accommodated in the German power sector at relatively low costs. If wind power expansion potentials are limited, heat pumps can be accompanied by an expansion of solar photovoltaic (PV) capacities in combination with moderate additions of electricity storage and other firm generation technologies, while also leveraging the flexibility potentials of the European interconnection. Short-duration heat storage helps to integrate renewable electricity efficiently and reduce peak loads, hence diminishing the need for additional generation and storage capacities. We find a strongly diminishing additional system value of longer-duration heat storage. Finally, we assess the impact of the heat pump roll-out on German natural gas consumption, CO_2 emissions, and costs. We conclude that an ambitious roll-out can contribute significantly to decreasing Germany's gas consumption while reducing emissions and overall system costs.

Results

Heat pump rollout triggers investments in electricity generation and storage

In the following, we present the power sector effects of three different rollout speeds of heat pumps (*slow*, *government*, and *fast*). In these, the number of heat pumps increases from 1.7 million units (in the *reference* scenario) to 3.0, 6.0, and 10.0 million respectively (see Table 1). We also discuss how the size of short-duration buffer heat storage attached to decentralized heat pumps affects the results. All these are part of our set of *baseline* scenarios. In these, we assume expansion limits of 115 gigawatt (GW) for onshore wind power and 30 GW for offshore wind power, no regulated phase-out of coal-fired power plants, and a natural gas price of 50 Euro per MWh.

Expanding the stock of heat pumps requires additional investments into electricity generation infrastructure. Looking first at inflexible heat pumps, we find that in the *reference* rollout, the cost-optimal capacity mix for reaching 80% renewable energy in Germany entails 115 GW of onshore wind, 26 GW of offshore wind, and 98 GW of solar PV (Fig. 1A). Further, 10 GW of hard coal and 47 GW of gas-fired power plants (sum of open and combined cycle gas turbines) are present. A rollout beyond the reference scenario requires higher generation capacity additions. The total additional generation capacities are around 5 GW and 20 GW (Fig. 1B) in the scenarios *slow* and *government*. For the *slow* rollout, 2 GW of offshore wind power and less than 1 GW of solar PV capacities are added, while around 3 GW combined of gas-fired power plants and lithium-ion batteries are added. For the *government* rollout, these numbers increase to 7 GW of additional gas-fired power plants and 8 GW of additional solar PV, driven partly by the fact that offshore wind capacities have reached their upper bounds and can only be expanded by an additional 4 GW. In the scenario *fast* with the highest rollout of 10 million heat pumps, 57 GW of solar PV capacity is added. In parallel to this large expansion of solar PV capacities, firm capacities in the form of gas-fired power plants increase by 18 GW to ensure the coverage of peak loads, while also 9 GW of lithium-ion battery storage is added. The optimal storage energy capacity of batteries increases by 3, 8, and 49 gigawatt-hours (GWh) in the three respective rollout scenarios (Fig. SI.4).

Heat storage reduces capacity needs for electricity generation and storage

Equipping heat pumps with heat storage reduces the need for additional electricity generation and storage capacities (Fig. 1C, D). Introducing heat storage with an energy-to-power (E/P) ratio of 2 hours (h) reduces the need for additional solar PV capacities (e.g., 6 GW instead of an additional 8 GW in the *government* rollout) compared to the *reference*. In addition, the need for battery storage is reduced by around 7 GW compared to the case without heat storage in the *government* rollout, and by 5 GW compared to the *reference*. This effect can be explained as lithium-ion batteries and heat storage of heat pumps are both short-duration storage technologies and, therefore, serve as complements, especially when taking up daily PV surplus generation peaks. Expanding the heat storage of heat pumps beyond an E/P ratio of 2 h, even lower additional solar PV capacities are needed, but especially additional capacities of gas-fired power plants are reduced. The capacity-reducing effect of the buffer storage of heat pumps can also be seen in the decreasing left-hand side of the residual load duration curves (Fig. SI.8). If combined with heat storage larger than 6 h in the *government* rollout (Fig. 1C) or larger than 24 h in the *fast* rollout (Fig. 1D), the introduction of heat pumps even reduces the overall need for gas-fired power plants as compared to the reference. Qualitative results are largely similar between the *government* and *fast* rollout.

We find a substitution between lithium-ion batteries and heat storage not only for storage power but also for storage energy capacities (Fig. SI.4). While the deployment of heat pumps leads to additional lithium-ion energy capacities in all three rollouts, the introduction of a 2-h heat energy storage does not only reduce the additional need for storage energy capacities but even turns it negative: hence the introduction of heat pumps in combination with 2-h heat storage is reducing the overall need for lithium-ion energy capacities. For larger heat storage capacities of 24 and 168 h, this absolute reversal cannot be detected, yet additional energy capacities are still considerably lower than in the case of inflexible heat pumps.

Table 1 | Heat pump data

		Reference	Slow	Government	Fast
Number of installed heat pumps	[million]	1.7	3.0	6.0	10.0
Heat pump power rating	[GW_e]	8.7	14.5	27.5	52.6
Maximum thermal heat pump output	[GW_{th}]	19.6	32.7	61.9	118.5
Share of air-sourced heat pumps		0.8	0.8	0.8	0.8
Share of ground-sourced heat pumps		0.2	0.2	0.2	0.2
Yearly heat supplied by heat pumps	[TWh_{th}]	24.7	53.2	92.9	226.3

Heat includes space heating and domestic hot water.

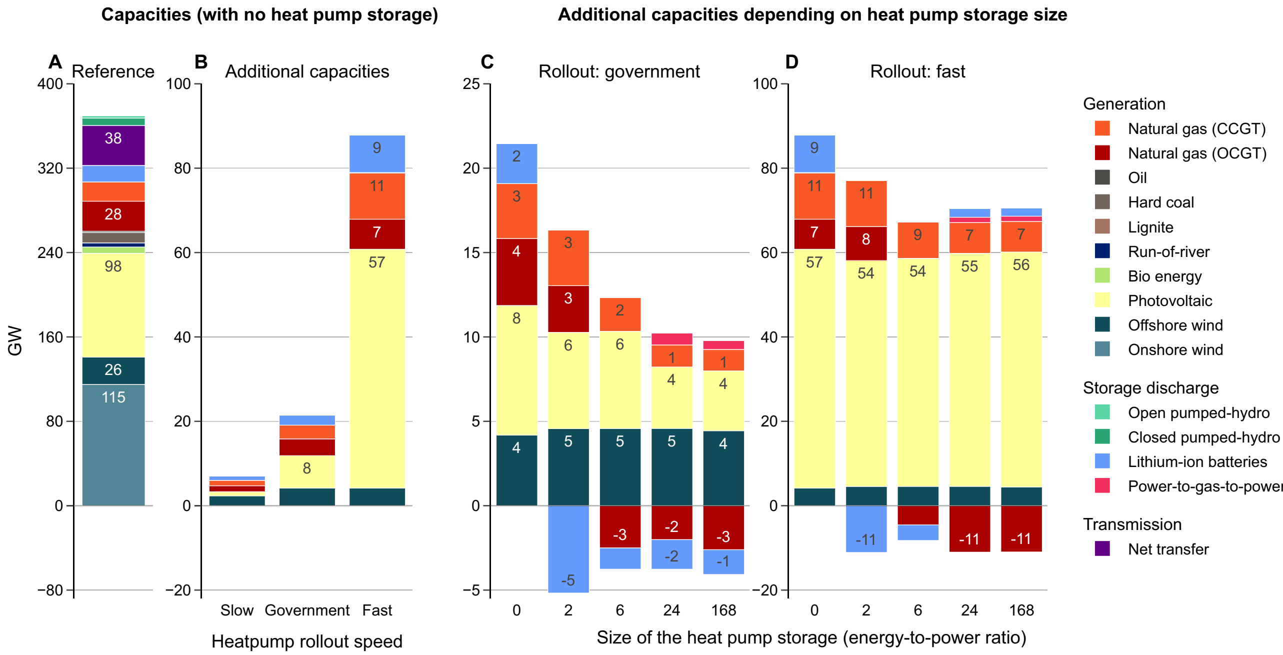


Fig. 1 | Capacity investments under baseline assumptions with different heat pump rollouts and heat storage sizes. A Optimal capacity investments in the *reference* scenario. **B** Changes induced by the rollout of heat pumps in the case of inflexible heat pumps. **C**, **D** Capacity changes to the respective references for different heat storage sizes in the *government* rollout (**C**) and *fast* rollout (**D**). The changes shown in **C** and **D** are to their respective references with different heat storage sizes. Reference results (**A**) are almost identically for different heat pump storage sizes. For better visibility, only one *reference* rollout is shown. Please note the different y-axis ranges of the different panels. The complete set of results, including those for storage energy, is shown in Fig. SI.4.

