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Replacing gas boilers with heat pumps is the fastest way to cut German gas consumption

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The supply security of fossil gas has been disrupted by the Russo-Ukrainian War. Decisions to relocate the production and transport of gas have become so urgent that new long-term contracts are imminent that undermine the Paris Climate Agreement. Here, we simulate how quickly the addition of renewable electricity and the installation of heat pumps can substitute enough gas to reduce supply risk, while taking a decisive step towards meeting the Paris Agreement. Our bottom-up modelling, using Germany as an example, shows technical pathways on how installing heat pumps is one of the fastest ways to reduce gas consumption, in addition to reducing the load hours of gas-fired power plants. With targeted efforts, maximally 60% of gas from the Russian Federation can be substituted by 2025 with heat pumps and grid expansions, and enough electricity will remain available that the phase-out of coal and the entry into e-mobility will still be practicable.

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To avoid a global mean temperature increase beyond 1.5 °C above pre-industrial levels, a rapid defossilisation of global energy systems is necessary[1]. The accepted pathway to achieve this cost-effectively[2] in the electricity sector is a rapid replacement of fossil fuels with mainly photovoltaics (PV), wind power and additional balancing from various renewable sources[3]. Another energy sector that causes greenhouse gas emissions is heating[4]. Curtailing emissions in heating may need to be achieved through various means simultaneously, including thermal insulation of buildings, solar thermal, and replacing gas and oil boilers with heat pumps[5,6] powered by renewable electricity, which are considered a major component for defossilising the energy system[3,7,8]. Important for the effective use of heat are furthermore conscious consumer behaviour[9], district heating networks based on the use of industrial waste heat, solar thermal and geothermal energy as well as various storage technologies[10]. The expansion of wood, pellets and other biomass for heating is limited and is often unsustainable[11]. There is widespread agreement that renewable hydrogen is unsuitable for domestic heating because it would have to be supplied at half the price of electricity (but it takes about three times as much electricity to produce an equivalent amount of hydrogen) and the total system cost would be about twice as high as for heat pumps[12,13]. With all this diversity, heat generation has been assigned a wider variety of development pathways in the integrated assessment models[4] than for electricity.

The supply security of fossil gas has been suddenly disrupted by the recent Russo-Ukrainian War. Decisions to relocate both production and logistics have become so urgent that new long-term contracts are threatening to undermine the Paris Climate Agreement[14]. In this paper, we develop a pathway that reduces supply risk while taking a decisive step towards meeting the Paris Agreement. We hypothesise that one of the fastest ways is to install heat pumps, as they require little planning and approval procedures and are modular, similar to PV. However, heat pumps compete for the same renewable electric power as the displacement of gas-fired electricity generation. In addition, on a number of winter days when solar and wind power are insufficient, the electricity for heat pumps must be supplied by gas-fired power plants. Therefore, it is unclear how much gas can be substituted in this way, especially if insulation of buildings is modest where heat pumps may operate ineffectively. We therefore model the gas consumption in the building stock, in industry as well as electricity generation in Germany in hourly resolution. Priority is given to maximum replacement of fossil gas with renewable electricity. We use Germany as a case study since access to the required data is widely available and heating is mainly based on natural gas (50%) and oil (25%)[15]. However, our methodology and results are broadly applicable to other temperate countries.

We explore bottlenecks in the installation of heat pumps in Germany from the bottom up by collecting narratives from tradespeople, balanced with an expert interview. From this, we develop concrete scenarios to accelerate the installation of heat pumps. Finally, by incorporating these constraints into our scenarios for our hourly model, we calculate the substitution of fossil gas by renewable electricity in the coming years and the associated impact on the energy transition.

Modelling of fossil gas consumption in Germany

In 2020, a total of 285 TWh of gas was taken for space heating and cooking in private households in Germany[16], which we divide into 273 TWh for space heating and 12 TWh for cooking, based on statistical empirical values.

The largest industrial gas consumers[17] in Germany include the chemical, paper and food processing industries. We like to emphasise that we only consider gas-powered heat below 100 °C, as it can be replaced most quickly by heat pumps. We arrive at the following annual gas volumes in 2020: chemical industry 116.9 TWh, food processing 38.6 TWh, and paper industry 25.4 TWh (for details, see the Method Section and Supplementary Note 1). These quantities include an estimated three quarters of industrial process heat below 100 °C[18]. We do not model the trade and services sector as it is too diverse, although additional heat pumps will surely be installed in these sectors as well.

