nature portfolio

Peer Review File

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

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

16th Aug 22

Dear Dr Altermatt,

Your manuscript titled "Rapid substitution of fossil gas with renewable electricity and heat pumps: modelling scenarios to support decisions in line with the Paris Agreement" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms (that is, either to incorporate the suggestions or provide a compelling argument why the point made by the reviewer is not valid, or relevant to the editorial threshold as outlined below) and meet our editorial thresholds as outlined below, then we would be happy to look at a substantially revised manuscript.

In the following, we list our main editorial concerns:
** better specify the impact on GHG emission to clearly show the potential of the proposed solution;
** clearly address the concerns about the qualitative analysis proposed;
** discuss potential limitations of your work deriving from the lack of specification of the energy or power-system model.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We understand that due to the current global situation, the time required for revision may be longer than usual. We would appreciate it if you could keep us informed about an estimated timescale for resubmission, to facilitate our planning. Of course, if you are unable to estimate, we are happy to accommodate necessary extensions nevertheless.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers’ comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact me if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Alessandro Rubino, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-2737-9052

Joe Aslin
Locum Chief Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Overall this paper looks to consider how much rapid heat pump deployment could reduce gas imports in German and the barriers to this. The paper is interesting and timely but has some limitations, most importantly, the qualitative nature of the research is limited and detracts from the modelling. It is so brief that I believe the paper would be better off without it as it is simply some headline results from two interviews, without significant justification.

The omission of the greenhouse gas reduction potential is also a clear limitation. If this paper were to be published it would be most valuable if it could demonstrate how rapidly gas imports could be cut by heat pumps and by how much as well as by how much the deployment would lead to emission reductions. The paper would then demonstrate a clear win-win for heat pumps.

Some consideration of the recent policy literature around heat pumps would also have value to bolster the relevance and findings of the paper and to also consider policy recommendations. This piece is Germany specific: https://static.agora-energiewende.de/fileadmin/Projekte/2022/2022-04_DE_Scaling_up_heat_pumps/Waermepumpen_Praesentation.pdf and this is EU wide https://www.raponline.org/knowledge-center/the-perfect-fit-shaping-the-fit-for-55-package-to-drive-a-climate-compatible-heat-pump-market/

Some specific comments:

Keywords: Require some simplification
Figure 3 and associated data: is 1 heat pump data sheet sufficient? how does this compare to others?
COP of 1 for hot water is overly conservative. If a heat pump is in place it will most likely be used for hot water and immersion used only for pasteurisation cycles. Data is poo but based on the COP chart even if water was heated to 55 degrees Celcius, that would be a COP of over 2.5 at O degrees outside.

Reviewer #2 (Remarks to the Author):

The analysis is a highly topical issue from a European perspective, but also from a German perspective. In this respect, the conducted scenario analyses promise a high added value. All in all, the bottom-up modelling carried out for the calculation (including the models themselves) can be classified as adequate and corresponding to the state of the art. It should be particularly emphasized that the modelling of the electricity and heat generation is done on an hourly basis (high timely resolution), which does properly consider the high volatility of heat demand but also of electricity generation from renewable energies. Similarly, it is also positive that different weather years were considered and also different regions (cities) where the heat pumps are used.

The suitability of the methodological approach applies regardless of the fact that many, from today's perspective, uncertain assumptions had to be made for the modelling and simplifications were necessary (e.g. assumption of the same output temperature of the heat pumps of 60°C, same annual performance factor for industrial applications of 2.0). However, it can be stated that the main assumptions made are made transparent in the text or the supplementary material and are derived in a well-founded manner from the specific authors' point of view.

Basically, the modelling of the effect of a massive market ramp-up of electric heat pumps (in combination with an expansion of renewable energies) is not new. What is new, however, is the focus of the analysis on the achievable reduction of natural gas consumption and thus of natural gas imports from Russia, without any doubt a central issue in the current geopolitical situation. Ultimately, it is modelled how much additional natural gas is needed for electricity generation (assuming a constant amount of additional electricity from renewable energies as defined as a target in the so-called "Easter Package" of the German government). This additional demand for natural gas is related to the demand for natural gas that is eliminated by the use of heat pumps for heat supply.

The results of the model calculations show the basic potential of the expansion of heat pumps. However, it would be useful to place the focused consideration of the ramp-up of electric heat pumps for heat supply in a broader context, at least in the introduction and conclusion. This is only done in a rudimentary way in the text. It would be important to note, however, that this measure is only one strategy element of several that can contribute to a solution for the reduction of natural gas demand, albeit probably the most important one besides improved thermal insulation (refurbishment of buildings). The expansion of district and local heat supply (based on renewable energies or industrial waste heat), for example, remains unmentioned, as do measures on the behavioural side (e.g. reduction of average room temperature).

Even though it is emphasized several times in the text that conservative calculations have been carried out, optimistic assumptions have been made at various points (e.g. regarding the limited need to adapt the heating distribution system or the size of radiators to the requirements of heat pumps), which revise this classification “conservative” somewhat. This should be presented more transparently.

It is interesting to note the inclusion of manufacturer interviews in the design of the scenarios and the derivation of assumptions. However, it should not be forgotten that these actors have a vested interest and it would have been good to flank the manufacturers' statements with independent expert interviews.

Apart from varying the market ramp-up scenarios for electric heat pumps, no sensitivity analyses are performed. This is problematic in view of the high uncertainties in the system and should at least be mentioned in the text, even if it is quite understandable that due to time restrictions (publication of the results in the context of the current gas price and gas supply crisis) detailed sensitivity considerations could not be carried out.

The text refers several times to necessary contributions to the implementation of the Paris Agreement. However, statements on the climate protection impact of the modelled market ramp-up scenarios are completely missing. This is also true for a discussion of the extent to which other power plants (especially coal-fired power plants) are affected in their mode of operation.

Even though a whole series of restrictions for the expansion of electric heat pumps are mentioned (e.g. suboptimal heat distribution systems in existing buildings), a more in-depth discussion of other limiting variables such as manufacturing capacities and space requirements in existing buildings for the subsequently installation of heat pumps) is definitely missing. Also, the estimates of short-term qualification measures and the availability of craftsmen may well be considered optimistic. Somewhat more cautious wording would certainly be appropriate here.

Finally, at the very end of the text there is an assertion that is very broad but has not been further qualified. This concerns the classification of the massive expansion of electric heat pumps as a "less regrettable option" in relation to the construction of LNG terminals in Germany. This statement, in its absolute formulation, is not necessarily correct, provided that it is ensured that the LNG terminals are embedded in a broader hydrogen expansion strategy and that a switch to hydrogen imports is possible without any problems.

Reviewer #3 (Remarks to the Author):

Review of manuscript COMMSENV-22-0522-T Rapid substitution of fossil gas with renewable electricity and heat pumps: modelling scenarios to support decisions in line with the Paris Agreement

Altermatt and co-workers present an interesting work on a highly relevant and urgent problem; how to prevent replacing the offset of Russian gas with other fossil energy supply. Their focus is the German heating sector with the hypothesis being that a sharp increase in heat pump (HP) installations and continued development in renewables is a promising pathway to decarbonize domestic heating in Germany.
The paper is a pleasant read and contains interesting, important results. My concerns and comments mainly relate to the methodology, justification of some choices made in study and presentation of findings.