Due to the interconnection with its neighboring countries, the heat pump expansion in Germany could be partly supported by non-German generation and storage capacities. To avoid unintended support of German heat pumps by foreign power plants, we also co-optimize the power plant portfolios of neighboring countries, assuming an upper limit for fossil-fuel power plants outside Germany. Therefore, we ensure that German heat pumps in the model do not unduly benefit from an oversized exogenous power plant fleet outside Germany. Figure SI.6 confirms that aggregated generation capacities in all countries except Germany barely change after the introduction of heat pumps in Germany.

Heat storage helps to integrate renewable electricity

The rollout of heat pumps affects optimal generation and storage discharge (Fig. 2) similarly to optimal capacities. The additional electricity needed for heat pumps is primarily generated by offshore wind power and solar PV. The latter plays a more important role in the *fast* rollout due to the upper capacity bound of offshore wind power. As the profiles of solar PV generation and heat pump load only align to some extent, the expansion of heat pumps triggers additional generation by gas-fired power plants. Battery storage is also used more in the case of inflexible heat pumps, but less if heat storage is available. If no heat storage is available, the rollout of heat pumps is also accompanied by additional generation from bioenergy, which is another flexible generation technology but comes with relatively high variable costs. Accordingly, additional bioenergy use decreases if heat storage is available. Net imports of electricity slightly decrease with the rollout of heat pumps, especially when they do not come with heat storage, i.e., are operated inflexibly. That is due to more exports of renewable energy surpluses triggered by additional renewable energy capacities needed for the additional heat pumps. Figure SI.5 shows the dispatch results of all scenarios.

While the capacity and dispatch results already show that heat storage can help integrate renewable energy into the energy system, this effect is highlighted in Fig. 3. It provides an illustration of hourly electricity generation and demand in combination with additional electricity demand by heat pumps. The figure depicts two exemplary weeks under *baseline* assumptions with a *government* rollout and heat pumps with 2 h of heat storage. The diurnal fluctuations of solar PV generation are clearly visible, especially in the autumn week. In contrast, wind power generation has less regular yet longer variability patterns. In hours of low wind and solar PV generation, gas-fired power plants and imports cover the remaining residual load. Even with only 2 h of heat storage capacity, heat pumps can align a substantial part of their electricity consumption with PV peak generation periods. This indicates that even small heat storage capacities already improve the integration of heat pumps into the system. Hours of electricity exports, storage charging, and heat pump use often coincide, which are also hours with relatively low prices. Conversely, heat pumps largely avoid drawing electricity from the grid during hours when imports take place, which often coincides with hours of low renewable generation and relatively high prices.

In our model, heat pumps are operated in a way that minimizes system cost, which can be interpreted as if they are following wholesale market price signals. The presence of heat storage enables and increases their potential to do so. As visible in Fig. 4, there is a strong alignment of heat pump electricity intake and relatively low residual load levels when heat pumps are equipped with heat storage. Heat pumps with no heat storage are inflexible electricity consumers, which directly follow the hourly heat demand profile. In Fig. 4 that is visible by the parallel movement of heat output (gray line, right y-axis) and the electricity demand in case of no heat storage (red line, left y-axis). This changes when heat storage is added. Even small 2-hour heat storage makes heat pumps sufficiently flexible that they can adjust their demand to the overall system conditions to a considerable extent. If heat storage is expanded further, heat output and electricity intake are even less correlated. For the *fast* rollout scenario, results are more pronounced but qualitatively similar (Fig. SI.7).

The shifting of electric loads through heat storage is also depicted in Fig. 5. The figure shows the electricity demand of heat pumps depending on the size of the heat storage over the course of an entire year. Fig. 5A shows the electricity demand of heat pumps without heat storage, which

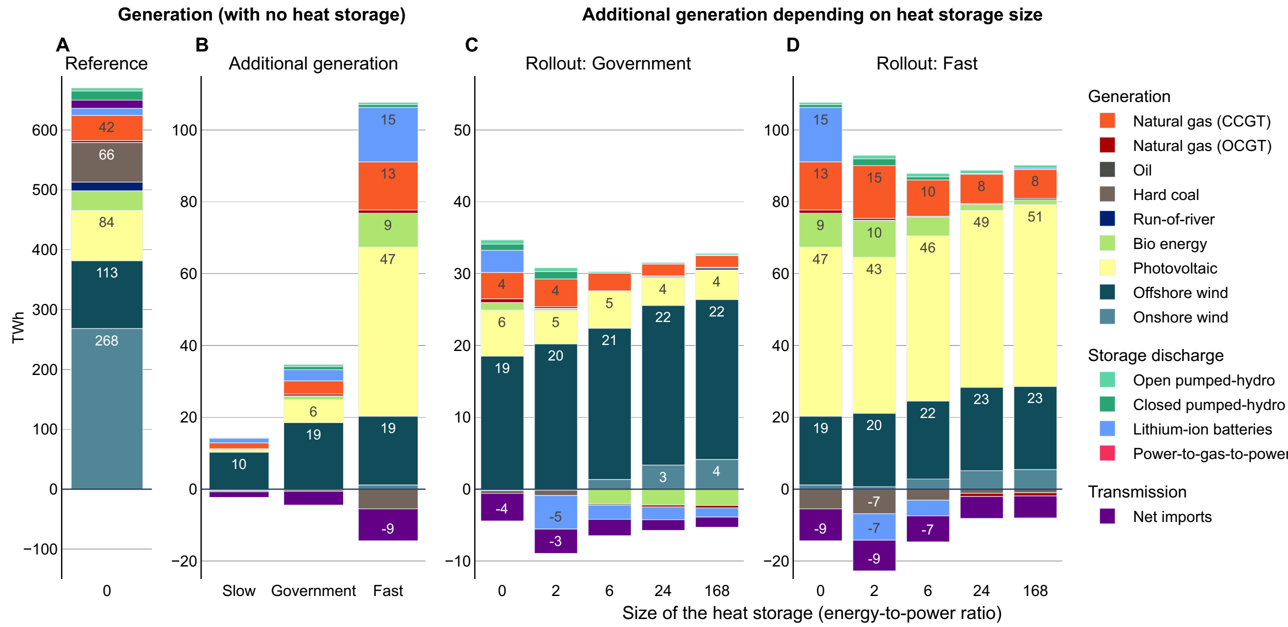


Fig. 2 | Yearly electricity generation by source under baseline assumptions. **A** Optimal dispatch in the reference scenario. **B** Changes induced by the rollout of heat pumps in the case of inflexible heat pumps. **C**, **D** Changes in dispatch to the respective *reference* scenarios for different heat storage sizes in the *government* rollout (**C**) and *fast* rollout (**D**). The changes shown in **C** and **D** are to their respective *reference* scenarios with different heat storage sizes. The results for the different *reference* scenarios (**A**) are almost identically for different heat pump storage sizes. For better visibility, only one *reference* rollout is shown. Please note the different y-axis ranges of the different panels. The complete set of results is shown in Fig. SI.5.