We quantify the variation in gas consumption over the course of the year by load profiles as a function of the daily average temperature, individually for each industrial sector and for room heating[19,20]. A distinction is made between working days and weekend days. In order to properly consider the high volatility of heat demand and also of electricity generation from renewable energies, hourly load curves are taken for the industry from refs. [19,21], depending on the seasons, and for heat pumps from ref. [22], depending on the daily average outdoor temperature. Heat pump data are based on approximately 600 households and account for frost formation and defrosting at the heat pump. See Supplementary Note 2 for more information.

Modelling the German electricity system

The starting point for modelling the entire public electricity grid in Germany is the hourly generation data of all contributing power plants, wind farms and decentralised PV, as well as storage capacities in the reference year 2020[23]. For modelling the near future power generation, we include additions to onshore and offshore wind and to PV according to the plans of the Federal Ministry of Economics and Climate Protection[24] (shown in Supplementary Note 3). The advantage of this modelling approach is that all details of the entire system are included, as well as the climate data throughout Germany. The three main accompanying approximations and limitations are discussed in the Method Section, for example that we assume sufficient grid expansions.

Substitution of gas by electricity

A crucial question is whether more gas can be substituted by installing heat pumps instead of continuing to heat with gas and using the additional renewable electricity to reduce the load hours of existing gas-fired power plants. This depends on the achievable coefficient of performance (COP) of heat pumps, which is the heat generated divided by the electric power required for it[25,26], and needs to be compared to the efficiency of gas-fired power stations.

In Germany, combined cycle gas turbines (CCGT) provide the bulk of gas-based electricity. Their average annual efficiency in 2020 is the ratio between their electricity generation, which was 95.0 TWh, and the gas consumed, which was 171.4 TWh[27], yielding 55%. To account for grid losses, we lower this value to 50%.

For process heat in industry, we use a COP of 2 for industrial heat pumps, which accounts for the need to achieve fairly high temperatures (associated with low COP values), especially for drying purposes, but also the fact that the source temperature can often be quite high due to the use of residual heat (allowing high COP values)[28].

For residential space heating, we find an annual averaged COP of heat pumps too approximative because buildings with less insulation require higher heating temperatures and therefore yield lower COP values. We therefore model the COP with hourly resolution and broken down into energy classes of buildings that reflect the insulation status[29]. A common parameter for quantifying insulation of buildings is the specific room heat, which is the annual heat used per square metre of heated rooms. We gathered data from ref. [30] and consolidated them, as described in the Supplementary Note 4. Figure 1 shows the resulting amount of heat consumed in Germany in each segment (energy class), distinguishing between standalone houses and apartment buildings.

The next important input parameter for our model is the water temperature that the heat pump must feed into the heating circuit to ensure adequate thermal comfort. Besides the insulation of the building, it also depends on how the heating circuit is designed. Underfloor or panel heating systems require the lowest temperatures and enable the highest COP values, while radiators require higher temperatures and lead to lower COP values. We rely on a data set of hundreds of buildings in Germany[31]. With a rapid spread of heat pumps, it cannot be expected that floor or panel heating will be installed. Therefore, it is important to notice that we only consider buildings from this data set[31] where radiators are still used despite the heat pump. Figure 2 shows examples of water supply temperature as a function of outdoor intake temperature in such buildings (thin lines), as well as our conservative, linear fit for the model (bold lines). We assume that buildings in the energy class H will not be fitted with heat pumps without prior improvement of insulation.

The differences within the individual energy classes result mainly from the different sizes of the radiators. We emphasise that in many cases, strategically increasing the size of just one or two small radiators already greatly reduces the required flow temperature[32] and therefore, the installation of heat pumps often does not have to be accompanied by extensive work on the heating circuit. This systematic observation[31] is contrary to widely held beliefs from pioneering times of heat pumps. Nevertheless, to stay on the conservative side, we add 10 °C to our fits in the higher energy classes (see Supplementary Note 5).

Finally, we take the COP from a data sheet of a commonly sold air-to-water heat pump[33] as a function of the temperature difference at which a heat pump must operate, see Fig. 3. Again, we make a conservative estimate, with the quadratic polynomial[34]. We consider only the COP of air-to-water heat pumps to stay conservative and to facilitate rapid installation. There exist alternatives, such as air-to-air and water-to-water heat pumps, which have even higher COP values. For a sensitivity analysis to lower COP values, see Supplementary Note 6.

For hot water, we assume an average COP of 2.5, since immersion heaters or instantaneous water heaters may be used for either all water heating or for heating water from heat pumps to higher temperatures.