1. In the abstract, you write "…installing heat pumps is one of the fastest ways to reduce gas consumption by modernisation of infrastructure." Modernisation of infrastructure sounds here as rather broad; I would suggest being more specific as you only consider the HP itself for investment, not other parts of the heating infrastructure.
2. In the introduction, you mention different measures to reduce the carbon footprint of heating. One of which you forget is the use of surplus heat in connection with district heating. Furthermore, referring to RepowerEU, energy efficiency is lifted as a key measure to reduce depends on Russian gas. Installing heat pumps is one, however, while improved building insulation is another – also possible with (arguable) relatively modest efforts. Would it be possible to comment on why you specifically choose HP and do not consider other energy efficiency measures?
3. In the final paragraph of the introduction, you refer to your (later presented) scenario construction. You state that you will "….incorporating these constraints into our hourly model." Immediately, I would except that you include mathematical constraints in an energy system model to analyze the impact on these on the distribution and installation of HPs. Later, it becomes clear that you do not use an energy of power system model of the German electricity system, but rather a simplified computational approach. I would suggest being more precise to prevent this ambiguity.
4. The first paragraph of the section "Substitution of gas by electricity" is to be a bit vague. You write that "A crucial question is whether more gas can be substituted by installing heat pumps instead of using all the additional renewable electricity to reduce the load hours of

existing gas-fired power plants." Which alternative to you refer to (i.e., instead of using all the RES…)? Is it direct heating with electric furnaces run on renewables? Or other alterntive use of the renewables?
5. My major concern is methodological: unless I miss details of your methods, it appears that you do not include any energy or power-system modell that includes transmission. Moreover, you use a deterministic approach with only a single, nominal realization of the renewable generation (although it appears that you include some uncertainty on the demand side related to outdoor temperature variations). This is clearly a limiting factor, although it does not exclude you from getting interesting results. In any case, this should be commented on. By not including a energy-system or power-system model, e.g. PyPSA, you do not account for distribution of generation. Hence, wind energy generation in the North Sea is available for heat pumps in southern Germany. Grid transmission congestion is a well-known challenge in Germany from and a challenge for RES utilization. This should be commented on/addressed as it might be a significant limiting factor – at least affecting your results, even though you take conservative choices in many of your parametric choices.
6. To my understanding, you consider only air-to-water heat pumps. While existing radiators and water-born infrastructure facilitates rapid installation of HPs, there exists alternatives. Air-to-air (used a lot in Nordic countries) and water-to-water. For the transferability of your analytical approach to other countries, as you lift in the conclusion, the technology choice of HPs is integral part. Also, for the industry sector, high-temperature HPs are becoming promising alternatives to decarbonize heat supply, e.g. steam production. Please elaborate in your manuscript more on the choice of HP technologies, possibly also for other use at broadens the applicability of your approach.
7. The legends of figure 2 are difficult to interpret.
8. In your results, you set for the "Very fast scenario" a maximum of 4 million HP units annually. But there is no invest analysis/decision/degrees-of-freedom in your model? So, this is a fixed number and not an upper limit? Or am I missing something..
9. Figure 5; why do you include uncertainty bars only for year 2025 and 2026 for year-to-year weather fluctuations, and not for each year? And does the weather fluctuations also impact renewable generation?
10. I miss more numbers/quantitative results in your conclusions. It is rather "thin" on results in its current form. Conclusions should be strengthened.
11. Have you also considered hydrogen or other alternatives of decarbonizing domestic heating, for comparison of your results?

Response letter

We appreciate that all three reviewers (R1, R2 and R3) find our findings "interesting and timely" (R1), that “the conducted scenario analyses promise a high added value” (R2) and that “the paper is a pleasant read and contains interesting, important results” (R3). We find that all their suggestions improve the quality and usability of our work, and we are pleased to address them. Very few suggestions are based on minor misunderstandings, so we clarify these in our revised manuscript.

Besides the reviewers, the editor has the following concerns:

1. better specify the impact on GHG emission to clearly show the potential of the proposed solution;
2. clearly address the concerns about the qualitative analysis proposed;
3. discuss potential limitations of your work deriving from the lack of specification of the energy or power-system model.

We are pleased to address all three concerns in detail in our revised manuscript.

1. GHG emissions

In our first manuscript, we did not calculate the savings in CO_2 emissions because our modelling clearly shows that the installation of heat pumps saves natural gas, which of course reduces CO_2 emissions. We thought, what is the value of putting a number to something obvious? However, R1 states that “... it would be most valuable if it could demonstrate ... how much the deployment would lead to [CO_2] emission reductions. The paper would then demonstrate a clear win-win for heat pumps.” R2 writes: “The text refers several times to necessary contributions to the implementation of the Paris Agreement. However, statements on the climate protection impact of the modelled market ramp-up scenarios are completely missing.”

We see the benefits that R1 and R2 are aiming for, and we now calculate the amount of CO_2 emissions saved. However, we have two reservations in doing this:

1. Heat pumps are an end-user appliance that can be powered by various electricity mixes, and also gas heatings can be powered by various gas mixes. The primary CO_2 saving comes from considering the greenhouse gas emissions all along the value chain of LNG, which is mainly used in present government initiatives. This stretches the scope of this paper.
2. In the last two years, satellite and bottom-up assessment studies have detected large amounts of methane leakage all along the gas and oil value chains. These are not included in official greenhouse gas inventories yet, making it difficult for us to give a realistic number.

Combustion of pure methane gives a CO_2-to-methane mass ratio of 2.75. Since LNG is not pure methane, the official ratio is 2.56. However, the official inventory of some LNG companies in Australia adds an average of 54.3% to local CO_2 emissions. This is due to the extraction, processing, cooling and subsequent transportation, and also depends on the CO_2 content of the raw gas before the clean gas is cooled. This amount of CO_2 is normally discharged into the atmosphere. This results in a CO_2-to-methane mass ratio of 3.95. However, methane leakage is not accounted for and, in the case of coal, is well above the official Australian government inventories. As these considerations are beyond the scope of our paper, we use the ratio of 3.95 and note that this is a lower bound and neglects methane emissions. We then use the official conversion of 1 TWh to 0.692 Mt of LNG. We add in the context of Fig. 5:

The very fast scenario will also save at least 180 Mt of greenhouse gas emissions cumulatively by 2025 (see Supplemental Note 8)

We describe our calculations of avoided CO_2 emissions in the new Supplemental Note 8 in detail.

2. Qualitative analysis

R1 writes: "The paper [...] has some limitations, most importantly, the qualitative nature of the research is limited and detracts from the modelling. It is so brief that I believe the paper would be better off without it as it is simply some headline results from two interviews, without significant justification."

R2 writes: "It is interesting to note the inclusion of manufacturer interviews in the design of the scenarios and the derivation of assumptions. However, it should not be forgotten that these actors have a vested interest and it would have been good to flank the manufacturers' statements with independent expert interviews."