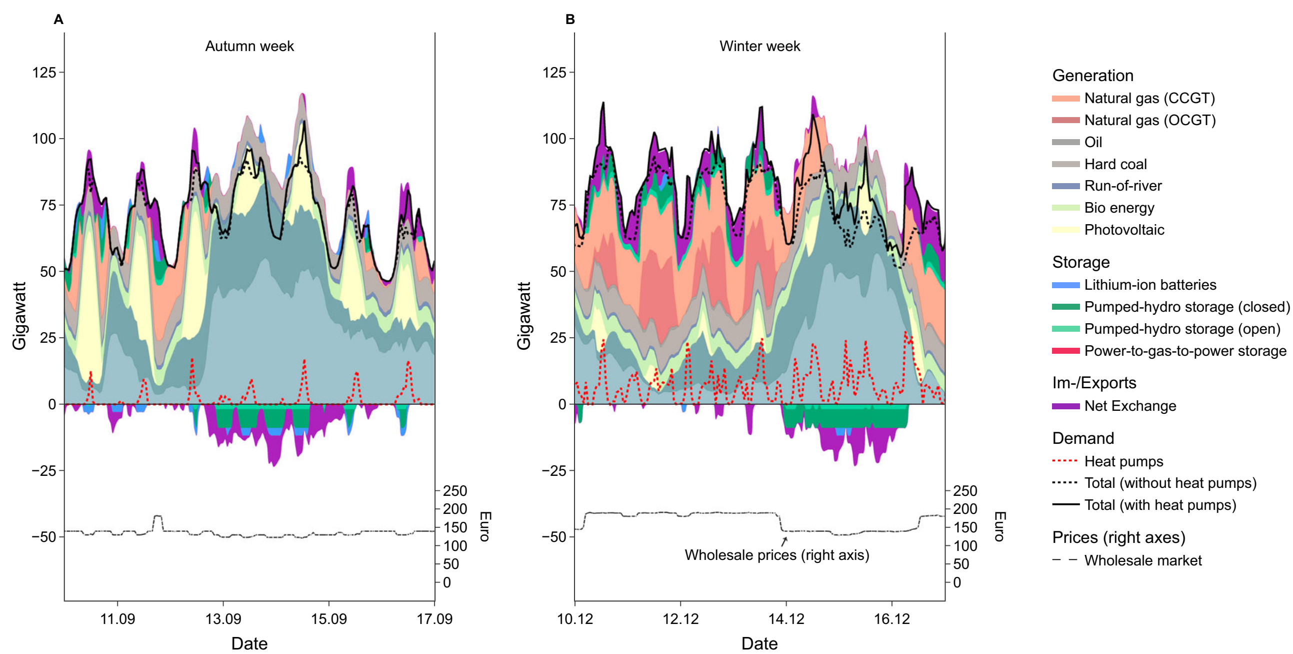


Fig. 3 | Exemplary weeks of electricity generation, heat pump operation, and wholesale prices. Two exemplary weeks are shown for the *government* rollout of heat pumps with heat storage of 2 hours: **A** autumn week and **B** winter week.

mirrors the heat demand (also shown in Fig. SI.3). We see that in winter months, hence on the bottom and top of every panel, demand is higher than in summer months. In all days of the year, heat demand during the first hours of the day is assumed to be zero. Moving from Fig. 5A to Fig. 5B–E on the right, we see that the electric load patterns change when heat pumps are operated in a more flexible manner. Already with heat storage of 2 h, heat pumps are used to integrate excess solar energy from the middle of the day. Furthermore, due to the flexibility enabled by heat storage, heat pumps can draw electricity in hours of no heat demand, such as at night, and hence smooth heat consumption peaks in morning hours. For larger heat storage sizes, such as 24 and 168 h, the electric load of heat pumps increasingly resembles the charging of a longer-duration storage asset, sometimes consuming excess electricity for extended periods and avoiding consumption later. While this mode of operation may not be realistic for small, decentralized heat pumps due to limited potential for low-cost heat storage installations, such operational patterns appear more plausible for centralized heating solutions with larger and lower-cost heat storage options.

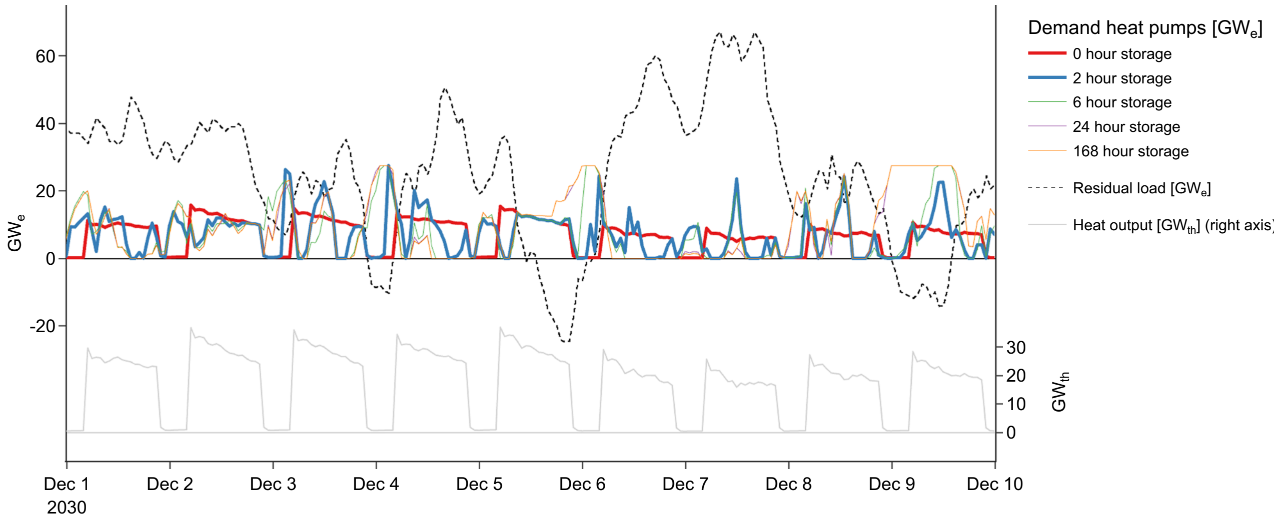


Fig. 4 | Heat output, heat pump electric load with different storage sizes, and residual load. Residual load, the heat output of heat pumps, and their electricity demand for different heat storage sizes in the *baseline* setting with a *government* rollout are shown.