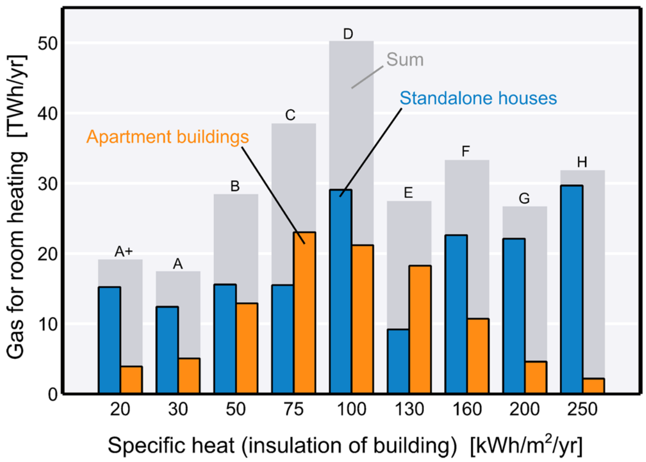

Fig. 1 The gas for domestic space heating used in Germany. Amounts are per year, in standalone houses and apartment buildings, respectively, distinguished in energy efficiency classes (building insulation) from A to H[31], expressed as specific heating energy, from a compilation of data[30]. Data are listed in Supplementary Table S3.

Exemplary narratives

We are aware that installing heat pumps may be limited by the circumstances that prevail in plumbing and heating businesses. In Germany, there are currently about 50,000 plumbing/heating/air-conditioning companies with about 380,000 employees that install about 1 million heating units per year[35]. On average, this is 7.6 employees per business and only about 3 heating units per employee and year. Many companies prefer working in the sanitary sector (e.g., renovating bathrooms or constructing new buildings). Of all 50,000 companies, only 10–20% regularly install heat pumps[35] and have the necessary additional training[35].

We, therefore, decided to build our scenarios from bottom-up by conducting semi-structured, qualitative interviews with some owners of such businesses. These expert interviews have no claim to be representative. Nevertheless, we want to reproduce selected key statements (memory transcript) from owners of two quite typical companies. Both companies are average in size, family-owned, and have operated for more than four decades in business in the Rhine-Main Metropolitan Region. They give important insights into the perspectives of practitioners.

Key statements of the owner (A), whose company does not install heat pumps:

A1). Heating (regardless of the type of heating) is currently only attractive for plumbers if there are too few orders in the sanitary sector.

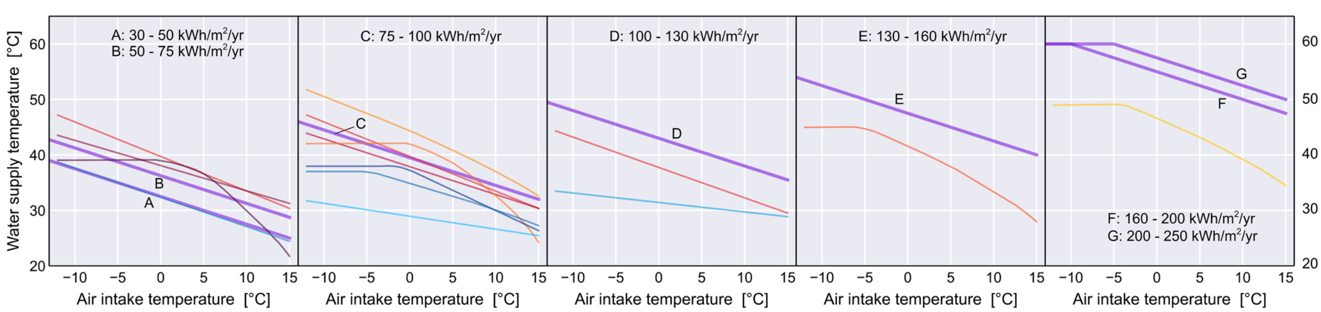

Fig. 2 Water temperature of heat pumps in buildings with different insulation levels. Thin lines: Measured water supply temperature of the heating circuit as a function of outdoor intake temperature of the heat pump[31]. Only circuits with radiators are considered. The supply temperature varies among buildings having the indicated energy efficiency (building insulation) from A to G, which is indicated as the range of the specific heating energy. Bold lines: Our linear fit for the model. For poorly insulated budlings, it is conservative to consider rather inefficient heating circuits. Data are listed in Supplementary Table S4.

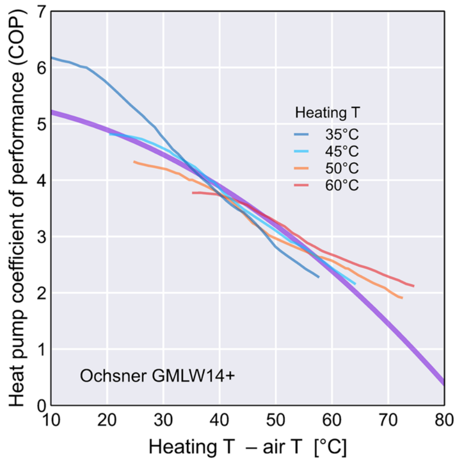

Fig. 3 Performance of a typical modern heat pump in a wide range of conditions. The coefficient of performance (COP) of a widely sold air-to-water heat pump for various water supply temperatures to the heating circuit, as a function of the temperature difference at which the heat pump operates (i.e., water supply temperature minus outdoor intake air temperature)[33]. Bold line: Our conservative estimate with a quadratic polynomial[34], given in Supplementary Note 6.