Four of the authors have dealt with owners of plumbing/heating businesses over the years and are therefore aware that these tradespeople are an important constraint in the deployment of heat pumps. We therefore aim that tradespeople must be considered when building our scenarios, otherwise the paper runs the risk of being unrealistic. Since the two reviewers have somewhat opposing views, we arrive at a synthesis between R1, R2 and ourselves by adding an independent expert interview as suggested by the second reviewer:

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 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[27] 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.

We also add in the last paragraph of the Introduction:

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.

We believe that the addition of the expert interview not only compromises between the two opposing views of the auditors, but also significantly improves the qualitative part and gives the scenario building a better basis.

3. Limitations of model calculations

The limitations of our model calculations were mainly addressed by R2 and in two aspects also by R3. We are glad that R2 finds the model overall sufficient: "All in all, the bottom-up modelling carried out for the calculation (including the models themselves) can be classified as adequate and corresponding to the state of the art." And: "The suitability of the methodological approach applies regardless of the fact that many, from today's perspective, uncertain assumptions had to be made for the modelling and simplifications were necessary ... it can be stated that the main assumptions made are made transparent in the text or the supplementary material and are derived in a well-founded manner from the specific authors' point of view."

R2 suggests: "It should be particularly emphasized that the modelling of the electricity and heat generation is done on an hourly basis (high time resolution), which does properly consider the high volatility of heat demand but also of electricity generation from renewable energies."

We added in the last paragraph of the chapter "Modelling of fossil gas consumption in Germany":
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...

R2: "...optimistic assumptions have been made at various points (e.g. regarding the limited need to adapt the heating distribution system or the size of radiators to the requirements of heat pumps), which revise this classification 'conservative' somewhat. This should be presented more transparently."

Below Fig. 4 in the description of how we arrived at the very fast scenario, we have added the expert's comments on various arguments. For example, the fact that in most cases the heating distribution system only needs to be adjusted slightly if at all has been quantified in field tests and is therefore not too optimistic, see expert comment E4 and the reference given there.

R2: “Apart from varying the market ramp-up scenarios for electric heat pumps, no sensitivity analyses are performed. This is problematic in view of the high uncertainties in the system and should at least be mentioned in the text, even if it is quite understandable that due to time restrictions, ... detailed sensitivity considerations could not be carried out.”

We take the reviewer’s point and now introduce a sensitivity analysis to COP in the entirely new Supplemental Note 6, containing new figures S5 and S6.

R2: “Even though a whole series of restrictions for the expansion of electric heat pumps are mentioned (e.g. suboptimal heat distribution systems in existing buildings), a more in-depth discussion of other limiting variables such as manufacturing capacities and space requirements in existing buildings for the subsequently installation of heat pumps) is definitely missing.”

Manufacturing capacities of heat pumps are unlikely to pose a limitation, as justified in our 1st manuscript directly below Fig. 4. Despite of this, we added:

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[35].

Regarding the “space requirements in existing buildings”: We add at the end of the Supplemental Note 4 that:
Not all houses will be equipped with heat pumps, therefore space requirements won’t be limiting the deployment of heat pumps.

R2: “the estimates of short-term qualification measures and the availability of craftsmen may well be considered optimistic. Somewhat more cautious wording would certainly be appropriate here.

We now write (below Fig. 4):
For all these reasons, the very fast scenario does not seem utopian to us, but it requires targeted efforts and cooperation between government, companies, and customers.

Instead of “is not utopian”.

R2: “...concern[ing] the classification of the massive expansion of electric heat pumps as a ‘less regrettable option’ in relation to the construction of LNG terminals in Germany. This statement, in its absolute formulation, is not necessarily correct, provided that it is ensured that the LNG terminals are embedded in a broader hydrogen expansion strategy and that a switch to hydrogen imports is possible without any problems.”

LNG terminals will continue to be used for fossil LNG for at least 10 years until hydrogen is available in significant quantities. The two LNG terminals under construction in Germany will have a total capacity of about 200 TWh of LNG per year. Within 10 years, the LNG they supply will account for about 10% of Germany's remaining carbon budget. Using heat pumps powered by the newly installed renewables will therefore be a less regrettable option. Please bear in mind that even if we manage to keep warming below 1.5°C, the impact on the climate will be more severe than today, and the younger generation will have to remove all the CO_2 from the atmosphere that we emit from now on to avoid severe damage.

However, to avoid disagreement leading to a second round of reviewing, we remove the 'non-regrettable' from the conclusions and the methods section.

R3: "you use a deterministic approach with only a single, nominal realization of the renewable generation (although it appears that you include some uncertainty on the demand side related to outdoor temperature variations). This is clearly a limiting factor, although it does not exclude you from getting interesting results. In any case, this should be commented on."

Right at the beginning of the Method section, we add: We use a deterministic approach with only a single, nominal realization of the renewable generation for heat pumps. This approach is justified in Fig. 6 showing that only part of the planned new renewable generation capacities will be used for heat pumps.

R3: "unless I miss details of your methods, it appears that you do not include any energy or power-system model that includes transmission." Similarly, R3 says: "By not including a energy-system or power-system model, e.g. PyPSA, you do not account for distribution of generation. Hence, wind energy generation in the North Sea is available for heat pumps in southern Germany. Grid transmission congestion is a well-known challenge in Germany from and a challenge for RES utilization. This should be commented on/addressed as it might be a significant limiting factor – at least affecting your results,even though you take conservative choices in many of your parametric choices."

We are only assuming the already planned increase in renewable electricity, as announced by the Federal Government. The Federal Network Agency (Bundesnetzagentur) has already been mandated to implement the grid expansion. We therefore do not consider it the objective of this paper to deal with this. Only if we had proposed *additional* installations of renewable electricity sources would we feel responsible for a detailed quantification of the necessary grid expansion. The hourly load curves of heat pumps shown in Fig. S3 do not burden the electricity grid significantly more than any other use of renewable electricity, e.g. through electromobility.

As a result of improving some of the input parameters, we have done the modeling again. Therefore, the results in Fig. 4 look slightly different than in the 1st version of the manuscript, but do not impact any conclusions made.

Specific comments:
R1: “Keywords: Require some simplification”

The keywords now read:
Climate emergency; fossil heating; heat pumps; installation limits; renewable electricity

R1: “Figure 3 and associated data: is 1 heat pump data sheet sufficient? how does this compare to others?”

We have added Supplemental Note 6 with the new figure S5, where we take norm DIN V 18599 as a lower bound of COP. It would not be reasonable to assume an even lower bound.

R1: “COP of 1 for hot water is overly conservative. If a heat pump is in place it will most likely be used for hot water and immersion used only for pasteurisation cycles. Data is poor but based on the COP chart even if water was heated to 55 degrees Celcius, that would be a COP of over 2.5 at O degrees outside”

We agree and adjust the COP for hot water to 2.5, according to the expert who gave the expert interview, this is still conservative. We included this change in our revised calculations.

Instead of:
For hot water, we assume an averaged COP of 1 as a conservative estimate, since...
We now write:
For hot water, we assume an averaged COP of 2.5, since...