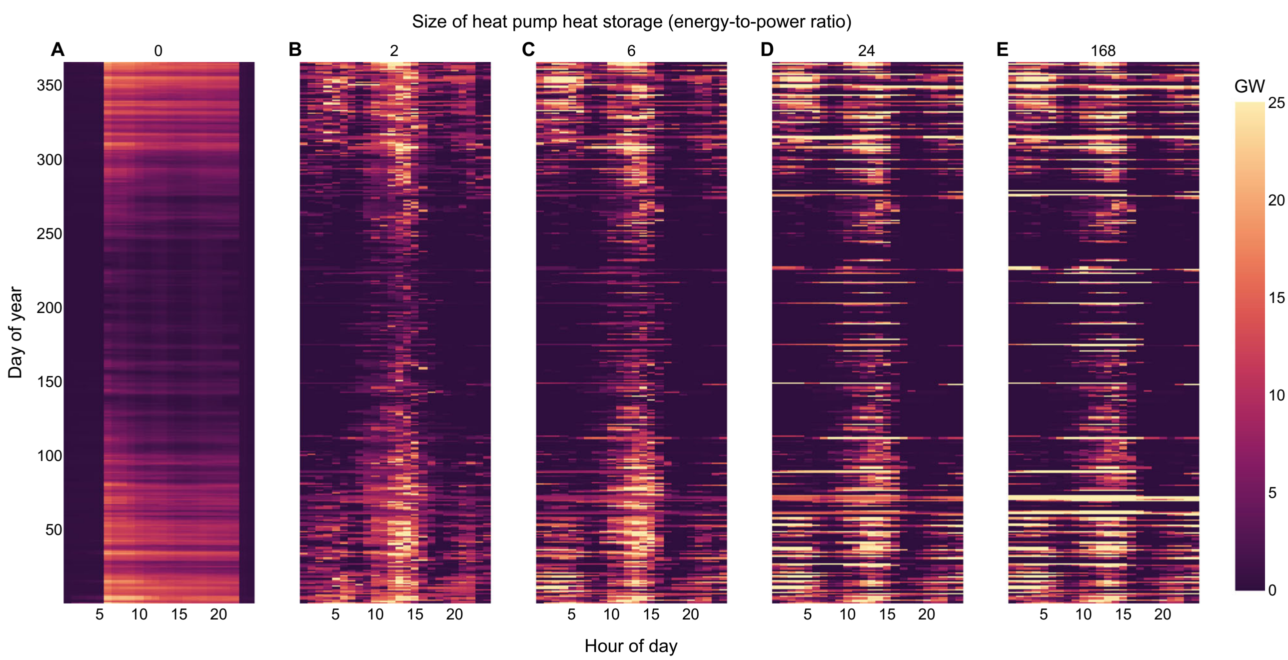


Fig. 5 | Heatmap of the electricity demand of heat pumps for different heat storage sizes. A–E show the electricity demand of heat pumps for different heat storage sizes. Values are from the *baseline* scenarios with *government* rollout.

Heat storage reduces electricity sector costs

Our analysis focuses on additional electricity sector costs caused by the heat pump expansion. We relate these costs to the additional heating energy provided (Fig. 6). More heat pumps lead to additional costs for the electricity sector due to additional investment into generation and storage capacities and higher variable costs. We find that electricity sector costs increase by around four Euro-cent per kilowatt-hour (ct/kWh) of additional heating energy provided in the *government* rollout scenario with inflexible heat pumps.

This cost effect decreases with larger heat storage sizes. The relative decline in additional costs is the largest when moving from no storage to a 2-h storage. With larger heat storage sizes, the decreases become smaller and are almost negligible between a day (24 h) and a week of heat storage (168 h). This means that the additional value of long-duration storage compared to shorter-duration storage is relatively small in the modeled setting with an 80% renewable share in Germany. In other words, the marginal electricity sector cost savings decrease with larger heat storage. The cost effects shown in Fig. 6 do not include the installation costs of heat pumps and heat storage, but only the costs related to the electricity sector, such as investment and operational expenses of generation and electricity storage capacities. Therefore, we can interpret these figures as opportunity costs of heat storage.

We calculate the break-even overnight investment costs of heat storage that would be required to deliver overall system cost savings. We do so by relating the power sector cost differences between scenarios with different heat storage sizes to the respective storage capacity and deriving annualized overnight investment costs. For the latter, we assume that heat storage installations have a lifetime of 20 years, face an interest rate of 4%, and do not incur any variable or fixed operation and maintenance costs. As the marginal power sector cost savings decrease with larger heat storage capacities, the specific break-even costs of heat storage decrease even faster. For example, specific heat storage investment costs have to be below around 80 Euro/kWh_{th} in the *government* rollout with 2 h of heat storage. This break-

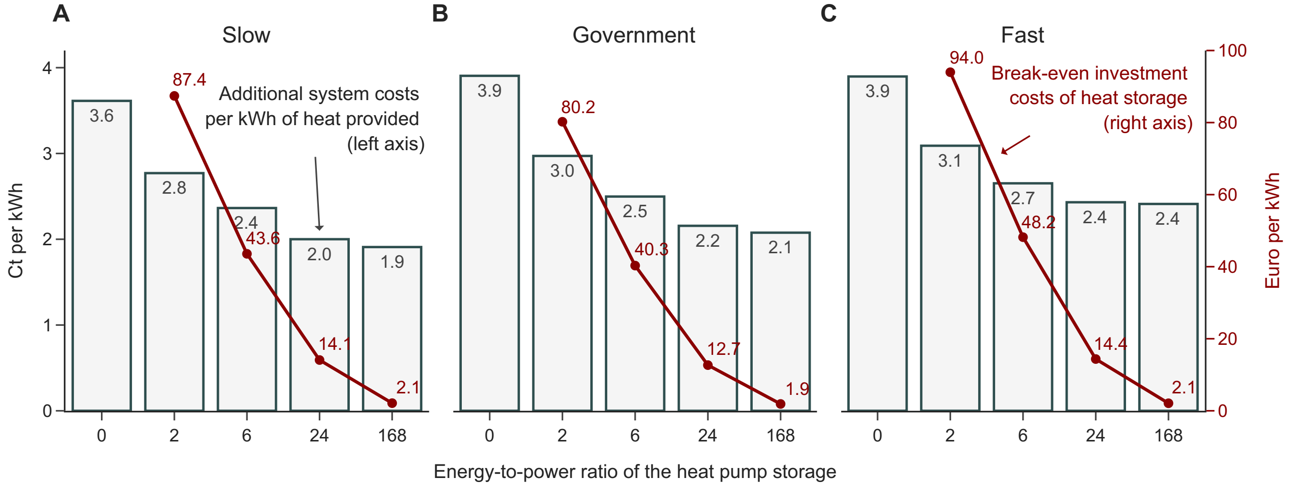


Fig. 6 | Additional electricity sector costs and break-even investment costs of heat storage. For different rollout scenarios (**A**–**C**), the gray bars depict the additional costs in Euro-cent per kilowatt-hour$_{th}$ of additional heating energy provided for different rollout scenarios and heat storage sizes (compared to the respective reference, left y-axis). The red lines show the break-even investment costs in Euro per kilowatt-hour$_{th}$ of heat storage (compared to the respective scenario without heat storage, right y-axis).

even cost decreases to 40 Euro/kWh$_{th}$ in the case with 6 h of storage and sharply declines to only about 2 Euro/kWh$_{th}$ for a heat storage size of one week. In other words, long-duration heat storage would have to be very cheap. Results are qualitatively similar for the *slow* and *fast* rollouts. In the latter, break-even costs are slightly higher at around 94 Euro/kWh$_{th}$ in the 2-h case, as the additional PV generation in this scenario increases the value of temporal flexibility. While the real-world costs of short-duration heat storage technologies are likely well below the range of 2-h break-even costs determined here, we consider it implausible that storage sizes of a day or more could be realized in combination with decentralized heat pumps at the required costs. Low-cost, long-duration heat storage appears much more plausible in combination with district heating networks and large-scale, centralized heat pumps, which is beyond the scope of our analysis.

Qualitative results also hold in sensitivity analyses

In addition to our *baseline* scenario in which we vary the rollout speed of heat pumps and heat storage duration, we conduct several sensitivity analyses. Those help us judge how strongly our results hinge on certain fundamental model assumptions. We alter the assumptions on the upper bounds of wind power expansion, the level of natural gas prices, and the possibility of electricity generation from coal. We also introduce a week of a stylized "renewable energy drought" with no wind and solar availability. Table SI.6 provides an overview of all sensitivity analyses.

In the following, we summarize the principal takeaways of these sensitivity analyses. An extensive description and discussion of the results of the sensitivity analyses, including additional figures, can be found in the Supplementary Information (Section SI.2.2).