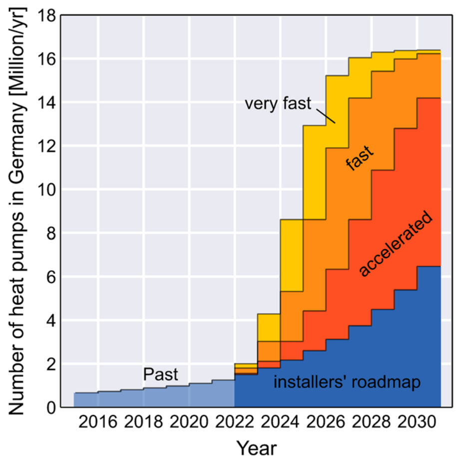

Fig. 4 Scenarios for the number of heat pumps installed in Germany per year and the evolution to date. The very fast scenario considers narratives from owners of plumbing and heating companies, necessary government incentives, and a training offensive for professionals. The fast and accelerated scenarios overcome these limiting factors only to lesser degrees. The installers' roadmap of the German Heat Pump Association[35] was developed before the Russo-Ukrainian War started[38]. Data are listed in Supplementary Table S5.

A2). There are too few employees. The labour market is empty, apprentices are hard to find.

A3). There is too little training for heat pumps on offer, and the quality of the training is often poor.

A4). Heat pumps are not technically mature, they often cause trouble, regardless of the manufacturer.

A5). An underestimated problem with heat pump installation is that the hot water supply is often connected to the heating system.

Owner (B) makes about 10% of his turnover from installing heat pumps, and the trend has been slowly increasing for years. Half of the employees are qualified to install heat pumps. The key statements of owner (B) are:

B1). The lack of skilled workers as the main problem.

B2). The training courses on offer as boring and far removed from practice.

B3). Things could only move quickly if heat pumps with an output temperature of 70 °C and more became established: "Then we could get to the old buildings without endless effort and expense. After all, people live in old buildings—and complete renovations of old buildings are too expensive and take far too long."

B4). "If politicians want heat pumps in households, they have to make gas as well as oil heating really expensive, even more expensive than now – but at the same time must cap the price of electricity. Then it will all work out." [Note: The interview was conducted after the price surge due to the Russo-Ukrainian War but before the federal government announced a ban[36] on conventional heating systems using less than 65% renewable energy, for the beginning of 2024].

B5). A multiplication of heat pumps by 2030 is illusory: "We'll never manage that; anyone who says that's possible is a'dream dancer'."

Since these owners have a vested interest, we flank these statements with an interview of an economically independent expert[37]:

E1) There is indeed a shortage of staff (A2 and B1), but recently there has been a big push for training opportunities, including a day of practical exercises organised by heat pump manufacturers (relativises A3 and B2).

E2) Regarding lucrativeness: Circumstances have changed completely in recent months (in contrast to A1). Those offering to install heat pumps have a choice of eager customers, and the waiting time is currently around 12 months. However, many business owners still seem to be hesitant.

E3) Regarding technology: Heat pumps are mature. Initial problems only arise in a few cases due to incorrect settings and possible incompatibilities with combi-storage tanks. There is a widespread outdated opinion from the pioneering days in the 1980s that the technology is problematic (puts statements A4 and A5 into perspective).

E4) Systematic studies over 15 years in about 350 existing buildings, 100 of which are very old, have repeatedly proven[31] that heat pumps rarely need to supply more than 55 °C to the radiator heating circuit and virtually never up to 70 °C (relativises B3). In the minority of old buildings, one or two radiators may need to be replaced with larger ones, but usually both the existing gas heating and the radiators are oversized.

These narratives are used in the following to create scenarios.

Scenario building

The number of heat pumps to be installed in houses was determined by ref. [38] for ref. [35] at 15–17 million units. This is less than 44 million households, as only one large heat pump is usually installed per apartment building, for cost reasons, and buildings are also connected to a heating network, which is partly fed by large heat pumps.