R3: “The first paragraph of the section “Substitution of gas by electricity” is a bit vague. You write that “A crucial question is whether more gas can be substituted by installing heat pumps instead of using all the additional renewable electricity to reduce the load hours of existing gas-fired power plants.” Which alternative to you refer to (i.e., instead of using all the RES…)? Is it direct heating with electric furnaces run on renewables? Or other alterntive use of the renewables?

We clarify this point now by writing:
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.

R3: “To my understanding, you consider only air-to-water heat pumps. While existing radiators and water-born infrastructure facilitates rapid installation of HPs, there exists alternatives. Air-to-air (used a lot in Nordic countries) and water-to-water. For the transferability of your analytical approach to other countries, as you lift in the conclusion, the technology choice of HPs is integral part. Also, for the industry sector, high-temperature HPs are becoming promising alternatives to decarbonize heat supply, e.g. steam production. Please elaborate in your manuscript more on the choice of HP technologies, possibly also for other use at broadens the applicability of your approach.”

We agree. In context to Fig. 3, we now add:
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.

R3: “The legends of figure 2 are difficult to interpret.

It is now improved:
Figure 2 | Thin lines: Measured water supply temperature of the heating circuit as a function of outdoor intake temperature of the heat pump[29]. 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.

R3: “In your results, you set for the “Very fast scenario” a maximum of 4 million HP units annually. But there is no invest analysis/decision/degrees-of-freedom in your model? So, this is a fixed number and not an upper limit? Or am I missing something.”

This is a misunderstanding. Based on the interviews and the limited training capacities for tradespeople (70’000 in the next few years), we set a yearly upper limit of 4 million HP units not earlier than 2025. Our degrees-of-freedom are the three slower scenarios.

To avoid this misunderstanding, we now write:

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,

We also add some more explanations in the proceeding text.

R2 writes: “it is also positive that different weather years were considered and also different regions (cities) where the heat pumps are used.” But R3 writes: “Figure 5; why do you include uncertainty bars only for year 2025 and 2026 for year-to-year weather fluctuations, and not for each year? And does the weather fluctuations also impact renewable generation?”

Of course, we also take into account the effects of weather fluctuations on electricity generation from renewable energies. We only give the annual weather fluctuations for the year 2025, as these are small and similar for all years. The error bars in 2026 refer to fluctuations within Germany, which are also small and similar for all years. To clarify this, we now add in the caption of Fig. 5:

These variations are relatively small and similar in all years.

R3: “Have you also considered hydrogen or other alternatives of decarbonizing domestic heating, for comparison of your results?”

Our paper mainly looks a few years into the future. Within this period, there will not be sufficient infrastructure to produce hydrogen from renewables in sunny countries, compress it, ship it and distribute it in Europe. Hydrogen production in Europe consumes about three times more renewable electricity per hydrogen energy delivered than direct renewable electricity and is therefore not an option to save fossil gas effectively. Apart from that, local distribution networks for fossil gas are mostly not suitable for hydrogen, as they often contain pipes made of cast iron. For these and other reasons, there is widespread agreement that hydrogen is not a likely candidate for heating homes, definitely not in the next few years, which is the focus of this paper.

It is beyond the scope of this paper to argue for and against hydrogen for heating. We therefore add a short sideline in the introduction:

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[11,12].

Abstract

R3: “In the abstract, you write “…installing heat pumps is one of the fastest ways to reduce gas consumption by modernisation of infrastructure.” Modernisation of infrastructure sounds here as rather broad; I would suggest being more specific”

in the sentence, “... is one of the fastest ways to reduce gas consumption by modernisation of infrastructure, in addition to” we now deleted the “by modernisation of infrastructure”.

Introduction

R1 suggests: “Some consideration of the recent policy literature around heat pumps would also have value to bolster the relevance and findings of the paper and to also consider policy recommendations.”

Due to limitations in the number of references, we have only added two but in-depth and complementary policy papers (refs. 11 and 12)

R2 writes: “it would be useful to place ... the ramp-up of electric heat pumps ... in a broader context, at least in the introduction and conclusion.” and “It would be important to note ... that this measure is only one strategy element of several that can contribute to a solution for the reduction of natural gas demand, albeit probably the most important one besides improved thermal insulation (refurbishment of buildings).”

We have already done that in the introduction. We mention six different contributions to the decarbonisation of heat, namely: thermal insulation of buildings, solar thermal, replacing gas and oil boilers with heat pumps[5,6] powered by renewable electricity, district heating networks based on the use of industrial waste heat, solar thermal and geothermal energy as well as various storage technologies[9]. We find this a near exhaustive list.

R2: “The expansion of district and local heat supply (based on renewable energies or industrial waste heat), for example, remains unmentioned, as do measures on the behavioural side (e.g. reduction of average room temperature).” And R3: “One of which you forget is the use of surplus heat in connection with district heating.“
R3: “...referring to RepowerEU, energy efficiency is lifted as a key measure to reduce depends on Russian gas.”

We already described district heat in the 1st version of the manuscript. We add the behavioral side now as: Important for the effective use of heat are furthermore conscious consumer behaviour, district heating networks based on the use of industrial waste heat, solar thermal and geothermal energy as well as various storage technologies[9]

R3: “Installing heat pumps is one, however, while improved building insulation is another – also possible with (arguable) relatively modest efforts.”

We have already listed this as an option in the 1st version of the manuscript: “Curtailing emissions in heating may need to be achieved through various means simultaneously, including thermal insulation of buildings, ...”

R3: “Would it be possible to comment on why you specifically choose HP and do not consider other energy efficiency measures?”

We have included this now more explicitly above. And the first version of the manuscript already says: “... install heat pumps, as they require little planning and approval procedures and are modular, similar to PV.”

R3: “You state that you will ‘….incorporating these constraints into our hourly model.’ Immediately, I would except that you include mathematical constraints in an energy system model to analyze the impact on these on the distribution and installation of HPs. Later, it becomes clear that you do not use an energy of power system model of the German electricity system, but rather a simplified computational approach. I would suggest being more precise to prevent this ambiguity.”

This was a mistake. We have fixed this mistake again by adding:

Finally, by incorporating these constraints into our scenarios for our hourly model, we calculate

We included the limitation mathematically in our scenarios.

Conclusions

R3: “I miss more numbers/quantitative results in your conclusions. It is rather “thin” on results in its current form. Conclusions should be strengthened.”

We believe that the conclusions are not a summary. The paper provides clear quantitative results, and we see no need to repeat them in the conclusions, also given the limitation of the number of words allowed. As for strengthening the conclusions: we have derived a list of clear policy proposals from the quantitative model and from the interviews. We would have liked any government to have adopted at least part of our or similar recommendations given in our conclusions.

8th Dec 22

Dear Dr Altermatt,

Please allow us to apologise for the delay in sending a decision on your manuscript titled "Rapid substitution of fossil gas with renewable electricity and heat pumps: modelling scenarios to support decisions in line with the Paris Agreement". It has now been seen again by our reviewers, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License) provided you remove your policy recommendations and clearly acknowledge the limitations and uncertainties associated with the methods and data (e.g. with respect to the expansion of the grid).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at https://www.nature.com/documents/commsj-file-checklist.pdf .