In the *baseline* scenarios, we assume an upper limit for on- and offshore wind power capacity expansion in Germany of 115 GW and 30 GW, respectively. This appears to be realistic and policy-relevant from a 2030 perspective. Considering real-world constraints related to regulation, land availability, and public acceptance, unbounded wind power capacity expansion seems implausible. Still, removing these limits (scenario *no wind cap*), generates complementary insights into a less constrained equilibrium setting. Results show an increase in wind onshore capacities at the expense of offshore wind and a slight reduction in PV capacity. This leads to higher onshore wind generation and less offshore wind dispatch (Fig. SI.11). The seasonality of heating demand aligns well with wind power and additional system costs due to heating decrease slightly compared to the *baseline*.

Scenarios with higher gas prices (*gas100* and *gas150*) show fewer gas-fired power plants and more solar PV capacities in the *reference* and different rollout scenarios. Especially in *gas150*, additional capacities are mostly solar PV as offshore wind is already at its limit in the *reference*. In parallel, dispatch sees reduced gas-fired generation both in the *reference* and the rollout scenario (Fig. SI.11). The system costs per heating unit increase considerably due to more expensive natural gas (Fig. SI.10).

Without coal-fired power plants (*coal phase-out*), gas-fired generation and electricity imports increase in the *reference* rollout. Yet, the dispatch effects of a heat pump rollout do not substantially differ from the *baseline* setting. Combining coal phase-out with higher gas prices leads to system effects similar to the scenarios *gas100* and *gas150*.

As the share of variable renewable energy increases, the security of supply during prolonged periods with low renewable energy supply becomes an increasing concern[17,18]. Therefore, we assess how a week of a severe renewable energy drought in Europe would affect our results. To simulate an extreme case of such a week, we artificially set wind and solar PV capacity factors to zero in all modeled countries during one winter week. Such a week-long renewable energy drought (scenario *RE drought*) requires substantially more firm capacity, which is provided by gas-fired power plants in the *reference* (Fig. SI.9). The effects of a heat pump rollout on electricity generation and storage technologies are also higher than in the *baseline*, and we see higher cost increases. Yet, the overall yearly dispatch in the reference, and also the dispatch effects of a heat pump rollout, hardly change compared to the *baseline*. Similarly, heat pumps still provide power system flexibility by aligning their electricity demand to the residual load if equipped with heat storage (Fig. SI.12).

Overall, our sensitivity analyses indicate that the key insights and results from the *baseline* scenarios hold true under varying assumptions. The addition of heat pumps, depending on the rollout speed, requires additional investments in wind offshore, solar PV, gas-fired plants, and short-duration storage to meet renewable energy constraints. Unlimited onshore wind power expansion offers some benefits, but overall cost reductions are modest.

An ambitious rollout of heat pumps leads to large savings of overall system cost, natural gas use, and carbon emissions

Based on the power sector optimization results, we also examine the effects of different rollout speeds of heat pumps on natural gas usage and carbon emissions. We compare the *reference* rollout of 1.7 million heat pumps with 4.3 million additional heat pumps in the *government* rollout scenario and 8.3 million additional heat pumps in the *fast* rollout scenario. The underlying assumptions for the calculation of gas and emission savings are stated in Table SI.3. Table 2 summarizes the results.

Table 2 | Yearly savings of natural gas, CO_2 emissions, and costs related to heat pumps

Gas price	Euro per MWh_{th}	50		100		150	
Heat pump rollout		Gov.	Fast	Gov.	Fast	Gov.	Fast
Natural gas displaced by additional heat pumps	TWh_{th}	−75.75	−223.97	−75.75	−223.97	−75.75	−223.97
Additional gas usage for electricity generation	TWh_{th}	+2.58	+18.01	+1.92	+12.75	+4.90	+20.35
Total gas savings	TWh_{th}	−73.17	− 205.96	−73.83	−211.22	−70.85	−203.62
Total emissions savings	Mio t CO_2	−14.63	− 41.19	−14.77	−42.24	−14.17	−40.72
Change in overall system costs	Billion EUR	−2.05	−6.73	−5.48	−16.80	−9.07	−27.07

Changes and savings are shown relative to the respective reference scenario. *Gov*. refers to the *government* rollout scenario of heat pumps.

Under the assumption that each heat pump replaces one gas boiler with a thermal efficiency of 0.9, which means that 1 kWh_{th} of natural gas will be transformed to 0.9 kWh_{th} of heat, additional heat pumps displace around 76 terawatt-hours$_{th}$ (TWh) of natural gas in case of a *government* rollout and 224 TWh_{th} in a *fast* rollout (Table 2 and Table SI.5), compared to the *reference* rollout. At the same time, natural gas usage for electricity generation slightly increases in both scenarios, but this is by far overcompensated by natural gas savings in the heating sector, leading to total savings of around 206 TWh_{th} in the *fast* rollout compared to the *reference* rollout. For the more moderate *government* rollout with lower gas prices, overall natural gas savings still amount to around 73 TWh_{th}. To put these numbers into perspective, 73 (206) TWh_{th} of natural gas corresponds to around 9% (24%) of Germany's overall natural gas consumption in 2022, or around a fifth (three-fifths) of private and commercial natural gas demand. In the scenarios with higher natural gas prices of 100 Euro or 150 Euro per MWh_{th}, we find largely similar effects on overall natural gas usage.

We observe an increase in overall system cost savings with a higher number of heat pumps and increasing gas prices. In this calculation, overall system cost effects include the increase in power sector costs due to higher electricity demand, the total annualized overnight investment costs of the additional heat pumps, the savings in natural gas expenditures, savings of CO_2 emission cost of gas heaters, as well as investment costs of replaced natural gas boilers. As the investment- and installation costs of heat pumps might even fall below our cited values due to technical progress, our cost-saving numbers can be interpreted as a lower bound. Overall system cost savings are between 2.0 and 6.7 billion Euro in the *government* or *fast* rollout scenarios for a conservative natural gas price assumption of 50 Euro per MWh_{th}. Savings increase substantially with higher gas prices, up to 27.1 billion Euro per year in the *fast* rollout scenario with a gas price of 150 Euro per MWh_{th}.

Our overall system cost calculations depend on the assumption that every new heat pump substitutes a new gas boiler, which would otherwise have to be installed. We do not consider retiring existing gas boilers before the end of their lifetime. The extent to which an accelerated heat pump rollout would lead to a replacement of existing gas boilers, which have not yet reached the end of their lifetime, is unclear due to a lack of data on the age of existing gas boilers in the buildings modeled here. We calculate a counterfactual extreme case that assumes that the gas boilers replaced by heat pumps could have been used for another 20 years, which means we do not consider their investment costs in the calculation. This leads to smaller, but still positive, overall system cost savings below between 0.8 billion Euro in the *government* rollout and 4.6 billion Euro in the *fast* rollout.

The reduced consumption of natural gas correspondingly leads to lower greenhouse gas emissions. In a *fast* rollout scenario of heat pumps, yearly emission savings in the range of 41–42 million tons CO_2 can be expected under different gas price assumptions. This corresponds to around 51% of German households' carbon emissions from buildings in 2022. For the *government* rollout, we can expect emission savings of around 14–15 million tons CO_2 (18% of households' carbon emissions). Hence, an ambitious heat pump rollout, as described in this paper, could make a major contribution to Germany's carbon emission reductions. A further expansion of heat pumps beyond 2030 would lead to even higher reductions in carbon emissions. Note that the assumed emission factor of natural gas of 0.2 tCO_2/MW_{th} appears to be a conservative estimate, as it does not take methane leakage within the natural gas supply chain into consideration. Thus, the emission savings from switching to heat pumps presented here can be considered a lower bound and might be substantially higher because of methane leakage.