Figure 4 shows the growth of the heat pump stock according to the roadmap of the German Heat Pump Association (BWP), showing about 20% annual growth in dark blue[35]. It was developed before the increase in gas prices and before the Russo-Ukrainian War. However, new technologies that become mainstream usually come to a point where it is either economically beneficial to switch to the new devices or there is an increase in usefulness[39]. From this point, faster penetration is triggered according to an S-curve[40]. The war and related political decisions make this likely.

At the macro level, rapid growth in the number of installations is possible because worldwide about 10 million heat pumps are produced each year, and in Germany alone, investments of over one billion euros were made this year to expand production[41]. As the narratives show, the limiting factor is the situation at the micro level.

Based on the interviews and the limited training capacities, we set the very fast scenario to add a maximum of 4 million heat pumps per year in Germany, which appears feasible to us for the following reasons. From the narratives (A5 and B3), we assume a nationwide average of 4–6 person-days per installation of a heat pump[42], which is longer than an installation in a suitable location, and also gives time to enlarge one or two radiators (E4), for example, or to overcome difficulties in integrating the heat pump to the warm water system (A5). Even in such a year of 4 million new heat pumps, not more than a quarter of the 380 000 full-time employees will be needed to install heat pump systems. Considering the statements (A2, B1, and E1) that the labour market is empty, we do not add new workers. Based on complications with old buildings (B3, E4), we restrict the water supply temperature to 60 °C (Fig. 2), which implies that on very few very cold winter days (shown in Fig. S8 in the Supplement), the heat pump may not deliver a room temperature of 20 °C for all rooms.

Regarding additional training (A3, B2, and E1), we assume that heat pumps are installed in small teams, so it is sufficient that only every second tradesperson completes the additional training. This training currently lasts for 3 to 4 days[42] and the participants are expected to gain practical experience afterwards. In this maximum scenario, it is thus assumed that this course is given to a total of about 70 000 employees over the first few years.

For all these reasons, the very fast scenario does not seem utopian to us, but it requires concerted efforts and cooperation between the government, companies, and customers. In the fast and accelerated scenarios, a correspondingly smaller number of employees must be trained and assigned to the installation of heat pumps (for details, see Supplementary Note 7).

For industrial applications below 100 °C, we assume the same, proportional scenarios as for the room heat, noting that a far smaller number of far larger heat pumps will be installed. An assessment of favourable government incentives for the industry is beyond the scope of this paper.

Results

Figure 5 shows the amount of gas substituted by renewable electricity through the installation of heat pumps and through reducing the load hours of gas-fired power plants, in the four scenarios of Fig. 4. The amount is plotted in relation to the total gas imported to Germany in 2020, which was 971 TWh. In the installers' scenario, only a small part is substituted, even by 2030. Targeted efforts are needed, such as the very fast scenario, which accomplishes fossil gas savings of about 30% by 2025 (about 290 TWh or 28 billion m^3). Considering that in 2020, about 50% of the gas was imported from the Russian Federation, the very fast scenario can save about 60% of this gas by 2025. It can therefore be expected that targeted efforts reduce the price volatility and supply risk of fossil gas, while at the same time, they move Germany decisively further along the path towards fulfilling the Paris Climate Agreement. The very fast scenario will also save at least 180 Mt of greenhouse gas emissions cumulatively by 2025 (for more details, see Supplemental Note 8).

Figure 6 shows how the newly added (not the total) renewable electricity is divided and used. In the first two years, the additional wind and PV capacity reduce mostly the load hours of the gas-fired power plants (rather automatically in competitive day-to-day markets). Our hourly resolved modelling shows that this is because in these first years, there are many hours when the sun is shining and/or the wind is blowing, but not enough wind farms

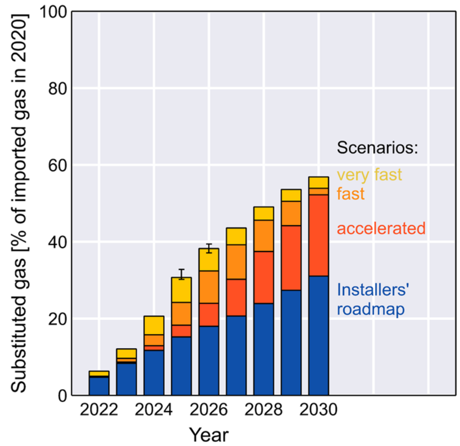

Fig. 5 Gas substitution in Germany by heat pumps. Modelled percentage of imported gas to Germany, substituted by renewable electricity through the installation of heat pumps in private households and in the chemical, paper, and food processing industries, in the four scenarios of Fig. 4. The columns in the background show the amount of gas substituted without installing new heat pumps (by using newly installed PV and wind generation to displace electricity from gas-fired power plants). The error bar in 2025 indicates the year-to-year weather fluctuations as standard deviation, the error bar in 2026 the local weather variations within Germany (see Supplementary Note 9). These variations are relatively small and similar in all years. Data are listed in Supplementary Table S7.