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication under a CC BY license (Creative Commons Attribution 4.0 International License). This license allows maximum dissemination and re-use of open access materials and is preferred by many research funding bodies.

For further information about article processing charges, open access funding, and advice and support from Nature Research, please visit <a href="https://www.nature.com/commsenv/article-

processing-charges">https://www.nature.com/commsenv/article-processing-charges

At acceptance, you will be provided with instructions for completing this CC BY license on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:
[link redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alessandro Rubino, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-2737-9052

Joe Aslin
Senior Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Overall I am satisfied that my comments on the original manuscript have been dealt with, in particular with regards to the inclusion of greenhouse gas savings and the usefuleness of the qualitative section which now contains more information and justification.

Reviewer #2 (Remarks to the Author):

No further comments ti the amended version! Would recommend to accept the paper as it is now!

Reviewer #3 (Remarks to the Author):

Review of revised manuscript COMMSENV-22-0522-T Rapid substitution of fossil gas with renewable electricity and heat pumps: modelling scenarios to support decisions in line with the Paris

Agreement

I appreciate the authors' efforts in addressing and clarifying my questions and concerns to the original submission. The manuscript has been improved. Yet, I still remain with a few concerns:

1. **Regarding 3. Limitations of model calculations: I am a bit surprised by your relatively simple response to my concern regarding the lack of a power-grid or energy-system type model to support that the renewable power can indeed be delivered to the residences installing heat pumps - also considering the editor's request to address this concern. Personally, I believe it is a limitation of the method used to produce your quantitative results on how fast HP run by renewable electricity can be implemented to replace fossil (gas) heating. That being said, I think it is OK not to use such a method and I still certainly see merit in your study. Yet, I think you should address this issue better than you currently for the following reasons: the planned renewable generation expansions will be requested by a range of users with varying demand, including residential and industrial use, electromobility as you mention, and others. Only parts are typically "locked-in" by long-term contracts, much will be available in competitive day-to-day markets. Even though The Federal Network Agency as you refer to has mandated to implement grid expansions, that does not necessarily mean that sufficient grid capacity will be available all over Germany <i>at the same time <i>new renewable generation capacity is ready (installed and connected to the grid). Grid expansions take time and are expensive, you consider a relatively short time horizon in your study – until 2030, and many examples exist of stranded renewables due constrained grid capacity. In your scenarios, the additional load from running the HPs is considerable (Fig. 6) – both absolutely and relatively. Potentially large variability in renewable generation may be another issue for the security of renewable supply, and this is addressed only superficially in your method since you use only a single wind and sun time series. I think you should address these potential issues somehow in your paper – with a remark or short discussion that at least include reference to literature/other studies that show that the planned renewable generation expansion in Germany indeed will be accompanied and comply with planned grid expansion that will enable the renewable generation to be supplied across Germany – as your results assume.**

2. Conclusions: You misunderstand my request for conclusions targeted on your quantitative results. I do not ask you to summarize results once more. In its current form, I think there is a sort of gap from your results and conclusions. That is, I feel that you jump into policy recommendations (even though you have had little if no focus on current or prospective energy-efficiency or HP policies throughout the rest of the text/results – except from mentioning in the abstract that you will provide policy recommendations) and projections on the feasibility of implementation also in other countries, for which you provide little if any justification. For this reason, I recommend that you focus conclusions more on your specific results, their limitations and implications, and not just generalizing your results to countries. The latter will be highly data dependent and I struggle to see justification for such conclusions from your method and results from the German case study.

3. Regarding your answer to my point on using only a single realization: "Right at the beginning of the Method section, we add: We use a deterministic approach with only a single, nominal realization of the renewable generation for heat pumps. This approach is justified in Fig. 6 showing that only part of the planned new renewable generation capacities will be used for heat pumps. " Although in several years of the scenarios, the share of renewable capacity used by the HP is modest, in the very fast scenario, Fig. 6, HP uses up to 75% of new renewable generation. With

such high share of the renewable generation together with potentially high variability of the renewable generation, I do not concur that Fig 6. justifies a single realization (i.e. the intermittency of the renewable generation may periodically jeopardize renewable supply). Hence, I would say it is a limitation of your method, and not fully justifiable in all scenarios for each year over the considered horizon.

Response Letter

We appreciate that the two first reviewers are satisfied with our correction, and we also appreciate the good comments from the third reviewer, which improve our paper further.

Reviewer #3:
1. Regarding limitations of model calculations: I am a bit surprised by your relatively simple response to my concern regarding the lack of a power-grid or energy-system type model to support that the renewable power can indeed be delivered to the residences installing heat pumps - also considering the editor's request to address this concern.

Editor:
Also the editor asked us to acknowledge the limitations and uncertainties associated with the methods and data (e.g. with respect to the expansion of the grid).

Response:
Now we have included these concerns already in the abstract:

ways to reduce gas consumption by changing infrastructure, in addition to reducing the load hours of gas-fired power plants. With targeted efforts, about 60% of gas from the Russian Federation can be substituted by 2025 with heat pumps and grid expansions, and enough electricity will remain available from the planned addition of renewable electricity so that the phase-out of coal and the entry into e-mobility will still be practicable.

...in the main text (where only little space is left):

shining and/or the wind is blowing, but not enough wind farms 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

...and more detailed in the Methods section:

unlikely that the reduction in fossil generation capacity will lead to significant 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 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 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

Reviewer #3:
I think you should address these potential issues somehow in your paper with a remark or short discussion that at least include reference to literature/other studies that show that the planned renewable generation expansion in Germany indeed will be accompanied and comply with planned grid expansion that will enable the renewable generation to be supplied across Germany as your results assume.

Response:
We have added two new references, 48 and 49, but we have not found studies applicable to our required case. What would be required is not only a spatially well resolved multi-node model for Germany embedded in the European energy system, but also one that includes full sector coupling and fully interconnected grids. To our knowledge, no such model exists, especially for a rapid energy transition with PV, wind and heat pumps. The usual publications on grid expansion only consider the electricity grid alone and with a heavy load from transport and heat, but without sector coupling. It is not surprising that they arrive at a strong expansion. Or the publications look at sector coupling without enough detail on the power grid, like our new Ref 48, which we included because it does a spatio-temporal analysis and strengthens your point. We assume that a variable electricity price based on production and demand will lead to a lot of flexibility in heat demand and vehicle charging, and that many grid expansions will only require thicker cables in the distribution grid, which is much faster than building new (ultra) high voltage lines. To our knowledge, the Federal Network Agency is well aware of this.

Reviewer #3:
2. Conclusions: I feel that you jump into policy recommendations [...] and projections on the feasibility of implementation also in other countries, for which you provide little if any justification. For this reason, I recommend that you focus conclusions more on your specific results, their limitations and implications, and not just generalizing your results to countries.

Editor:
Also the editor asked us to remove our policy recommendations.

Response:
We have done so:

Conclusions and outlook

If renewable electricity capacities are installed, accelerated installation of heat pumps is an effective strategy option to significantly 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 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.

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.

