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Heat Pumping Technologies

MAGAZINE

Heat Pumps for All: How to Extend the Working Envelope of Heat Pumps

Vol.42 Issue 2/2024
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In this Issue

Welcome to Heat Pumping Technologies Magazine, Issue 2/2024: "Heat Pumps for All: How to Extend the Working Envelope of Heat Pumps."

As heat pumping technologies continue to evolve, they offer an ever-more viable and sustainable solution for heating and cooling across the residential, commercial, and industrial sectors. The growing demand for energy-efficient and eco-friendly systems drives the industry to innovate, but with that comes the challenge of extending the operational limits of heat pumps to meet a wider range of conditions and applications.

In this edition of Heat Pumping Technologies Magazine, we explore the cutting-edge advancements and research focused on broadening the working envelope of heat pumps. From extreme temperature environments to diverse and unique application scenarios, this issue is dedicated to highlighting the innovations that push the boundaries of what heat pumps can achieve. We aim to uncover how these systems can reliably deliver efficient performance in an expanding range of settings.

Our Foreword, titled "Broadening Horizons: Heat Pumps for Every Apartment," emphasizes the importance of making heat pump technology accessible to all types of living spaces. Additionally, in our Column, "Heat Pumps: Powering the Future of Sustainable Heating and Cooling" we take a closer look at three crucial areas of heat pumps that demand our attention: expanding their working envelope, their role in system integration, and ongoing innovations in their design and functionality.

This issue also features a comprehensive National Market section titled "France: Heat Pump Market Report," providing insights into the current landscape and growth prospects within the French market.

Throughout this edition, our topical and non-topical articles will delve into the opportunities and challenges that come with pushing the boundaries of heat pump technology, highlighting the practical strategies, real-world applications, and future potential of these systems.

Enjoy your reading!
Metkel Yebiyo, Editor
Heat Pump Centre
The central communication activity of the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

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Foreword

Broadening horizons: Heat pumps for every apartment

By Thomas Nowak, VP Government Relations and Public Affairs Qvantum Industries AB, Sweden

Nowadays, heat pumps are a hot topic. Recently, they've been hailed as crucial for reducing reliance on (Russian) fossil fuels, even earning the nickname "peace pumps" from environmentalist Bill McKibben. This technology is praised for its efficiency, use of renewable or waste energy, and significant reduction of CO_2 emissions, helping Europe meet energy and climate targets. However, high electricity prices limit its success, and critics put forward doubt on its suitability for old, unrenovated buildings. Despite these concerns, more than 20 million heat pumps are in operation throughout Europe, with thousands of examples in various building types, industrial applications, and district heating.

Regarding the challenging segment of multi-family buildings, the observed lack of heat pump deployment is more an information gap and less a technical issue. And hence, addressing this segment requires a social or policy innovation more than technology improvement.

Available solutions include:

1. commercial heat pumps with larger capacity that deliver heating and hot water to entire buildings,
2. apartment-based heat pumps for individual units providing heating, cooling, hot water, and potentially ventilation.

The choice depends on the building's needs, layout, available space, access to energy sources, power supply and, not least, ownership structure and financing options.
While all this is known in expert cycles and has been documented by the International Energy Agency[1], by the European Heat Pump Association[2] and by others, it is still not mainstream knowledge or the standard solution. To the contrary: a typical discussion with owners and

[1] See the joint website of Annex 50 and Annex 62: https://heatpumpingtechnologies.org/annex62/
[2] See the case study booklet on heat pumps in high rise homes: https://www.ehpa.org/news-and-resources/publications/heat-pumps-and-high-rise-homes-case-studies-from-across-europe/

operators of multiple-family buildings will show that they feel left alone. What they perceive is: policy makers force us to change the heating system because of heat planning and the energy transition without explaining to end-users how to do this, let alone providing planning, financing support, or subsidies to enable them to do so.

Indeed, there is an increase in pressure on building owners to transition away from fossil energy-based heating. As the buildings stock is planned to be carbon neutral by 2050 the latest no more fossil fuels can be used by then. To accelerate this change, efficiency requirements are set by policy makers and are increased both on the building and on the product level. They make it more difficult or de-facto impossible to install fossil-based solutions in new and existing buildings or to place them on the market. National governments are adding bans for such technologies on the country level. Typically, such bans are introduced in new buildings first and are extended to existing units later. With an expected lifetime of about 20 years, it is obvious, that the last fossil boilers should be installed between now and 2030. This has implications on the gas grids that are increasingly recognized. Think tanks, operators and consumer associations have started to raise the question of what happens to cost when fewer and fewer clients are connected to the grid. They also wonder how to finance the dismantling of grids if no further use can be found. It is by now agreed on, that a proper plan of the energy transition in heating must include a strategy to dismantle the existing gas grid.

In parallel, national governments, have the obligation to prepare and present heating and cooling assessment and planning documents. These plans will have to start on the city level. They must take climate, economics, and technical feasibility into consideration and should lead to the identification of the most cost- and resource efficient solution. Having such plans gives cities a much better view on the demand for heating and cooling as well as on existing sources of excess heat. It could be called the foundation of closing energy cycles.

The future energy system will integrate three major components:

1) heat pumps in many variations, big and small,
2) thermal grids connecting apartments, buildings and cities,
3) smart controllers that aggregate individual loads, providing demand-side flexibility to the electric grid.

The system's attractiveness lies in using thermal grids at ambient temperature, utilizing waste heat, and minimizing thermal waste to maximize efficiency and avoid thermal waste. On the apartment level, waste heat from an air conditioning can be stored in the form of hot water and to be used later, or it can be dumped into the thermal grid and used, where needed by other apartments or buildings connected to the same grid.

On the building level, instances such as hotels, hospitals, office buildings, or similar, that are typically cooled permanently make the waste heat required available in the grid. The combination of heat pumps with heating and cooling function and the thermal grid avoids the visual clutter of facades with cooling equipment. On the city quarter or city level, the many buildings connected via an ambient loop create a huge thermal battery that allows the system to operate at reduced overall energy demand by making the one user's energy waste the other user’s energy source.

Heat pump solutions designed and manufactured in Europe for Europeans bridge the gap between industrialization and green growth seamlessly. European innovation caters specifically to the continent's diverse building types, including multi-family residences. Advancing the deployment of heat pump-based solutions bolsters economic growth and technological advancement within Europe and pave the way for a greener future, where industrial progress and environmental stewardship go hand in hand.

Such systems have started to gain attention across the continent, and at Qvantum Industries in Sweden, we focus on this integrated approach with three components: heat pumps, thermal batteries, and smart controllers. Together, they offer a versatile solution for decarbonizing multi-family buildings, making the energy transition straightforward. ABC, as simple as one-two-three, that's how easy energy can be.

Against this backdrop, the theme of this issue, "Heat Pumps for All: How to Extend the Working Envelope of Heat Pumps," becomes even more relevant. By broadening the applications space and enhancing the capabilities of heat pumps, we pave the way for more inclusive and efficient energy solutions, ensuring that heat pumps can serve a wider array of needs in our journey toward a sustainable future.

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Column

Heat Pumps: Powering the Future of Sustainable Heating and Cooling

By Metkel Yebiyo, Researcher & Technical expert in Sustainability, Research Institutes of Sweden (RISE)

As the world races towards a sustainable future, heat pumps are stepping into the spotlight as a pivotal technology in the global energy transition. These devices, which move heat from one place to another, are becoming more than just a tool for heating or cooling, they're emerging as key players in the quest for energy efficiency and carbon reduction. But for heat pumps to truly fulfill their potential, three crucial areas demand our attention: expanding their working envelope, their role in system integration, and ongoing innovations in their design and functionality.