and PV capacities are installed to cover grid demand entirely (see Supplementary Note 10). In 2024 and 2025, heat pumps draw 70% of the newly added renewable power in the very fast scenario, which clearly reaches the limits of the model as it assumes sufficient grid expansion. Even though the Federal Network Agency has mandated grid expansion, it does not necessarily mean that sufficient grid capacity will be available everywhere in Germany in 2024 and 2025 (see Methods section). In later years, the renewable power capacities are large enough so that gas-fired power plants only need to run in situations where additional installed wind farms and PV capacities would not help, such as on windless nights. This situation will be reached in about 2030, when the annual share of renewables in electricity generation is about 80%[24] (see Supplementary Note 11).

Figure 6 also shows that over the years more and more electricity from renewable energies will be available for other purposes, such as to phase-out coal-fired power plants and to power electromobility.

Supplementary Note 12 contains a quantification for an immediate Germany-specific addition of renewable capacities to replace gas in the short term.

Conclusions

If renewable electricity capacities are installed, accelerated installation of heat pumps is an effective strategy option to greatly reduce fossil gas consumption, even if radiators remain installed in the majority of buildings, and part of the electricity is generated by fossil gas-fired power plants. With targeted efforts, maximally about 60% of the amount of gas, imported in 2020 in Germany from the Russian Federation, can be substituted by 2025 (about 40% in a less ambitious scenario). The scenarios assume targeted efforts that include cooperation between the government, companies, and customers to ensure that the installation of heat pumps is lucrative for installers, a training offensive for installers is launched and the electricity grid is expanded in the required places.

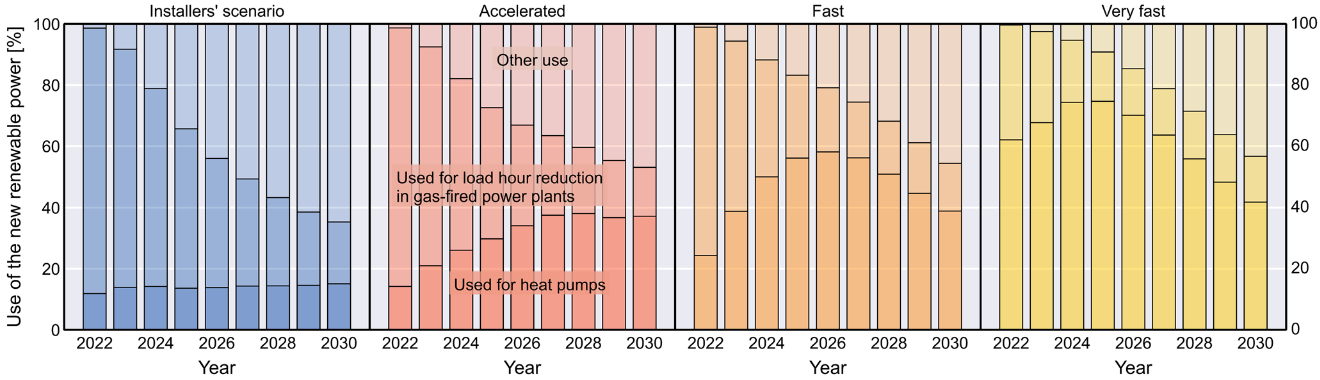

Fig. 6 Usage of newly added renewable power. The newly added (not the total) renewable electric power is used in different proportions in the four modelled scenarios: for heat pumps, for reducing the load hours of gas-fired power plants, and for other use such as coal phase-out and electromobility. Data are listed in Supplementary Table 7.

The scenarios, developed here for Germany, must accordingly be adjusted to specifics in other countries, but offer clear, tangible pathways to reduce the price volatility and supply risks of fossil gas while at the same time taking a decisive step towards fulfilling the Paris Climate Agreement.

Methods

The aim of the model is to estimate the substitution of gas by heat pumps with renewable electricity in Germany in hourly resolution. We, therefore, use a deterministic approach with only a single, nominal realisation of the renewable generation for heat pumps. The limits of this approach are critically assessed below.

For modelling electricity generation in the near future, we choose the reference year 2020, in which the following installed capacities were available: 55 GW for onshore wind, 6.3 GW offshore wind and 54 GW for PV. For the years between 2022 and 2030, we include the planned addition of onshore and offshore wind and PV shown in Supplementary Fig. S4. The advantage of this reference approach is that all details of the overall system as well as climate data for the whole of Germany are included.