Reviewer #3:

3. Regarding your answer to my point on using only a single realization: Although in several years of the scenarios, the share of renewable capacity used by the HP is modest, in the very fast scenario, Fig. 6, HP uses up to 75% of new renewable generation. With such high share of the renewable generation together with potentially high variability of the renewable generation, I do not concur that Fig 6. justifies a single realization (i.e. the intermittency of the renewable generation may periodically jeopardize renewable supply). Hence, I would say it is a limitation of your method, and not fully justifiable in all scenarios for each year over the considered horizon.

Response:

We have addressed these concerns fully together with your 1st point above, and additionally in the discussion of the Fig. 6:

shining and/or the wind is blowing, but not enough wind farms 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

All in all, we have generously addressed the three points of reviewer #3 and the two points of the editor and we hope that both are now satisfied.

Many thanks for the excellent input, it has improved our paper, and we mention this in our acknowledgements.

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

Pietro P. Altermatt[1,2], Jens Clausen[1,3], Heiko Brendel[1,4], Christian Breyer[1,5], Christoph Gerhards[1], Claudia Kemfert[1,6], Urban Weber[1,7], Matthew Wright[8]

1: Scientists for Future, Rigaer Str. 8, 10247 Berlin, Germany

2: Global Photovoltaic Simulation Group, Case Postale 1056, 1211 Genève 1, Switzerland

3: Borderstep Institute for Innovation and Sustainability, Clayallee 323, 14169 Berlin, Germany

4: University of Tübingen, Geschwister-Scholl-Platz, 72074 Tübingen, Germany

5: LUT University, Yliopistonkatu 34, 53850 Lappeenranta, Finnland

6: German Institute for Economic Research (DIW) Berlin, Mohrenstraße 58, 10117 Berlin, Germany

7: University of Applied Sciences Bingen, Berlinstraße 109, 55411 Bingen am Rhein, Germany

8: Department of Materials, University of Oxford, Oxford, OX1 3PH, United Kingdom

Deleted: University of Passau, Innstraße 41, 94032 Passau, Germany ...

Abstract

The supply security of fossil gas has been disrupted by the Russo-Ukrainian War. Decisions to relocate 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.

Deleted: suddenly

Deleted: , and affects the energy sectors in many countries

Deleted: logistics

Deleted: are imminent

Deleted: Therefore

Deleted: concrete

Deleted: and provides policy advice

Deleted: by changing infrastructure

Deleted: about

Deleted: will

Deleted: , and

Deleted: from the planned addition of renewable electricity so ...

Keywords: Climate emergency; fossil heating; heat pumps; installation limits; renewable electricity

Introduction

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.

Deleted: significant

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 insolation 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 insolation 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 insolation of buildings is the specific room heat, which is the annual heat used per square meter 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.

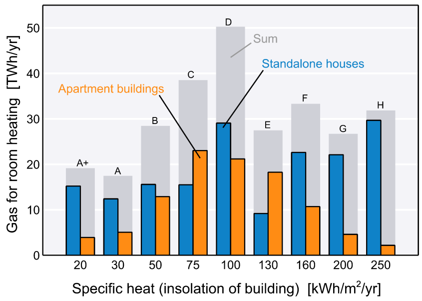

Figure 1 | The gas for domestic space heating used in Germany per year in standalone houses and apartment buildings, respectively, distinguished in energy efficiency classes (building insulation) from A to H[31], expressed as specific heating energy, from our data compilation of Ref. [30]. Data are listed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

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 insolation.

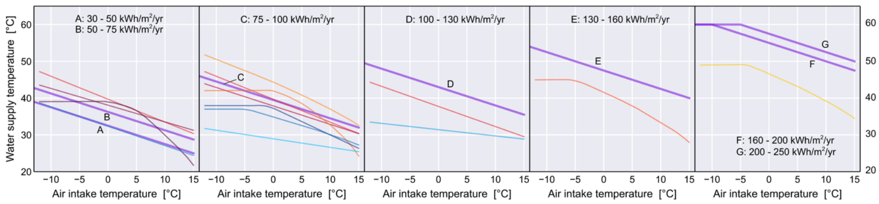

Figure 2 | Thin lines: Measured water supply temperature of the heating circuit as a function of outdoor intake temperature of the heat pump[31]. Only circuits with radiators are considered. The supply temperature varies among buildings having the indicated energy efficiency (building insulation) from 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.

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 hold believes from pioneering times of heat pumps.

Deleted: significan

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 Figure 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.

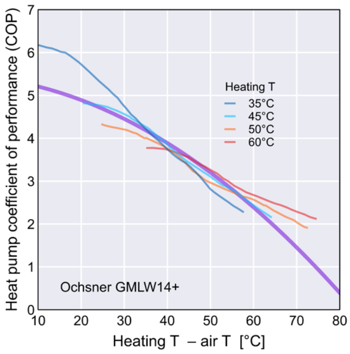

Figure 3 | The coefficient of performance (COP) of a widely sold air-to-water heat pump for various water supply temperatures to the heating circuit, as a function of the temperature difference at which the heat pump operates (i.e. water supply temperature minus outdoor intake air temperature)[33]. Bold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

For hot water, we assume an averaged 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.

Exemplary narratives

Deleted: about the installation of heat pumps

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 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.

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 the 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.

Deleted: significantly

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.

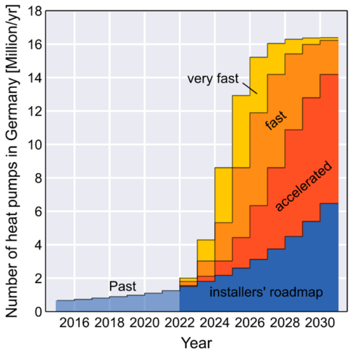

Figure 4 | **Scenarios for the number of heat pumps installed in Germany per year** and the evolution to date. The very fast scenario considers narratives from owners of plumbing and heating companies, necessary government incentives and a training offensive for professionals. The fast and accelerated 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 listed in Supplementary Table S5.

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, also to give 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 (Figure 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.

Deleted: 11

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 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 industry is beyond the scope of this paper.

Results

Deleted: Modelling r

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 Figure 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 saving 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).

Deleted: m

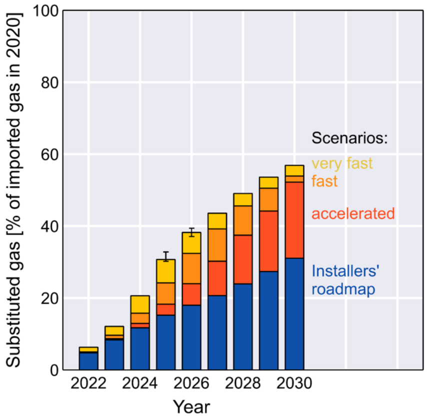

Figure 5 | Modelled scenarios for the percentage of imported gas to Germany, substituted by renewable electricity through the installation of heat pumps in private households and in the chemical, paper and food processing industries, in the four scenarios of Figure 4. The columns in the background show 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 in Supplementary Table S7.

Deleted: one

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 reduces 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 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 in 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).

Deleted: 9

Deleted: 0

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.