Conclusion

As heat pumps are considered a key technology in the heating transition, their potential future impact on the electricity sector is of interest. We determine the effects of different rollout paths of decentralized heat pumps, combined with heat storage of different sizes, on the power sector in Germany. We find that the expansion of the German heat pump stock from 1.7 to 10 million would require additional investments of around 54–57 GW of solar PV capacity in a least-cost solution, depending on how much heat storage is available. These results are driven by the assumption that the additional electricity consumption of heat pumps has to be covered by additional renewable electricity on an annual basis and that the expansion of wind power is limited to 115 GW (onshore) and 30 GW (offshore), respectively. For a slower rollout speed, which still achieves the German government's target of 6 million heat pumps by 2030, additional PV capacities of around 4–8 GW are needed.

Our results suggest a moderate need for additional firm capacity in the form of gas-fired power plants and lithium-ion batteries in most rollout scenarios, particularly in the *fast* rollout scenario. More flexible heat pump operations facilitated by short-duration heat storage can partially relieve these additional capacity needs. While this is in line with several previous studies[7,16,19], other research concluded that larger thermal heat storage of 12 to 24 h would be desirable in Spain and the United Kingdom[9]. Our findings further corroborate previous research which finds that heat pump deployment may increase optimal PV capacities[12]. The European interconnection also helps to integrate heat pumps into the power sector and to limit additional capacity needs. This is in line with a previous analysis[15], which also highlights the importance of interconnection, as large-scale heat pumps become more competitive if they can make use of renewable surpluses in other countries.

Already small buffer heat storage with an energy capacity of 2 h enables heat pumps to better align electricity consumption with the residual load. This results in power system cost savings of up to 0.9 ct/kWh of provided heat (or around 20%) compared to a case with inflexible heat pumps. Costs further decrease with increasing heat storage, yet the marginal cost savings strongly decline with larger heat storage size. This hints at the fact that heat storage mainly serves to smooth daily renewable energy fluctuations. For 2-h storage, it appears plausible that the costs of installing heat storage remain below the power sector benefits determined here. In contrast, long-duration heat storage would have to be very cheap to break even, which appears more plausible for large-scale thermal storage in district heating systems.

Sensitivity analyses show that results are generally robust against changes in key scenario assumptions. Assuming unconstrained expansion potentials for wind power substantially reduces solar PV capacity deployment since wind energy aligns better with heat demand[7], yet barely changes power sector costs. A complete coal phase-out in the electricity sector also does not have major effects on the impacts of accelerated heat pump rollouts on power sector capacities, dispatch, or costs. Higher natural gas prices have more substantial effects and, in particular, lead to higher additional power sector costs of additional heat pumps. Considering a week-long, pan-European renewable energy drought requires overall more firm capacities, and the rollout of heat pumps is accompanied by substantially higher solar PV investments in this case.

We further find that an accelerated replacement of gas boilers with heat pumps can bring yearly natural gas savings between around 71 and 211 TWh_{th}, depending on the rollout speed and gas prices, already accounting for increased gas usage in the electricity sector. For instance, in a *fast* rollout to 10 million units in 2030, the additional heat pumps could save more than half of the private and commercial natural gas demand in Germany, which corroborates related findings[6]. Overall yearly system cost savings depend, among other factors, on the natural gas price and range from around 2–27 billion Euro for different rollout scenarios and natural gas price assumptions. CO_2 emissions decrease by around 14–42 million tons per year, corresponding to around 18–53% of German households' carbon emissions from buildings in 2022.

As with any model-based analysis, our study has limitations. For example, we implicitly assume perfect distribution and transmission grids within countries that neglect any kind of grid congestion caused by heat pumps. In some distribution grid settings, the effect of heat pumps on grid congestion may be more severe than the impacts on system-wide generation capacities and dispatch modeled here. We also note that the hourly heat demand profiles used in our study are smoother than empirically measured heat pump operation patterns from the U.K.[20–22]. A "peakier" future heat demand pattern could potentially lead to higher load peaks and hence impact the flexibility potentials of heat pumps, which merits further investigation in future work. In addition, our heat demand time series follows a synthetic test reference year approach, while the renewable electricity generation profiles and ambient temperatures come from actual weather years. This may lead to underestimating the system challenges in case of situations where very low renewable availability coincides with very low ambient temperatures and, accordingly, high heat demand. Therefore, it appears advisable to use consistent electric and heat load data as well as renewable generation profiles from the same weather years in future work. In addition, our approach of exogenously fixing the bioenergy capacity may lead to an underestimation of its flexibility potential. Without increasing the overall use of bioenergy, its conversion into electricity could become more concentrated in fewer hours to better complement variable wind and solar power. This would require a higher installed generation capacity (with lower full-load hours), as well as appropriate storage of biomass or biogas.

Furthermore, Germany is not the only country pushing for an accelerated rollout of heat pumps. While we assume inflexible heat pumps outside Germany, future work could analyze rollouts in the whole of Europe in more detail to obtain more comprehensive insights into a wider European heating transition. Finally, our assumption of balanced charging of electric vehicles may not reflect reality. As the electric vehicle market evolves and charging infrastructure develops, there may be substantial changes in charging behavior and the adoption of smart and bidirectional charging technologies of cars[23] and trucks[24], which may decrease the value of flexibility provided by heat storage.

Our results show that even relatively small heat storage capacities may already have substantially positive power system effects. While in this analysis heat pumps were either operated totally inflexibly with no heat storage or perfectly system-oriented with heat storage, future research could analyze the effects of other, and potentially more realistic, operating behaviors. The benefits of short-duration heat storage should be examined further with more volatile heat demand profiles to gain a more comprehensive understanding of its flexibility potential in energy systems. Further, operating heat pumps in a flexible way requires the right incentives for consumers. Hence, from a policy perspective, it is important to make sure that electricity consumption can be measured and controlled on a continuous basis (sometimes referred to as "smart metering") and that consumers have the possibility to choose electricity tariffs that reflect the dynamics of wholesale electricity markets. While very large heat storage sizes do not appear to be realistic for decentralized heat pumps, our results still serve as an indication of how larger, centralized heating systems with long-duration heat storage could operate. As our analysis focuses primarily on the power sector effects of heat storage, the capacity of which is varied exogenously, future research might aim to investigate the optimal size of heat storage and its main influence factors.

In summary, we find the power sector impacts of an accelerated heat pump rollout in Germany to be moderate and manageable, even under the assumption that the electric load from heat pumps has to be met by a corresponding yearly increase in renewable electricity generation. If wind energy expansion is restricted, additional solar PV capacity can be deployed instead without substantially increasing the overall system costs, facilitated by the European interconnection. In general, operating heat pumps in a temporally flexible manner entails substantial power sector benefits. Even relatively small heat storage already helps to reduce the additional needs for firm capacities or electricity storage induced by heat pumps and lowers power sector costs. We conclude that operating heat pumps in a temporally flexible manner is not strictly a "must-have" in a power sector as modeled here, but it emerges as a desirable feature of the energy transition.

Methods

In the following, we describe the methodological approach as well as the sectoral and geographical scope of the study. First, we introduce the power sector model used in this analysis. Second, we provide details about the modeling of the heating sector and, in particular, the assumptions regarding the operation of heat pumps in our model. Third, we outline how other sector coupling options are considered in the model, namely electric mobility and the production of green hydrogen. Finally, we describe the geographical scope of the model.

Power sector model

In this study, we use the power sector model DIETER (Dispatch and Investment Evaluation Tool with Endogenous Renewables), which has already been used in various prior studies of energy storage and sector coupling[4,13,23–26]. It is an open-source linear program that determines the least-cost investment and dispatch decisions for a range of electricity generation and storage technologies. The model minimizes total system costs while considering all subsequent hours of a year to capture renewable energy variability and storage use accurately. A detailed description of the objective function and the most relevant constraints can be found in ref. 3. The model covers the electricity sector and includes a detailed space heating module, e-mobility, and flexible hydrogen production options. Input data include time series of electric load, heat demand, electric vehicle charging, hydrogen demand, and capacity factors of renewable energies. Cost assumptions and technology investment constraints are further inputs. We are following a brown-field approach, in which we consider exogenous bounds on investments to account for existing plants and path dependencies. These are aligned with the current renewable capacity expansion plans of the German government and the currently installed fossil-fuel capacities. More detail on the capacity bounds can be found in the "Scenario assumptions" section and Table SI.2.