Broadening the Working Envelope: Meeting Global Climate Demands

The versatility of heat pumps across diverse climate zones is a growing necessity. Traditional heat pumps often struggle in extreme temperatures, whether it's the frigid cold of a Nordic winter or the scorching heat of an Australian summer. To address this, engineers are focusing on broadening the working envelope of heat pumps. This involves developing systems that can operate efficiently in a wider range of temperatures, ensuring that they remain effective in both heating and cooling, regardless of the external environment.

Innovations such as advanced refrigerants, variable-speed compressors, and hybrid systems are paving the way for heat pumps that can perform optimally even in the most challenging conditions. These advancements are crucial for heat pumps to be a viable solution not just in temperate climates but across the globe, from the icy landscapes of Alaska to the sweltering deserts of the Middle East.

System Integration and Sector Coupling: The Role of Heat Pumps

Heat pumps are not just standalone devices; they are becoming integral components of a more interconnected and efficient energy system. Their ability to integrate with other technologies, such as solar panels, smart grids, and thermal storage systems, positions them at the heart of the emerging concept of sector coupling. This concept emphasizes the interconnection between different energy sectors electricity, heating, cooling, and even transportation, to optimize energy use across the board.

In this context, heat pumps contribute to energy flexibility by shifting energy demand to align with supply, particularly when renewable energy is abundant. For instance, during periods of high solar or wind energy generation, heat pumps can be used to store energy in the form of heat or coolness, which can be utilized later, thereby stabilizing the grid and enhancing energy efficiency.

Moreover, the ability of heat pumps to work in tandem with other technologies supports the broader goals of decarbonization and energy independence. By coupling with renewable energy sources and smart energy management systems, heat pumps play a critical role in reducing fossil fuel reliance and achieving climate targets.

Cutting-Edge Innovations: The Future of Heat Pump Technology

The field of heat pump technology is evolving rapidly, with research and development efforts focused on pushing the boundaries of what these systems can achieve. Cutting-edge research is focusing on several promising technologies:

1. Magnetocaloric heat pumps which use changing magnetic fields to create heating and cooling effects, potentially offering higher efficiency and eliminating the need for refrigerants.
2. Thermoacoustic heat pumps, harnessing sound waves to pump heat, promising a simpler and more reliable design.
3. Hybrid systems combining heat pumps with other technologies like fuel cells or solar thermal collectors, maximizing efficiency and reducing reliance on the grid.
4. Advanced control systems utilizing artificial intelligence to optimize performance based on weather forecasts, user behavior, and energy prices.
5. Additionally, research into heat pump applications in industrial processes is opening new doors for energy savings in sectors that have traditionally been difficult to decarbonize. By leveraging innovative designs and materials, heat pumps are being tailored to specific industrial needs, offering solutions that were previously unattainable.

As we look to the future, heat pumps are set to become a cornerstone of the global energy transition. Their expanding capabilities in diverse climates, crucial role in system integration, and the continuous stream of technological innovations ensure that they will remain at the forefront of sustainable heating and cooling solutions. As these developments continue to unfold, heat pumps will not only meet the demands of today but will also drive the progress needed for a sustainable tomorrow.

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Topical Article

Enhancing Energy Efficiency in Large-Scale Heat Pumps Using Digital Twins for Set Point Optimization

DOI: 10.23697/qade-hw72

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Large-scale heat pumps can contribute towards the decarbonization of the heat supplied to buildings and industries, as long as such systems operate as expected. Modern digital technologies, such as digital twins, can enhance the energy efficiency of industrial equipment in real-time, but their use in heat pumps remains limited. This article evaluates the use of set point optimization using digital twins for commercial large-scale heat pumps. The results highlight the energy efficiency potential of digital twin-based frameworks for real-time set point optimization and fault-tolerant set point optimization.

The electrification of the heating supply in buildings and industries is essential for the decarbonization of these sectors. In this context, large-scale heat pumps are expected to play a relevant role in future energy systems, provided they operate under expected performance and reliability levels [1].

Achieving energy efficient large-scale heat pumps often requires identifying energy-optimal controller set points. Optimal set points are typically determined during the commissioning phase of a heat pump system. However, there is no guarantee that these set points will remain optimal over time, particularly under the presence of performance degradation and varying boundary conditions. Digital technologies offer the possibility to retrieve and process large volumes of data in real-time, enabling enhanced control and surveillance strategies [2]. In particular, digital twin technology, represented by virtual replicas of physical systems that can adapt to changes in their behavior, can be used for services such as real-time operation monitoring and optimization. However, the use of digital twin technology in the heat pump industry remains limited, with a few examples found in the literature, such as in [3][4][5].

This study aimed at evaluating the energy efficiency potential of digital twin-based set point optimization frameworks for large-scale heat pumps. These frameworks were developed for two commercial large-scale heat pumps used for district heating supply.

Demonstration cases

The demonstration cases, named Case I and Case II hereafter, are located in Denmark. Case I uses seawater as a heat source, whereas Case II uses industrial excess heat. The nominal heating capacities of Case I and Case II are 1 MW and 2 MW, respectively.

The layout of the demonstration cases is shown in Figure 1. Case I comprises a cascade heat pump system with a steam compression bottom cycle and an ammonia cycle at the top. The bottom cycle uses an axial turbo compressor, while a reciprocating compressor is used in the top cycle. Case II is a two-stage ammonia system with a reciprocating compressor in each stage.

Case II is prone to evaporator fouling. This is a common fault affecting large-scale heat pumps, which is difficult to characterize. The evaporator of Case II is cleaned through a cleaning-in-place (CIP) system, aiming to reduce the fouling-related performance degradation of the heat pump.

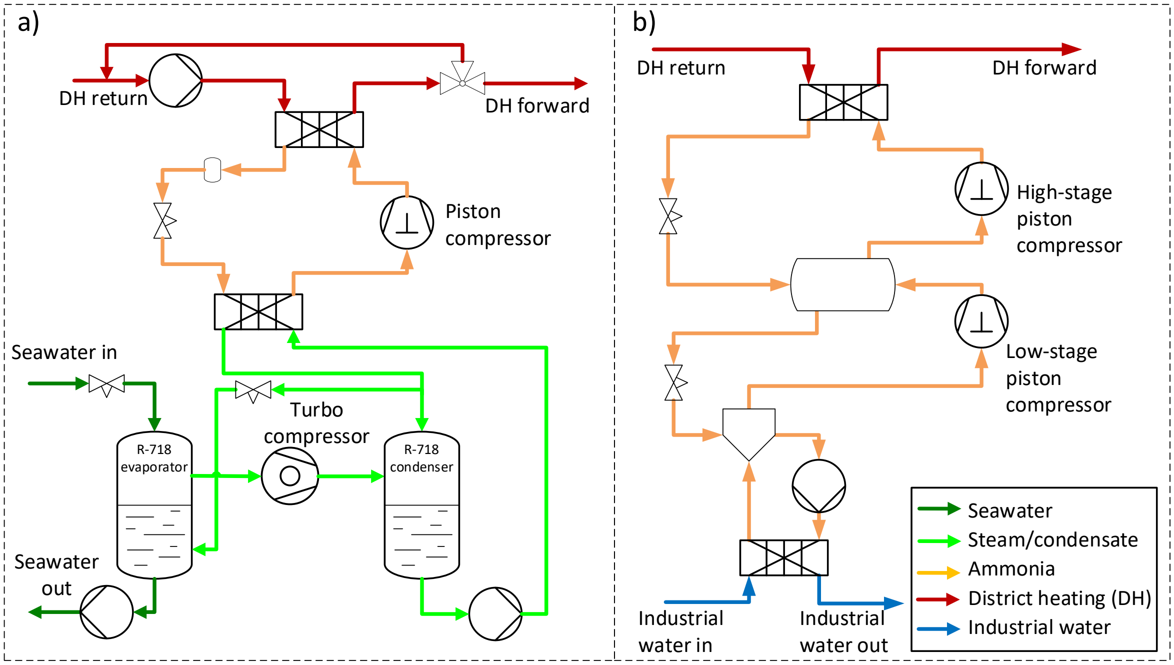

Figure 1: Layout of Case I (a) and Case II (b) of the demonstration cases.