Deleted: 1

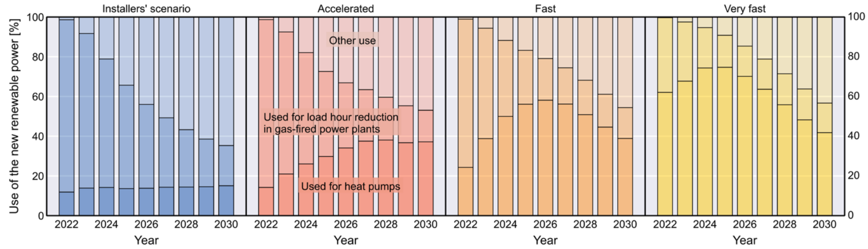

Figure 6 | The newly added (not the total) renewable electric power is used in different proportions in the four modelled scenarios: for heat pumps, for reducing the load hours of gas-fired power plants, and for other use such as coal phase-out and electromobility. Data listed in Supplementary Table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

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 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.

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 realization 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 Figure 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

Deleted: and

Deleted: recommendations

Deleted: significan

Deleted: This conclusion is based on the methodological approach that is broadly applicable to other temperate countries.

Deleted: may

Deleted: need to

Deleted: In many countries, however, accelerating the installation of heat pumps seems only possible through targeted efforts, cooperation between government, companies and customers, and by activating both pull and push effects. A government-imposed moratorium on gas heating (a possible push effect) should be combined with the following pull effects:¶
ensure that the installation of heat pumps is lucrative for installers, through, for example, targeted bonuses for installation.¶
launch a training offensive for installers so that they can assess the feasibility of heat pumps and install them;¶
if applicable, reduce the liability risk and administrative burden for installers. This can be done, for example, by minimizing risks through appropriate guidance and simplified approval and administrative procedures;¶
give customers a stronger incentive to have heat pumps installed despite a functioning oil or gas boiler, for example, by financial support for energy refurbishment, by reducing taxes and levies on electricity consumption of heat pumps, and taxation of fossil fuels.¶
launch an information campaign for customers on the technical feasibility and economic advantages of heat pumps, as well as on the price and supply risks of installing biomass boilers, as the supply of biomass is limited[10].¶
The new insights presented herein thus provide a feasible response of temperate countries with a dependency on fossil gas to the urgent energy issue caused by the Russo-Ukrainian War.¶

Deleted: is

Deleted:

Deleted: is justified in Fig. 6 showing that only part of the planned new renewable generation capacities will be used for heat pumps...

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].

Deleted: signific

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.

Deleted: I

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:

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

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 Figure 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: $G_{s,2020} = d(T_d) * h(T_h) * g_{s,2020}$, 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 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 Figure 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 Figure 3, which is $5.4 – 0.013 * (T_{heat} – T_h) – 0.00062 * (T_{heat} – T_h)^2$. A parameterisation of the heating water temperature (as a function of T_h) in the various building efficiency classes A to G is shown in Figure 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 Figure 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_{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: $G_{pp} = (H – R)/0.5$. In this case, G_{pp} is subtracted from the gas substituted by heat pumps, and the net amount is marked as "used for heat pumps" in Figure 6. If *H* is smaller than *R*, G_{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 Figure 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 Figure 6. In Figure 5, the sum of both "used for heat pumps" and "reduction of load hours in gas power stations" is shown. Finally, the columns in Figure 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.

References

1. ICPP Special Report. *Global Warming of 1.5°C*. (2019).
2. Tong, D. *et al.* Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature* **572**, 373–377 (2019).
3. Bogdanov, D. *et al.* Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy* **227**, 120467 (2021).
4. *Working Group III contribution to the IPCCC 6th assessment report (AR6)*. (2022). DOI: 10.1017/9781009157926
5. Knobloch, F. *et al.* Net emission reductions from electric cars and heat pumps in 59 world regions over time. *Nat. Sustain.* **3**, 437–447 (2020).
6. Gaur, A. S., Fitiwi, D. Z. & Curtis, J. Heat pumps and our low-carbon future: A comprehensive review. *Energy Res. Soc. Sci.* **71**, 101764 (2021).
7. Brown, T., Schlachtberger, D., Kies, A., Schramm, S. & Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* **160**, 720–739 (2018).
8. Jacobson, M. Z. *et al.* Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries. *One Earth* **1**, 449–463 (2019).
9. Bundesverband der Energie- und Wasserwirtschaft (BDEW) (Federal Association of the Energy and Water Industries), *Kurzfristige Substitutions und Einsparpotenziale Erdgas in Deutschland (Short-term substitution and savings potential for natural gas in Germany)*. https://www.bdew.de/media/documents/Kuzfristige_Gassubstitution_Deutschland__final_17.03.2022_korr1.pdf (2022).
10. Lund, H. *et al.* Perspectives on fourth and fifth generation district heating. *Energy* **227**, 120520 (2021).
11. Camia, A. *et al. The use of woody biomass for energy purposes in the EU, Publications Office of the European Union*. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC122719/jrc-forest-bioenergy-study-2021-final_online.pdf (2021) doi:10.2760/831621.
12. Olympios, A. V. *et al.* Delivering net-zero carbon heat: Technoeconomic and whole-system comparisons of domestic electricity- and hydrogen-driven technologies in the UK. *Energy Convers. Manag.* **262**, 115649 (2022).

13. Mills, E. Market spoiling and ineffectual policy have impeded the adoption of heat pump water heating for US buildings and industry. *Energy Effic.* **15**, 23 (2022).
14. Höhne, Niklas, Marquardt, Mats, & Fekete, Hanna. *German LNG terminal construction plans are massively oversized, NewClimate Institute, Cologne, Germany*. https://newclimate.org/resources/publications (2022).
15. Gerhards, C. *et al. Klimaverträgliche Energieversorgung für Deutschland – 16 Orientierungspunkte / Climate-friendly energy supply for Germany—16 points of orientation*. https://zenodo.org/record/4409334 (2021) doi:10.5281/zenodo.4409334.
16. Bundesverband der Energie- und Wasserwirtschaft (BDEW) (Federal Association of the Energy and Water Industries). *Energiemarkt Deutschland 2020 (Energy market Germany 2020)*. https://www.bdew.de/energie/bdew-energiemarkt-deutschland-2020/ (2020).
17. Federal Statistical Office of Germany. *Energieverbrauch der Betriebe im Verarbeitenden Gewerbe (Energy consumption of enterprises in the manufacturing sector), report number 43531-0001*. www-genesis.destatis.de (2020).
18. Madeddu, S. *et al.* The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environ. Res. Lett.* **15**, 124004 (2020).
19. BDEW/VKU/GEODE. *Abwicklung von Standardlastprofilen Gas (Processing of standard load profiles gas)*. https://www.bdew.de/media/documents/Leitfaden_20160630_Abwicklung-Standardlastprofile-Gas.pdf (2016).
20. Jesper, M., Pag, F., Vajen, K. & Jordan, U. Annual Industrial and Commercial Heat Load Profiles: Modeling Based on k-Means Clustering and Regression Analysis. *Energy Convers. Manag. X* **10**, 100085 (2021).
21. Fraunhofer Institute for Systems and Innovation Research ISI. *Energy load curve adjustment tool (eLOAD), Freiburg, Germany*. https://www.forecast-model.eu/forecast-en/content/methodology.php (2021).
22. Watson, S. D., Lomas, K. J. & Buswell, R. A. How will heat pumps alter national half-hourly heat demands? Empirical modelling based on GB field trials. *Energy Build.* **238**, 110777 (2021).
23. Agora Energiewende. Agorameter Version 11, 11.03.2021 (dataset not publicity available). (2022).
24. Bundesministerium für Wirtschaft und Klimaschutz (Federal Ministry for Economic Affairs and Climate Protection). *Opening balance climate protection (Eröffnungsbilanz Klimaschutz)*. https://www.bmwi.de/Redaktion/DE/Downloads/Energie/220111_eroeffnungsbilanz_klimaschutz.pdf?__blob=publicationFile&v=22 (2022).