Heating sector

The German space heating sector is characterized by twelve archetypes of residential buildings categorized by two size classes and six age classes, corresponding to varying energy efficiency levels. While the building stock is described in detail in ref. 13, we provide a brief overview here. We model twelve different building archetypes, which are distinguished by year of construction (six classes: before 1957, four periods between 1958 and 2019, and after 2019) and housing type (two classes: one -& two-family homes and multifamily homes). Depending on the year of construction, the building archetypes are characterized by different energy efficiency levels: younger buildings have a lower annual heating requirement, and buildings constructed after 2020 are characterized as passive houses. Table SI.1 depicts the building stock assumptions for 2030, which are based on ref. 13.

For each of the twelve building archetypes, an hourly heating demand time series is generated using the open-source thermal building model TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit,[27]) and the publicly available AixLib Library[28]. The thermal building model considers the physical components of all major building elements and their thermal inertia to derive hourly heat flows inside the building and toward the ambiance (conduction, convection, and radiation). We assume indoor temperature requirements of 22 °C in the daytime and a nighttime reduction to 18 °C between 10 p.m. and 5 a.m. Further, a test reference year approach is used to derive heating demand, which is representative of historical weather data in central Eastern Germany. Domestic hot water demand is modeled separately based on the Swiss SIA 2024 standard[29]. A graphic representation of the resulting hourly heat demand time series is provided in the Supplementary Information (Fig. SI.3).

We exogenously set the share of total space heating and hot water demand, which has to be covered by two different types of heat pumps for each scenario; hence, we implicitly only consider the part of the building stock where heat pumps are installed. On an hourly basis, the heat pumps must satisfy the demand for space heating and hot water, as determined by the shares. We assume that heat pumps can be combined with buffer heat storage of different sizes, which vary between scenarios. Based on these inputs and assumptions, the model optimizes the hourly electricity use by heat pumps.

Figure 7 depicts how heat pumps are modeled in DIETER. The electric energy needed depends on the coefficient of performance (COP), which in turn depends on the ambient temperature in the case of air-source heat pumps. Lower ambient temperatures decrease the COP, so more electric energy is required to provide the same amount of heating energy. For more information, see Section SI.1.2. How much heating energy is provided to the building depends on the heat outflow from the buffer storage, which can neither exceed the total amount of heating energy stored plus the storage inflow in the same hour, nor the installed heat output capacity of the heat pump. We only consider decentralized heat pumps with decentralized thermal energy storage. Centralized large heat pumps supplying district heating grids and centralized seasonal heat storage are not part of the analysis.

Other sector coupling options

As the electrification of other energy sectors is a policy target in Germany, we also account for electric mobility and the production of green hydrogen. The additional system load of electric vehicles enters the model as an electricity demand time series. Cars are assumed to charge with a balanced, yet not wholesale market price-driven time profile determined by the open-source tool “emobpy”[30] (for further details, see SI.1.3). The model also has to satisfy a given yearly demand for green hydrogen that has to be produced with electrolysis. The hourly hydrogen production profile is endogenously optimized, with given electrolysis capacity and assuming hydrogen storage at no cost. We provide the equations that describe the straightforward hydrogen model in Section SI.1.4 in the Supplementary Information.

Geographical scope

The study focuses on Germany, where an explicit heat pump rollout is modeled, but also includes Denmark, Poland, Czechia, Austria, Switzerland, France, Luxembourg, Belgium, the Netherlands, and Italy. To keep the model tractable while still considering the effects of European interconnection, we optimize investment decisions only in the German power sector while assuming (largely) fixed power plant fleets for other countries. We also do not explicitly model sector coupling for countries besides Germany. The “Scenario assumptions” section discusses capacity bounds for different countries.

Input data sources

Time series data for the electric load, capacity factors for renewables, and hydro inflow data for all countries are taken from the ENTSO-E Pan-European Climate Database (PECD 2021.3)[31]. We use the target year 2030 and the weather year 2008. Cost and technology parameters of electricity generation and storage technologies are depicted in Table SI.4 in the Supplemental Information. The relevant technical assumptions related to heating technologies and gas-based electricity generation technologies for the ex-post analysis of natural gas and emission saving are shown in Table SI.3.

Scenario assumptions

We refer to our main set of scenario assumptions as *baseline*. In the following, we briefly sketch out the most important features of this scenario. Whenever we deviate from the *baseline*, for instance when we present the sensitivity analyses, we make this explicit.

Heating sector

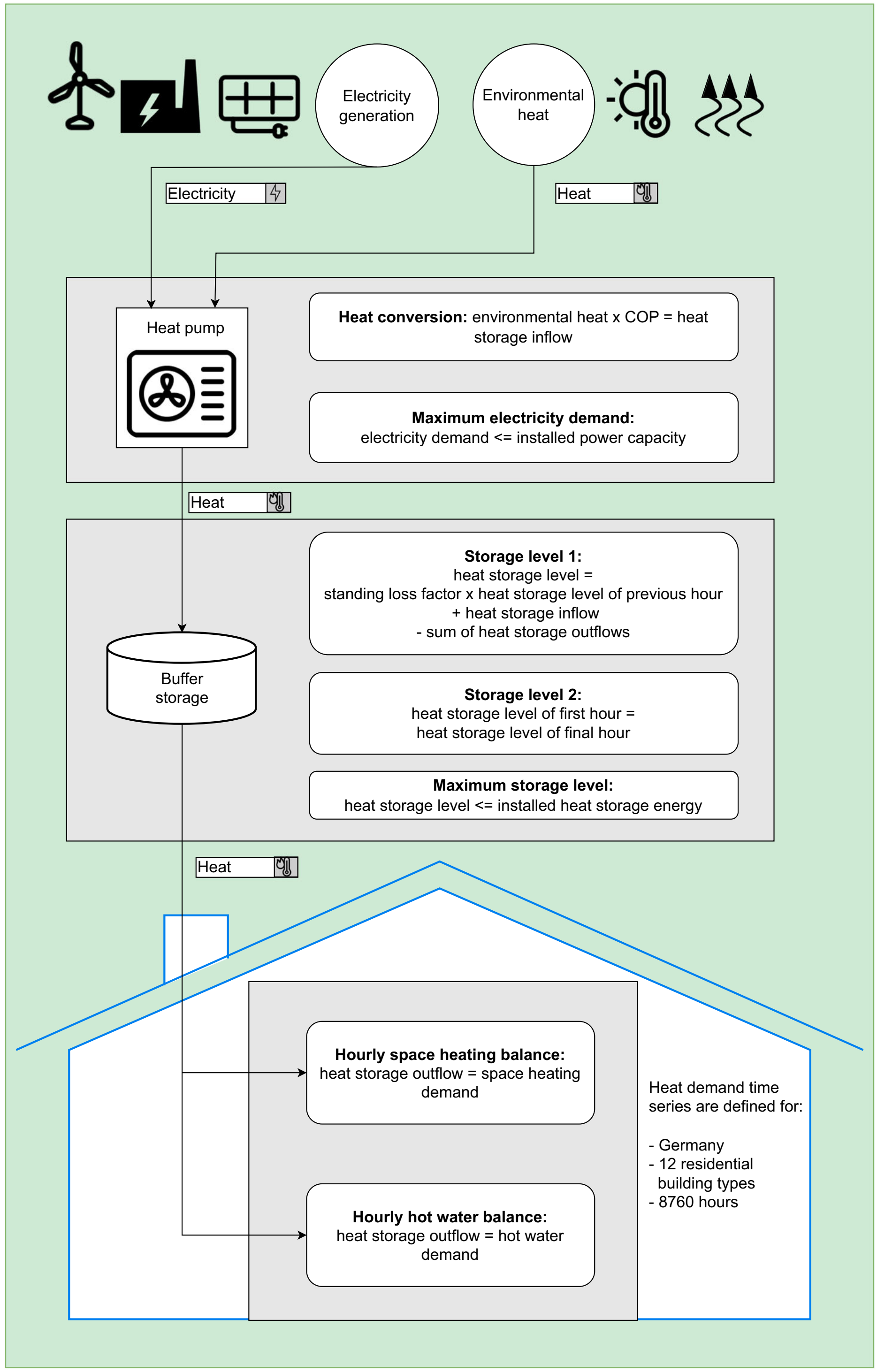
We distinguish between three policy scenarios of the overall heat pump stock in 2030 which we compare to a *reference* scenario. In this *reference* scenario, we assume 1.7 million decentralized heat pumps in 2030. This number reflects the stock of heat pumps installed in Germany at the time of writing, meaning no further pumps would be installed until 2030. In the *slow* rollout, the number of heat pumps would reach 3 million by 2030. Additional heat pumps would be exclusively installed in single- and two-family homes built between 1995 and 2009. This scenario largely corresponds to the current growth of heat pump deployment in Germany at the time of writing[32]. In the *government* rollout, the stock of heat pumps would reach 6 million in 2030, reflecting the target of the German government[2]. In this scenario, most single- and two-family homes built after 1995 would be equipped with heat pumps. In the *fast* rollout, heat pumps would be installed in more single- and two-family homes, even old ones built before 1979 with very low energy efficiency standards. In this scenario, the total number of heat pumps would increase to 10 million by 2030, and the total annual heat provided by heat pumps increases substantially. Table 1 provides an overview of the different heat pump rollout scenarios. Table SI.1 provides additional information on how heat pumps are rolled out across different building types. In the most ambitious scenario, decentralized heat pumps provide around 40% of total space heating and domestic hot water needs (Table 1). The electricity demand of heat pumps and other sectors in the different scenarios is depicted in Fig. SI.1.