Approximations of the model. There are three main accompanying approximations to this model choice:

Firstly, the geographical positioning of the new onshore wind farms is important[43], as the yield is greater in the north than in the south of Germany. It is realistic to assume that the new addition of wind farms will occur in a similar geographical distribution as in the 2020 inventory, as the energy transition in Germany has progressed so far that new wind farms are being re-powered in optimal locations and more wind farms have already been built in suboptimal locations as well. Multiplying onshore wind power of 2020 by a factor proportional to newly added capacity in the future is nevertheless conservative, because new wind turbines are usually bigger and higher and lead to more load hours than the capacities in 2020. In contrast, the geographical distribution of newly installed PV plants is less important and the hourly values are quite well correlated throughout Germany (except for the northern slope of the Bavarian Alps)[44].

Secondly, the electricity generation by power plants other than wind, PV and gas-fired units are left unchanged in all future years. It is apparent from the modelling results in Figs. 5 and 6 that apart from the operation of heat pumps and replacement of load hours of gas-fired power plants, an increasing part of the newly added PV and wind power will be left over for other applications. Because much of the electricity in Germany is traded according to the merit order principle, coal-fired power plants will be replaced by the leftover electricity, not by the electricity used for heat pumps and the replacement of gas-firing. Future changes in the generation of coal and other electricity therefore have only a minor influence on our results for gas substitution. So has the onset of e-mobility.

Thirdly, electricity generation from renewables fluctuates from year to year, more so for wind energy than for photovoltaics. To quantify year-to-year weather variability, we also model the years 2017, 2018 and 2019[23] for comparison with the 2020 reference. Our modelled gas consumption results in a standard deviation of 1.2% compared to imported gas in 2020 (970 TWh). This is in line with the standard deviation of gas imports[16]. Since we derive the standard deviation from only four years, we multiply it by a factor of two to be on the save side, as indicated by the error bar in 2025 in Fig. 5. In some winters, typical large-scale weather conditions[45] can lead to dark doldrums[46] in which neither wind energy nor PV can sufficiently meet grid demand. Such periods would only reduce gas savings to some extent, as these typical weather patterns do not cause very cold temperatures.

Limitations of the model. The model focuses on newly added renewable generation capacities and newly added heat pumps and neglects changes in fossil generation capacities. With the coal phase-out scheduled only for 2030 and an overcapacity of LNG terminals being installed due to the Russo-Ukrainian war[14], it is unlikely that the reduction in fossil generation capacity will lead to unexpected allocations of renewable electricity and thus have an impact on the results presented here. Furthermore, the model only considers the generation and consumption of electricity, not the details of electricity transmission in the power grid, where congestion may occur. This is a limitation of the model, especially in the very fast scenario for 2024 and 2025, where 70% of all new renewable power is used by heat pumps. The load curve in Supplementary Fig. S3 shows that heat pumps do not cause the notorious demand spikes, known from air conditioners on hot days, partly due to heat storage in boilers. Additionally, heat pumps can be operated very flexibly. As buildings are a large thermal energy storage, and many buildings have a boiler, heat pumps can be operated a few hours ahead of the heat demand, e.g., in the night hours when wind power is often available and the grid load is low. In spring and autumn[47], coupling heat pumps with local PV can provide heat during the day. This flexibility is not incorporated in the load curve in Supplementary Fig. S3. If heat pumps are operated in such a way that they run during times of low market prices, the power grid is considerably disburdened. Still, a combination of grid expansion[48,49] and electricity storage is necessary, as mandated by the German Federal Network Agency. And in no case should the model be used longer into the future than to the point of about 80% of renewable energy in the grid. At higher percentages, balancing capacities of multi-fuel internal combustion engines/open cycle gas turbines (ICE/OCGT) plants must be added during hours when there is no sufficient wind or sunshine. According to the plans of the Federal Ministry of Economics and Climate Protection[24], the 80% mark will be reached in 2030.

Gas load profiles. For quantifying the variation of gas consumption, we use the daily sigmoidal linear (sigLin) load profiles d from the Standard Load Profiles (SLP) manual[19], which depends on the daily average temperature T_d as follows:

$$d(T_d) = \frac{A}{1 + \left(\frac{B}{T_d - 40^\circ C}\right)^C} \tag{1}$$

For residential space heating, we use the profile DE_HEF04 with A = 3.1850191, B = −37.4124155 °C, C = 6.1723179, and D = 0.0761096, while for gas cooking, we use the profile DE_HKO03 with A = 0.4040932, B = −24.4392968 °C, C = 6.5718175, and D = 0.7107710. Both on all weekdays.