Digital twin-based frameworks

The frameworks for set point optimization are presented in Figure 2. Operational data was retrieved through a cloud service connected to existing control and supervisory systems. The operation of Case I was represented through a dynamic simulation model developed in Modelica, using the software Dymola [6] and TIL Suite [7]. This model was simulated in Python using a Functional Mock-up Interface and was calibrated based on measurements, as described in [4]. Case II was simulated through a quasi-steady-state model developed in Python. In this model, parameters related to the heat transfer coefficients and fouling were repeatedly adjusted by means of an online calibration approach, explained in [5]. This online calibrated model was referred to as the adaptive model.

The set point optimization for both demonstration cases was implemented in Python using the module Scipy [8]. In Case I, the validated dynamic simulation model was applied to calculate the process out temperature set point in the top and bottom cycles that maximized the coefficient of performance (COP) of the system. This led to an adjustment of the compressor speed in each cycle. In Case II, the adaptive model was used to determine the intermediate pressure set point that led to the highest COP of the system. Through this optimization, the speed of the high-stage and low-stage compressors were modified.

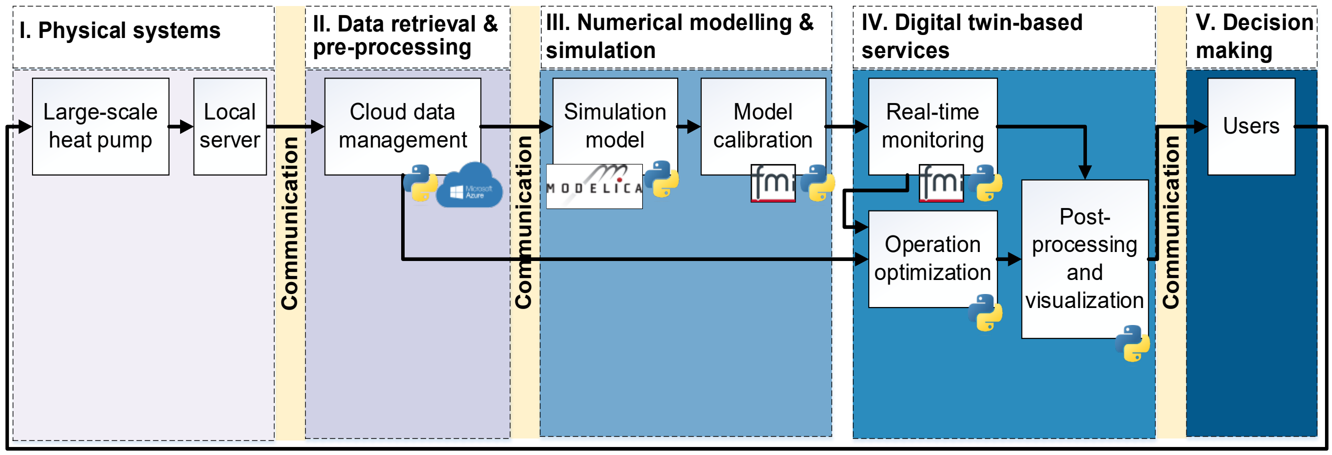

Figure 2: Diagram of the digital twin-based frameworks.

To reduce the time and computational resources required for the set point optimization in Case II, a surrogate polynomial regression model was derived from the adaptive model. The optimal set points obtained from the adaptive and surrogate models were compared with those from the simulation model without online calibration, referred to as fixed model. Additionally, these set points were compared with the geometric average value, a conventional approach for determining the intermediate pressure in two-stage vapour compression systems.

The comparison between the set points obtained from different approaches in Case II was done for six 2-hour periods of operation, extended over ten calendar months. In Case I, the set point optimization was performed every 3 hours over a period of 10 hours of operation data.

Software interface for operators

A software tool (shown in Figure 3) was created to monitor and optimize the operation of Case I, and hence provide a graphical user interface (GUI) to the operator and owner of the heat pump. Its interface displays real-time operational variables alongside simulation model results. The tool also allows testing of hypothetical scenarios. This enables a simulation-based analysis of performance indicators resulting from different control parameters.

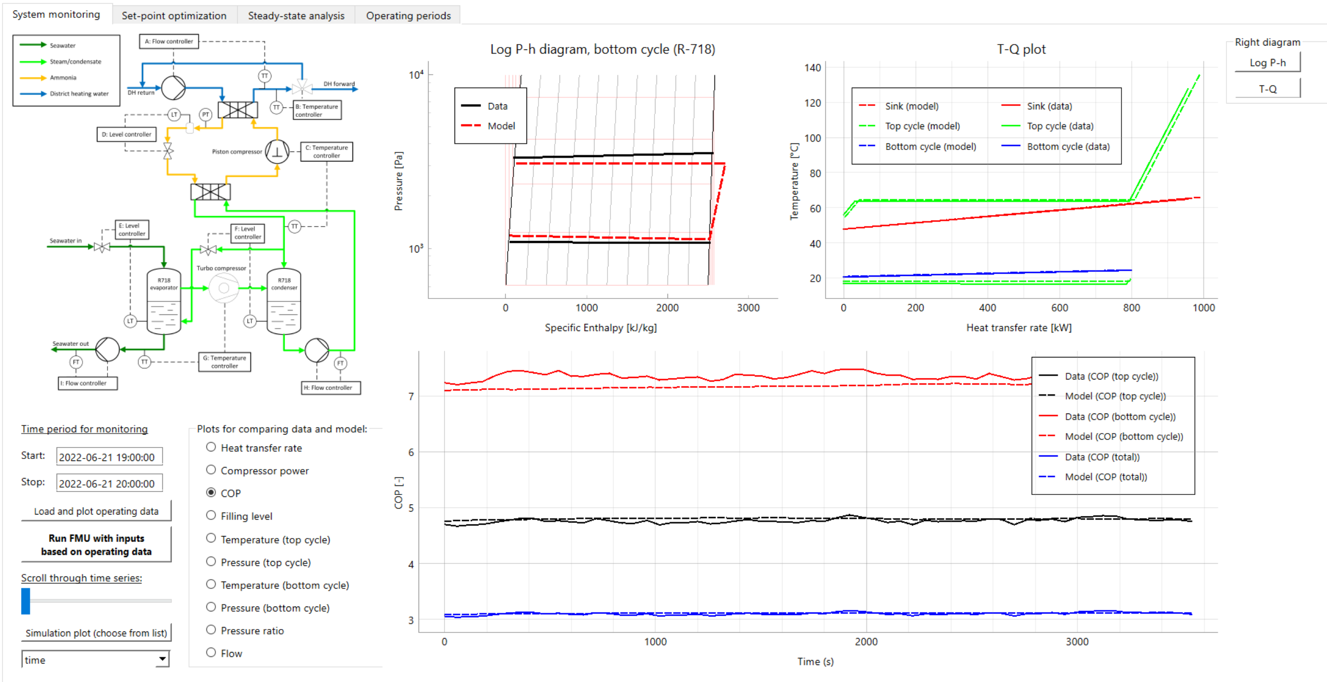

Figure 3: Screenshot of the GUI software interface with fans for various services.

Real-time set point optimization

An example of the set point optimization in Case I is shown in Figure 4, where the simulation model was used together with historical data to investigate the potential for performance increase.