Across all building types, air-source heat pumps account for 80% of installed heat pumps and ground-source heat pumps account for the remaining 20%. While ground-source heat pumps are more energy-efficient, air-source heat pumps are cheaper to install. We assume that all heat pumps can, in principle, be combined with thermal energy storage. We conduct analyses with varying storage energy capacities. The assumed energy storage size is expressed in energy-to-power (E/P) ratios ranging from 0 to 168 h (0, 2, 6, 24, and 168 h). In this terminology, a heat storage with an E/P ratio of 2 h has a total heat storage capacity that equals 2 h of the maximum heat output of the heat pump. Equipping heat pumps with a 0-h storage means that heat pumps have no attached heat storage and thus have to exactly follow the heat demand profile in every hour. Hence, heat pumps are operated inflexibly. With increasing the size of heat storage, heat pumps can be operated with more flexibility, allowing to decouple electricity consumption from heat provision to a greater degree. Importantly, our modeling approach assumes that heat pumps are operated in a system-friendly, i.e., cost-minimizing manner whenever possible. This could be interpreted as if heat pump operators faced hourly wholesale prices and operated their heat pumps to minimize overall system costs. As this is not the case today, we discuss the consequences of this assumption in the conclusion.

Capacity bounds

In Germany, we limit the capacities of coal- and oil-fired power plants to current levels. Capacities of gas-fired power plants, open cycle (OCGT), and

Fig. 7 | Heat module in DIETER.



combined cycle (CCGT) - following current policy discussions - can be expanded beyond current levels. In sensitivity analyses with a German coal phase-out, we assume the upper capacity limit for hard coal and lignite to be zero. Regarding wind energy, we align upper capacity bounds for on- and offshore wind energy with the current German government targets of 115 GW for onshore wind and 30 GW for offshore wind in the baseline scenarios. We use the government target for wind power as an upper limit, as wind capacity expansion in Germany is slow due to long assessment and permit processes, and limited by land (and sea) availability. In this context, the government targets can be considered ambitious. An even higher wind energy capacity expansion appears unrealistic to achieve by 2030[2]. In a sensitivity analysis, we remove these upper bounds on wind power capacities. The capacities of solar PV do not have any bounds. The electrolysis capacity is fixed at 10 GW_e.

In other countries, renewable energy capacities are fixed based on the values of the Ten-Year Network Development Plan (TYNDP)[33] of ENTSO-E and set as upper bounds for fossil generators. The reason for not fixing the fossil generators in other countries is to avoid an unduly large power plant fleet that could support the German heat pump rollout. Therefore, the model is free to choose the smallest capacity needed. In all countries, we fix the capacities of all hydropower technologies (run-of-river, reservoirs, and pumped-hydro) according to the ERAA 2021[31] and bioenergy under the assumption that their potential for further capacity expansion is exhausted. Table SI.2 provides an overview of all capacity bounds in all countries.

Sector coupling demand

While we assume an annual conventional load of 550 TWh in Germany in all scenarios, we additionally consider new electric loads related to electric mobility and hydrogen production. To incorporate the impact of electric mobility, we include a fleet of 15 million electric cars compatible with the government's goal of 2030[2]. This fleet would require approximately 36 TWh of additional electricity annually. Figure SI.2 depicts the hourly demand patterns of that fleet. Additionally, we account for 28 TWh_{H_2} of the hydrogen demand in Germany produced by domestic electrolysis, resulting in an additional electricity demand of around 39 TWh. This number is based on the target set in the updated German National Hydrogen Strategy of 2023 to build up an electrolysis capacity of 10 GW[34,35] and assuming 4000 full-load hours. This does not include hydrogen imports, which are expected to satisfy 50–70% of the German hydrogen demand (95–130 TWh_{H_2} in 2030)[34]. We further assume that hydrogen can be stored without additional investment costs, e.g., in existing cavern storage. This enables electrolyzers to operate with a substantial degree of flexibility to produce hydrogen over the course of the year. In countries besides Germany, additional loads related to sector coupling are included in the electric load time series data provided by ENTSO-E and thus assumed to be inflexible. Figure SI.1 provides an overview of the electricity demand of the different sector coupling options.

Renewable energy constraint

In all scenarios, 80% of the yearly electricity consumption in Germany (including the consumption of electric vehicles and electrolysis) has to be covered by renewable energy sources. That is in line with the goal of the current German government coalition. In addition, the electricity demand by heat pumps has to be entirely met by additional renewable energy sources over the course of a year (but not in every single hour). In other countries, we do not assume any renewable energy targets.

Fuel and carbon prices

Our fuel price assumptions are summarized in Table SI.4. In our *baseline* assumptions, we set the wholesale price of natural gas to 50 Euro per MWh_{th}. We further assume a carbon emission cost of 130 Euro per ton of CO_2 in 2030[36]. This cost is associated with the emission factor of fossil-based heating and electricity generation technologies and is considered a variable generating cost, along with fuel expenses.

Data availability

The input and results data used in this paper can be accessed here: https://zenodo.org/records/13844622.

Code availability

The model and analysis code used in this paper can be accessed here: https://zenodo.org/records/13844622.

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Author contributions

Conceptualization: A.R., W.S.; Methodology: A.R., C.G., D.K., W.S.; Software: A.R., C.G.; Formal analysis: A.R., D.K., W.S.; Investigation: A.R.; Data Curation: A.R., C.G., D.K., W.S.; Writing - Original Draft: A.R., D.K.; Writing - Review & Editing: W.S.; Visualization: A.R.; Supervision: W.S.; Funding acquisition: W.S.

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Competing interests

The authors declare no competing interests.

Additional information

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