Since air temperature varies across Germany, we modelled with hourly temperature data from the German Weather Service (DWD)[50] in the most populous metropolitan areas, see Supplemental Note 10. Hanover is closest to the median of these sites, and all data were modelled with the temperature data from Hanover. The standard deviation due to the choice of locality (multiplied by a factor of 2 to be on the safe side) is represented in Fig. 5 by the error bar in 2026.

As shown in the Supplementary Note 2, hourly load profiles h are taken as a function of hourly outdoor temperature T_h and normalised to 1.

Mathematical procedures. The amount of gas $G_{i,2020}$ consumed in each hour of 2020 in a sector s = {residential space heating, cooking, the chemical, paper and food processing industries} is: $G_{s,2020} = d(T_\mathrm{d}) * h(T_\mathrm{h}) * g_{s,2020}$, where $g_{s,2020}$ is a factor chosen so that the sum of gas consumption over the whole year 2020 in each sector is matched to the values given in the main text. Please, note that d and h have no unit, while g has unit $\mathrm{TWh_g}$, with g standing for gas.

To calculate the future quantity $G_{s,year}$ of substituted gas in the $year$ = {2022, 2023 … 2030}, we multiply $G_{s,2020}$ by a factor $f_{year,scenario}$, which depends on the $scenario$ = {installers' roadmap, accelerated, fast, very fast}. Note that we choose f to be the same for all sectors s, using the scenarios for the heat pumps in residential space heating shown in Fig. 4 in units of million. To obtain f, we therefore scale these numbers so the factor is 0 in 2020 and 1 if 16 million heat pumps are installed, as listed in Supplementary Table S5. Then, $G_{s,2020} * f_{year,scenario}$ yields the amount of substituted gas in TWh_g. To calculate the required electricity in TWh_e, $G_{s,2020} * f_{year,scenario}$ is divided by the (momentary) COP. For private space heating, $G_{s,2020} * f_{year,scenario}$ is divided by a quadratic polynomial shown in Fig. 3, which is $5.4 - 0.013 * (T_{\rm heat} - T_{\rm h}) - 0.00062 * (T_{\rm heat} - T_{\rm h})^2$. A parameterisation of the heating water temperature (as a function of $T_{\rm h}$) in the various building efficiency classes A to G is shown in Fig. 2 and listed in Supplementary Table S4.

The hourly sum of all these TWh_e values required by heat pumps, H, is compared with the added PV and wind electricity calculated according to Supplementary Fig. S4, specifically by multiplying the hourly PV and wind electricity values of 2020 by the factors given in Supplementary Table S1. If H is greater than the added renewable electricity R, the amount of gas, $G_{\rm pp}$, used by gas-fired power plants to meet this additional demand is calculated, taking an efficiency of 50% for these power plants, as explained in the main text: $G_{\rm pp} = (H - R)/0.5$. In this case, $G_{\rm pp}$ is subtracted from the gas substituted by heat pumps, and the net amount is marked as "used for heat pumps" in Fig. 6. If H is smaller than R, $G_{\rm pp}$ is negative, which means that at least part of R substitutes gas by reducing the output of the gas-fired power plants. That amount is labelled as "load hour reduction in gas power plants" in Fig. 6. If there is more R available than can be used for reducing the output of the gas-fired power plants, this remaining power is labelled as "other use" in Fig. 6. In Fig. 5, the sum of both "used for heat pumps" and "reduction of load hours in gas power stations" is shown. Finally, the columns in Fig. 5 labelled "no heat pumps" are a calculation with $H = 0$. The modelling results are listed in Table S7.

We do not calculate the investment and the price. Private investment, though, is kept to a minimum by limiting our model to the installation of heat pumps with only minor changes to the heating circuit.

Data availability

All input and output data can be found either in the main text and in the Supplement. Additionally, they are available as an Excel file at https://doi.org/10.5281/zenodo.7559161. The equations are given in the Methods section and in the Supplement. The data of the German electricity system for the years 2017 to 2020 were made available to the authors by ref. [23] for non-commercial use, but are not generally publicly available (request these data at https://www.agora-energiewende.de).

Code availability

Because the data of the German electricity system for the years 2017 to 2020 are not publicly available, we are unable to publish the original code, but it contains the equations given in the Methods section and in the Supplement.

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Author contributions
P.P.A. developed the model and performed the computations. J.C. contributed with his expertise on the heat transition and on technology adoption. H.B. conducted the interviews and contributed with his expertise in social sciences and general quantitative research. C.B. contributed to the model development with his expertise in the energy transition. C.K. contributed with her expertise on the gas system. U.W. and C.G. contributed with their expertise in energy systems and buildings. M.W. aided in the conceptualisation and validated the model. The first draft of the paper was written by P.P.A. and all other authors added sections with their expertise.

Competing interests
The authors declare no competing interests.

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