Here, the simulation model initially showed a COP of approximately 3.35 (black curve) with a compressor speed of 87 % (blue curve) during the first three hours. This speed represented the conventional operation of the system during that period. After the first optimization (performed at 09:00), the compressor speed was adjusted to around 83 % of its nominal value. This resulted in a COP of approximately 3.40, i.e. an increase of 1.5 % compared to the value before the optimization. The second and third optimizations did not lead to changes in the compressor speed, given that the optimal values were already reached with the given boundary conditions after the first optimization.

In this study, the optimization was done using only the COP as a target variable, but it could also include other variables for the same function such as, for example, the heating capacity of the heat pump. This would require the use of multi-objective optimization or a weighted average of the different target variables.

The use of the proposed digital twin-based framework has the potential to be extended for the assessment of hypothetical operational scenarios. The framework results can be used to represent trade-offs between conflicting variables of interest. This can enable heat pump operators to test different set points on a simulation model, providing accurate estimations of the performance of the system.

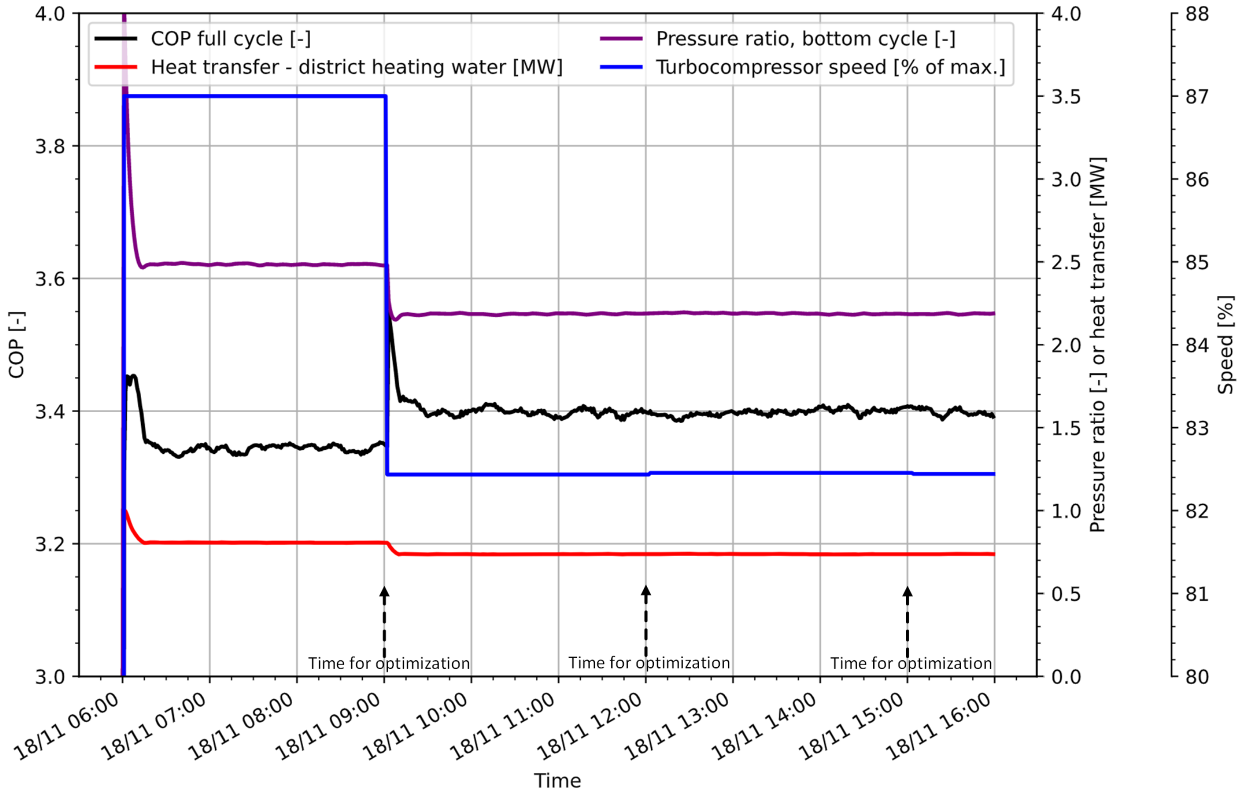

Figure 4: Real-time set point optimization in Case I, source [4].

Set point optimization under performance degradation

Figure 5 shows a comparison between the optimal intermediate pressure set points obtained from the geometric average, fixed model, adaptive model, and surrogate model, respectively. The optimal intermediate pressure set points resulted in a greater increase in COP compared to a decrease in heat capacity. This is applied across all the fouling levels and heat capacities analyzed. All model-based approaches in the study yielded similar estimations for the optimal intermediate pressure set point. These adjustments led to COP improvements within 0.2 % to 1.3 % above the geometric average value. Notably, the fixed model tended to overestimate COP improvement and heat capacity reduction due to the optimal set point, especially during periods when the heat pump operated at higher heat capacities (fouling calibration periods 4, 5, and 6). Comparing the surrogate model to the adaptive model, their estimations for optimal set points and related COP and heat capacity variations were similar. The most significant difference occurred during periods when the heat pump operated at the lowest heat capacities, specifically fouling calibration periods 1 and 3.

The results shown in Figure 5 highlighted the relevance of accounting for fouling on the set point optimization. Not including fouling in the model led to overestimated changes in the COP and heat capacity derived from the optimal set points.

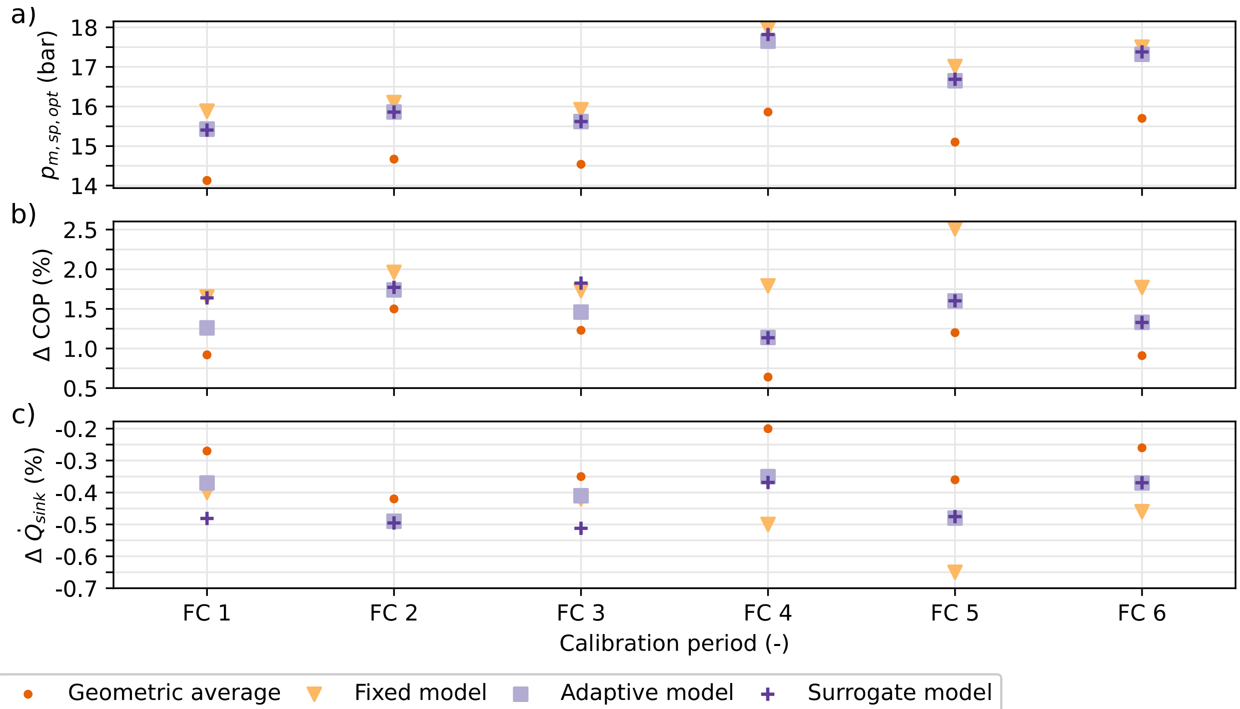

Figure 5: Set point optimization in Case II. Different approaches were used for determining the optimal intermediate pressure set point for six periods of operation (FC 1 to 6). Baseline (not optimized) set point equal to 10 bar, source [5].