25. Wang, Z., Luther, M. B., Amirkhani, M., Liu, C. & Horan, P. State of the Art on Heat Pumps for Residential Buildings. *Buildings* **11**, 350 (2021).
26. Staffell, I., Brett, D., Brandon, N. & Hawkes, A. A review of domestic heat pumps. *Energy Environ. Sci.* **5**, 9291 (2012).
27. Arbeitsgemeinschaft Energiebilanzen (Working Group on Energy Balances). *Auswertungstabellen zur Energiebilanz für die Bundesrepublik Deutschland 1990 bis 2010 (Valuation tables on the energy balance for the Federal Republic of Germany 1990 to 2010)*. https://ag-energiebilanzen.de/wp-content/uploads/2020/09/awt_2020_d.pdf (2021).
28. Heitkoetter, W., Medjroubi, W., Vogt, T. & Agert, C. Regionalised heat demand and power-to-heat capacities in Germany – An open dataset for assessing renewable energy integration. *Appl. Energy* **259**, 114161 (2020).
29. Priesmann, J., Nolting, L., Kockel, C. & Praktiknjo, A. Time series of useful energy consumption patterns for energy system modeling. *Sci. Data* **8**, 148 (2021).
30. Walberg, D., Gniechwitz, T., Paare, K. & Schulze, T. *Wohnungsbau, die Zukunft des Bestandes (Housing, the future of the stock), Arbeitsgemeinschaft für zeitgemäßes Bauen (Working Group for Contemporary Building)*. https://arge-ev.de/arge-ev/publikationen/studien/?465 (2022).
31. Fraunhofer Institute for Solar Energy Systems (ISE). *Wärmepumpen in Bestandsgebäuden (Heat pumps in existing buildings), Freiburg, Germany*. https://www.ise.fraunhofer.de/content/dam/ise/de/downloads/pdf/Forschungsprojekte/BMWi-03ET1272A-WPsmart_im_Bestand-Schlussbericht.pdf (2020).
32. Lämmle, M. *et al.* Performance of air and ground source heat pumps retrofitted to radiator heating systems and measures to reduce space heating temperatures in existing buildings. *Energy* **242**, 122952 (2022).
33. Ochsner, Germany. *Heat Pump GMLW 14 PLUS*. (2020).
34. Ruhnau, O., Hirth, L. & Praktiknjo, A. Time series of heat demand and heat pump efficiency for energy system modeling. *Sci. Data* **6**, 189 (2019).
35. Bundesverband Wärmepumpe (German Heat Pump Association). *Der Weg zur Dekarbonisierung des Gebäudesektors (The path to defosillising the building sector), Berlin, Germany*. https://www.waermepumpe.de/politik/waermemarkt/ (2021).

36. Koalitionsausschuss der Bundesregierung. *Ergebnis des Koalitionsausschusses vom 23. März 2022. Maßnahmenpaket des Bundes zum Umgang mit den hohen Energiekosten*. https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/Schlaglichter/Entlastungen/massnahmenpaket-bund-hohe-energiekosten.html (2022).
37. Miara, M., Coordinator of heat pumps at the Fraunhofer Institute for Solar Energy Systems (ISE) in Freiburg, Germany
38. Agora Energiewende. Zukünftige Anforderungen an eine energiewendegerechte Netzkostenallokation (Future requirements for grid cost allocation in line with the energy transition), Berlin, Germany. (2021).
39. Clausen, J. & Fichter, K. The diffusion of environmental product and service innovations: Driving and inhibiting factors. *Environ. Innov. Soc. Transit.* **31**, 64–95 (2019).
40. Rogers, E. M. *Diffusion of innovations*. (Free Press, NY, 2003).
41. International Energy Agency (IEA). Heat Pumps, Paris, France. *IEA* https://www.iea.org/reports/heat-pumps (2021).
42. Bundesverband Wärmepumpe (German Heat Pump Association), Berlin, Germany, (2022).
43. Kapica, J., Canales, F. A. & Jurasz, J. Global atlas of solar and wind resources temporal complementarity. *Energy Convers. Manag.* **246**, 114692 (2021).
44. Behr, H. D., Jung, C., Trentmann, J. & Schindler, D. Using satellite data for assessing spatiotemporal variability and complementarity of solar resources – a case study from Germany. *Meteorol. Z.* **30**, 515–532 (2021).
45. Drücke, J. *et al.* Climatological analysis of solar and wind energy in Germany using the Grosswetterlagen classification. *Renew. Energy* **164**, 1254–1266 (2021).
46. Ruhnau, O. & Qvist, S. Storage requirements in a 100% renewable electricity system: extreme events and inter-annual variability. *Environ. Res. Lett.* **17**, 044018 (2022).
47. Kozarcanin, S., Andresen, G. B. & Staffell, I. Estimating country-specific space heating threshold temperatures from national gas and electricity consumption data. *Energy Build.* **199**, 368–380 (2019).
48. Kockel, C., Nolting, L., Priesmann, J. & Praktiknjo, A. Does renewable electricity supply match with energy demand? – A spatio-temporal analysis for the German case. *Appl. Energy* **308**, 118226 (2022).

49. Keiner, D., Breyer, C. & Sterner, M. Coupling heat and electricity storage technologies for cost and self-consumption optimised residential PV prosumer systems in Germany. *Int. J. Sustain. Energy Plan. Manag.* Vol 21 (2019) (2019) doi:10.5278/IJSEPM.2019.21.4.

50. Deutscher Wetterdienst (DWD) (German Meteorological Service). *Produkte, Deutschland. Historische Werte für Temperatur Tagesmittelwerte (Products, Germany. Historical values for temperature daily averages), Frankfurt, Germany*. https://www.dwd.de/ (2022).

Acknowledgements

The authors acknowledge the Agora Energiewende team for the generous provision of data from the German grid. The authors thank the German Heat Pump Association for the generous provision of data about heat pump installations, and Prof. Heiko Werdin from the University of Applied Sciences in Dresden for providing data on the COP performance of heat pumps. The authors thank the three reviewers for improving the weak spots of this paper.

Deleted: , and

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 on social sciences and general quantitative research. C. B. contributed to the model development and with his expertise on the energy transition. C.K. contributed with her expertise on the gas system. U. W. and C.G. contributed with their expertise on 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.

Additional information

We provide Supplementarily Information in a separate document.

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 DOI: 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.