The development and implementation of the fixed model are expected to require less time compared to the adaptive and surrogate models. The adaptive model relies on a data infrastructure that enables the retrieval of real-time operational data. The development of the surrogate model will take longer due to its dependence on results from online calibration of the adaptive model using retrieved operational data. Once developed, the surrogate model is expected to provide similar estimations to the adaptive model for optimal intermediate pressure set points, but more rapidly, as it does not require an optimization routine. This can enable the use of the surrogate model in component or system controllers.

Conclusions

This study addresses frameworks based on digital twins for optimizing the operation of large-scale heat pumps in district heating systems. The first framework optimized real-time process outlet temperature set points in a cascade heat pump system. The second framework defined optimal intermediate pressure set points for a two-stage heat pump system, considering varying levels of fouling. The results demonstrated the potential to enhance energy efficiency in large-scale heat pumps by extending the proposed frameworks using digital twin technology. It is essential to define suitable model complexity levels and multiple optimization targets for an optimal integration of these frameworks in existing heat pump control systems.

Acknowledgments

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Topical Article

Roll-Out of Large-Scale Heat Pumps as A Key Factor for The German Energy & Heat Transition

DOI: 10.23697/t6w2-4j23

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From less than 1 GW to more than 90 GW installed thermal capacity in less than 25 years: For the climate-neutral transformation of German district heating networks and the decarbonization of process heat, large-scale heat pumps are no-regret measures. This is one of the key findings of a 2023 study by Berlin-based think tank Agora Energiewende and Fraunhofer-Institution for Energy Infrastructures and Geothermal Systems IEG. However, to unlock their full potential and accelerate the market ramp-up, several measures need to be taken. The main fields of action are 1) adaptation of German energy policies and regulations, 2) further industrialization and automation of heat pump manufacturing, and 3) reduction of bureaucracy in the planning, approval, and building process.

Introduction

Germany has set itself the binding target to become fully climate-neutral by 2045. Since the demand for space heating and hot water in the building sector and the supply of process heat in the industry sector together account for more than half of the final energy demand in

Germany, their decarbonization plays a key role in the German energy transition. Yet, currently, about 80 % of the heat demand in buildings and industry is met by fossil fuels. [1]

At the same time, most of the demand for heat is in the low-temperature range below 200 °C, which includes the whole building sector, all district heating, and about a third of the industrial heat demand [2]. Specifically, the demand for heat up to 200 °C accounted for 43 % of Germany's final energy consumption in 2021, more than 75 % of natural gas consumption (around 494 TWh), and more than one-quarter of greenhouse gas emissions (around 215 million t CO2-eq) [1, 3, 4] (see Figure 1).

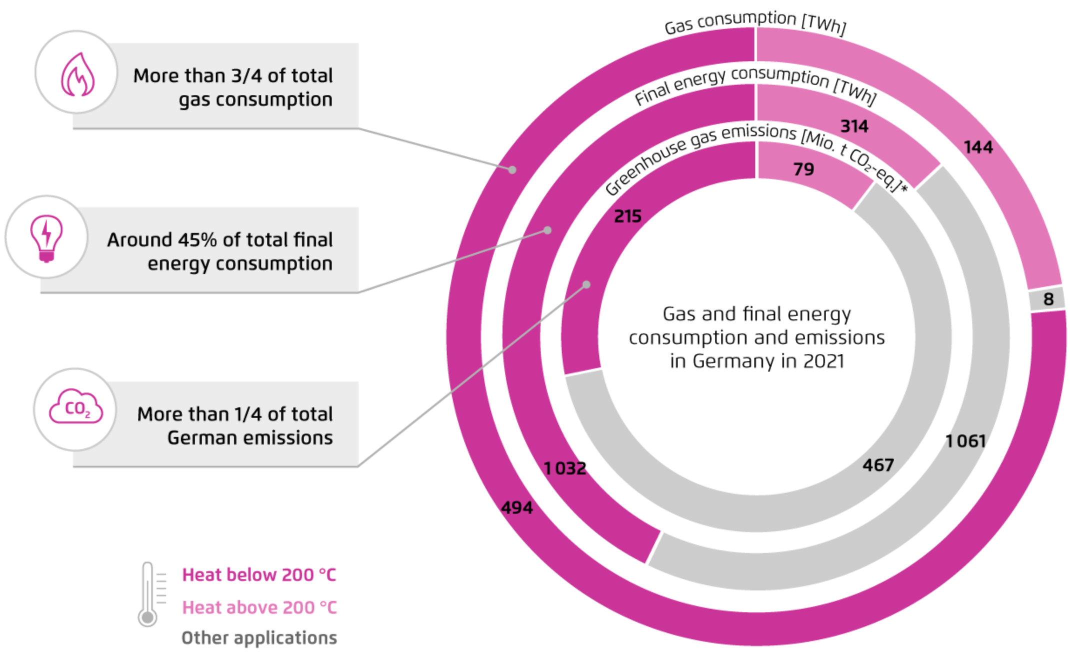

Figure 1: Heat demands up to 200 °C: high potential for reducing emissions, gas, and final energy consumption (Agora Energiewende based [1]. Emissions based on the breakdown by fuel type according to [1] and emission factors according to [3], not weather-adjusted. Own assumptions regarding the breakdown by fuel type across the different temperature levels based on [4]).

Modern large-scale high-temperature heat pumps can already efficiently reach those temperature levels. More and more original equipment manufacturers (OEMs) are entering the market with products that can easily achieve coefficients of performance (COP) of 2.5 or more (depending on the temperature spread between heat source and heat sink). However, only a relatively small number of large-scale heat pump projects have been realized in Germany so far, and the market is only slowly gaining momentum. The opportunities and challenges associated with a broad market ramp-up in Germany are illustrated in this article by (1) looking at the energy scenarios for heating networks and large-scale heat pumps to achieve the German climate targets by 2045, (2) showing the potential of large-scale heat pumps and renewable heat sources; (3) comparing that to the status quo of the heat pump market; and lastly (4) developing recommendations for action.

Fast ramp-up of large-scale heat pumps is key for the transformation of the district heating sector

In 2021, German district heating networks had a total installed thermal capacity of around 71 GW, with a share of large-scale heat pumps – here defined as plants with a rated thermal power of 500 kW or more – near 0.0%. Since then, the share has risen by a small fraction. [5] At the same time, different studies and scientific analyses indicate that for the full decarbonization of the German energy system, the fast ramp-up of large-scale heat pumps is a key factor. In the "Long-term Scenarios for the Transformation of the Energy System in Germany" from November 2022, which was developed by an expert group of research institutes on behalf of the German Federal Ministry for Economic Affairs and Climate Action, the future district heating system is dominated by large-scale heat pumps. The study, which has been updated since, models five different scenarios to reach climate neutrality with different pathways on how to get there. In all five scenarios, at least 90 GW of installed thermal capacity of large-scale heat pumps are needed in 2045, which would produce more than 70% of the total energy supply in district heating networks. [6] (see Figure 2).

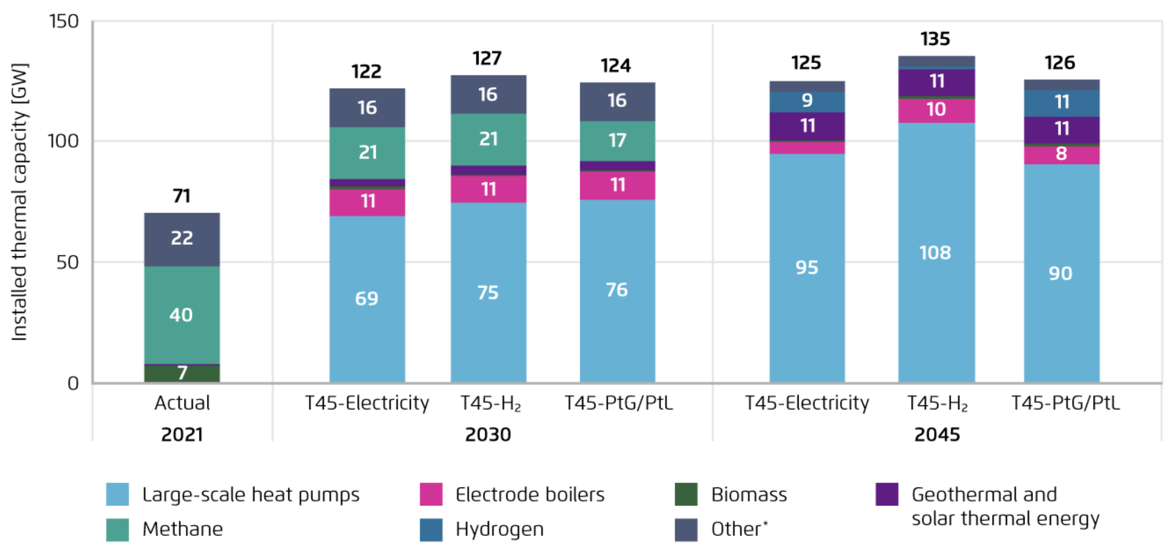

Figure 2: Projections from German Long-term Scenarios (version of Nov 2022) for installed thermal capacity in the German district heating sector (lignite, coal, waste, and other fossil fuels) [6, 7].*

Translated into actual investment in energy infrastructure, these figures require, on average, around 340 - 410 new large-scale heat pump projects with an installed heating capacity of 4.0 - 4.9 GW and 800 km of new heat pipes each year until 2045. As a rough estimate, this would correspond to new investments of at least €3.1 billion – €4.4 billion per year in the German district heating sector, not taking investments in the industry sector into account. [7] This is a big challenge, and the required private-sector capital needs to be mobilized by creating appropriate conditions for investors. Besides planning security and economic incentives, this also includes the provision of sufficient public funding. In 2022, the German government started a new federal funding scheme for efficient heating networks (Bundesförderung für Effiziente Wärmenetze - BEW). This programme is equipped with €3 billion until 2026 and could roughly mobilize investments of about €7.5 billion in total (when assuming a funding rate of 40%). Hence, to satisfy the actual demand, as shown in [7] and [8], and to lift private investments to the needed level, an increase and extension of funding will be crucial.

Potentials are high, and technology is mature

The possibilities of large-scale heat pumps, both technologically as well as looking at available heat sources, are enormous. In the long term, the entire heat demand up to 200 °C (including process heat in industry) in Germany can be met by heat pumps. A meta-analysis of different studies shows that the potential heat supply by climate-neutral heat sources that can be utilized by heat pumps exceeds the entire heat demand up to 200 °C in Germany, and that is without even taking ambient air as a heat source into account. Near-surface and deep geothermal energy offer by far the greatest potential, followed by lakes and rivers, industrial waste heat as well as wastewater, coal mine water drainage and data centers (see Figure 3).

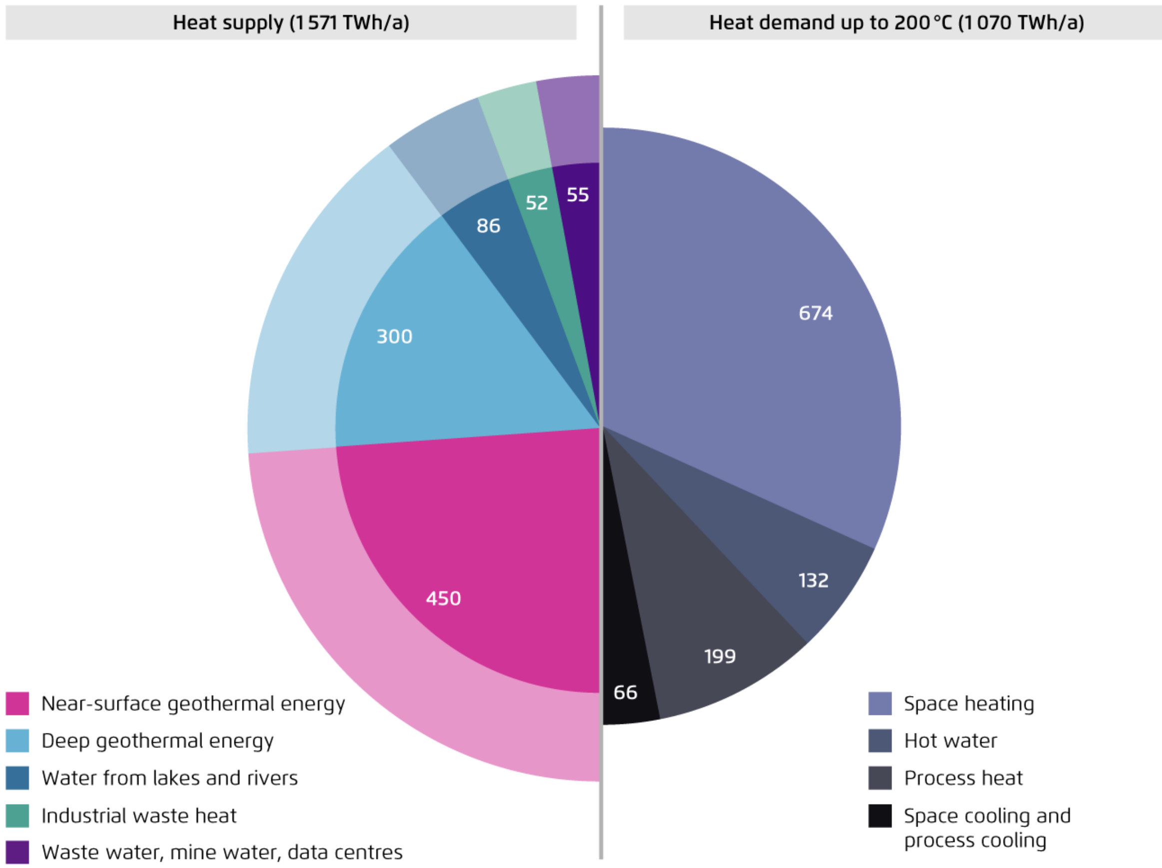

Figure 3: Comparison of the potential heat supply via heat pumps (excluding ambient air) and the heat demands up to 200 °C in Germany (Fraunhofer IEG, 2023) [7].

In addition, the technology of large-scale heat pumps is mature and reliable. Large-scale heat pumps have a long operation history in other countries (e.g., for district heating in Scandinavia), and state-of-the-art products already can reach temperatures which are suitable for district heating networks and many industrial processes (see Figure 4). Furthermore, large-scale heat pumps provide these temperatures efficiently, with COPs of above 2.5 in most cases (assuming an efficiency rating of 50 % and depending on the actual temperature spread between the heat source and the heat sink). For industrial processes, there are efficient combinations of large-scale heat pumps and mechanical vapor recompression systems available to provide steam.

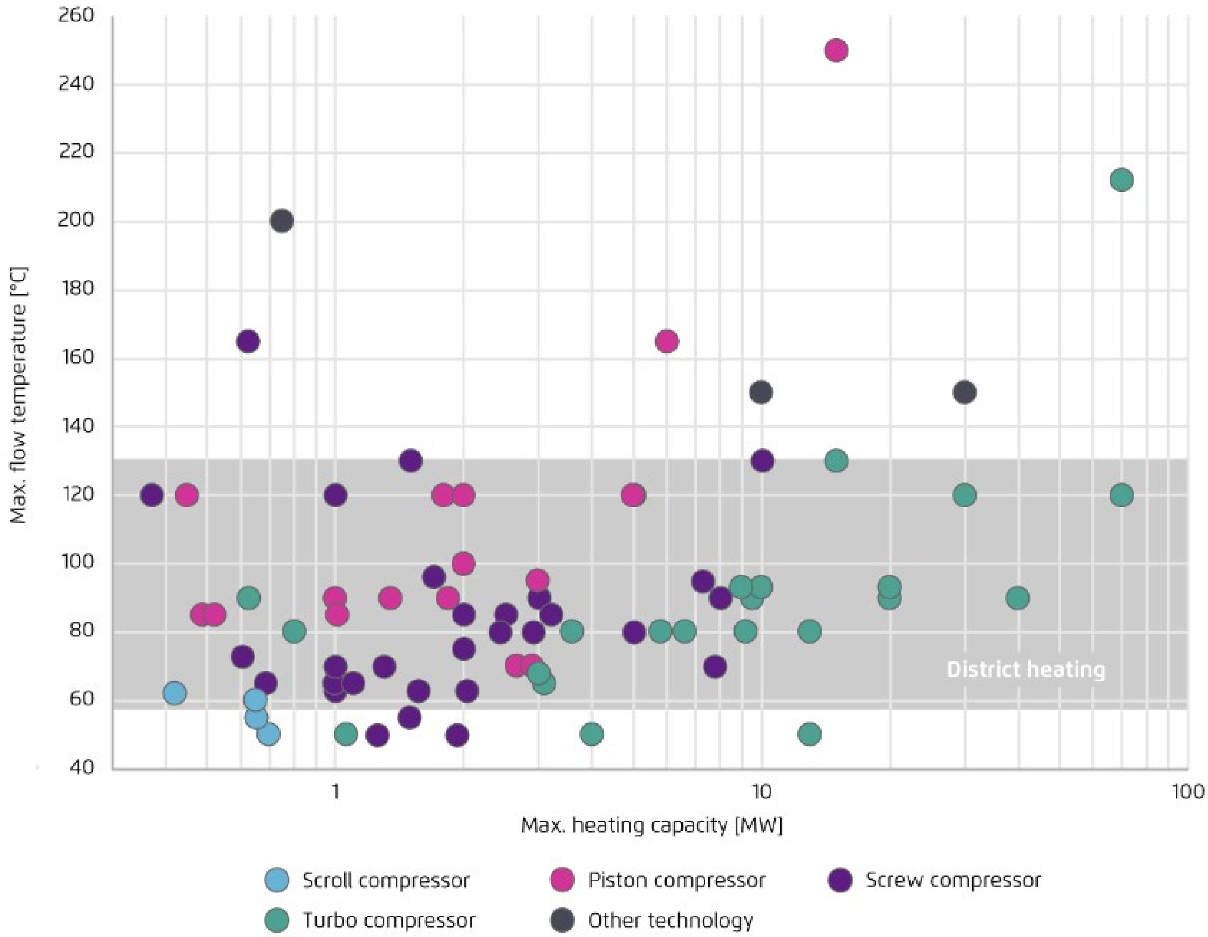

Figure 4: Maximum flow temperatures and thermal capacities of large heat pumps on the market (Fraunhofer IEG, 2023) [7].

Status quo: Small number of large-scale heat pumps in operation, but with rising demand

As of December 2023, at least 45 large-scale heat pumps with a total installed thermal capacity of around 130 MW are in operation in Germany, and additionally, around 1,000 MW are currently under construction or in planning (based on own market research by Fraunhofer IEG) [7]. In addition, OEMs report rising requests for new feasibility studies or project inquiries. However, only a small percentage of those projects are actually commissioned. Some major challenges that hinder the realization of large-scale heat pump projects in the current market phase include:

- Insufficient economic viability due to comparatively high electricity and low gas and CO_2 prices;
- Lack of municipal heat planning in many places, lack of heat registers, and hence little knowledge and high uncertainties about the technology and its profitability;
- Relatively small production volumes at OEMs and highly individual projects with elaborate planning and approval procedures.

Conclusion and recommendations for action

To successfully roll-out large-scale heat pumps while at the same time allowing supply chains and implementation capacities to grow without creating bottlenecks, an intelligent mix of price signals, support measures, and regulation is needed. The necessary measures can be categorized along three central fields of action.

Firstly, a coherent overall framework must be established. Therefore, all stakeholders, including policymakers, OEMs, as well as utility and district heating companies need to start a dialogue to develop a clear vision and to agree on joint strategic goals for the roll-out of large-scale heat pumps in Germany. Furthermore, price signals are crucial – here, the ratio of electricity-to-gas-price is decisive. Effective carbon emissions pricing is one important step to level the playing field in favor of climate-friendly energy sources. In addition, electricity in Germany continues to be subject to higher taxes, levies, and surcharges than fossil gas. A further reduction of these disincentives, for example, by lowering the electricity tax to the European minimum level, can remedy this situation. To meet the demands of a more and more flexible energy system, incentives for a flexible and grid-friendly operation of large-scale heat pumps should be established (such as time-variable grid fees), and grid connections need to be realized faster.

Secondly, the potential for innovation and cost reduction in production must be exploited consistently and quickly. Main fields of innovation are to reach higher levels of standardization of the products themselves and their main components, as well as further automatization and scaling of the manufacturing processes. Especially in the range from 1 MW to 10 MW, the availability of standardized solutions is central to a successful and quick market penetration, not only in Germany but all over Europe. Apart from that, there also is considerable potential for innovation in compressors – the key component of heat pumps. New refrigerants, more flexible operating modes, and higher target temperatures are some important features to make large-scale heat pumps fit for future district heating systems.

Thirdly, the transformation of heat grids, i.e., the expansion, new construction, and gradual lowering of flow temperatures of heat grids, must be structurally accelerated. Therefore, in Germany, subsidy schemes must be improved and harmonized. In particular, the parallel management of subsidies under the long-standing Combined Heat and Power Act (KWKG) and the new BEW funding program currently leads to misdirected incentives. Furthermore, municipal heat planning is very important to identify areas with a grid-bound heat supply. As of January 2024, heat planning is mandatory in Germany. Municipalities with more than 100,000 inhabitants are required to establish heat plans by mid-2026 and all other municipalities by mid-2028. Ideally, the heat planning would then be developed into an integrated energy distribution strategy to create clarity for the entire sector coupled energy infrastructure. Implementing these heat plans also requires a bundle of adjustments and simplifications in planning and approval procedures. Reducing bureaucracy and enhancing digitization would help to reduce the necessary workforce for these processes as well as to shorten the current project duration significantly.

For more information on this, we recommend our study on the "Roll-out of large-scale heat pumps as a key factor for the German energy & heat transition" [7].

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Topical Article

The Cost of CO_2 Emissions Abatement in Micro Energy Communities

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In 2027, Europe will introduce a new cap-and-trade market (EU ETS2) for CO_2 emissions from fuel combustion in buildings and other sectors. The residential sector is firmly moving towards the electrification of thermal services and the development of energy communities with collective energy systems, though these solutions are often perceived as expensive. How do traditional energy systems combined with paying the European emission tax to offset emissions affordability-wise compare to sustainable energy communities that structurally reduce CO_2 emissions in the built environment? Our findings demonstrate that micro energy communities are a viable and cost-effective solution for a sustainable future, given a more balanced electricity-to-gas price ratio.

Introduction

Energy communities are an appealing solution for decarbonizing the residential sector and, by extension, the urban environment when the tertiary sector and part of the transport sector are included. According to the European Commission, energy communities *enable collective and citizen-driven energy actions to support the clean energy transition,* *advancing energy efficiency and lowering bills within local communities*. That collective approach still forms a barrier in countries like Belgium, where citizens tend to think individually when it comes to energy supply. The high number of individual heat generation units – 84% of the Belgian households are heated by individual fossil fuel installations – compared to the collective district heating approach in other EU countries, such as Denmark and Sweden, confirms this. Besides this individual thinking, it is also legally not straightforward to set up an energy community. Consequently, installing individual heat pumps in a Belgian context could be considered a reasonable step toward decarbonizing thermal services. However, from an economic, material use, or sustainability perspective, this individual electrification may not be optimal. Moreover, it could be infeasible in densely built areas due to a lack of space.

A feasible solution involves sharing heat production units among neighbours, promoting smart use of resources, and enhancing overall system efficiency. Energy communities not only aim for a local, citizen-driven, bottom-up approach but also help increase public acceptance of renewable energy projects. A first step in this bottom-up approach could be a Micro Energy Community (MEC), a small-scale energy community, which might be a viable concept in Belgium. This article examines the benefits and the cost of CO_2 emissions abatement of an MEC in a tiny residential cluster of three existing houses in the Belgian context.

Four energy system scenarios

This article presents the CO_2 emissions abatement cost for three electrified energy system scenarios, including one individual and two MEC scenarios, compared to a reference scenario in a tiny residential cluster. The cluster consists of three single-family houses with moderate building envelope qualities and low-temperature radiators, inspired by real houses in Genk (Belgium). The occupancy varies from two adults to two adults with two children. Each energy system supplies heat for Space Heating (SH), heat for Domestic Hot Water (DHW), and electricity for household appliances.

The **reference scenario** represents a typical case in Belgium, where SH and DHW are provided by individual condensing gas boilers. This scenario is schematically presented in Figure 1. The full red lines indicate the thermal connections, the green lines denote the electrical connections, and the yellow lines represent the gas supply. The green and yellow dots signify the electricity and gas meters, respectively, which separate the individual buildings (solid lines) from the public distribution grid (dashed lines).

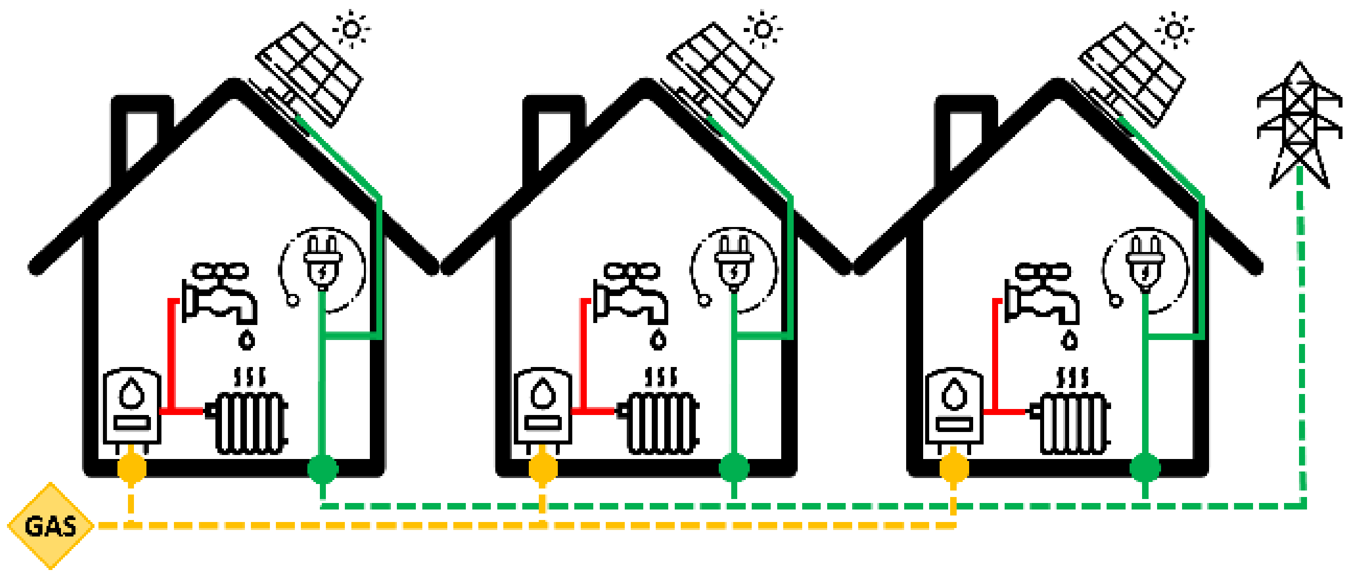

Figure 1: Diagram of the reference scenario.

In the **individual electrification scenario**, thermal services are electrified by replacing the gas boilers shown in Figure 1 by air-to-water heat pumps, as depicted in Figure 2. These air-to-water heat pumps are connected to the electricity grid.

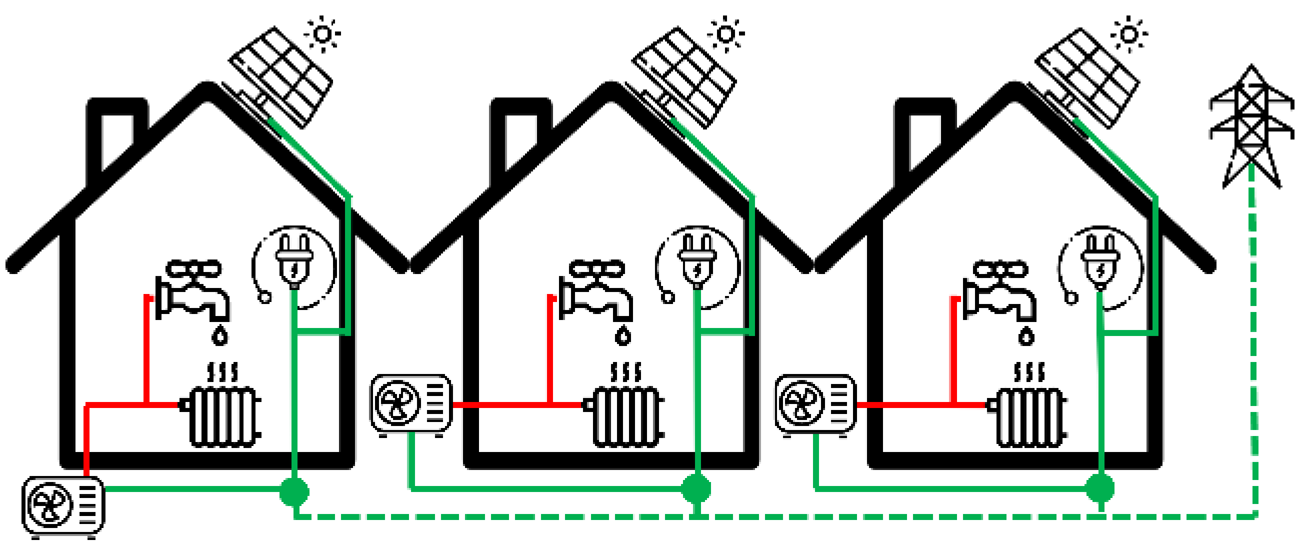

Figure 2: Diagram of the individual electrification scenario.

In the **electricity-sharing scenario**, the benefits of sharing electricity in the case of electrified thermal services are explored. In Belgium, sharing locally produced electricity with other parties is possible. Consequently, this allows the tiny cluster to be treated as a single entity by the distribution grid. Therefore, in Figure 3, the green dots and the solid and dashed green lines have been modified compared to Figure 2.

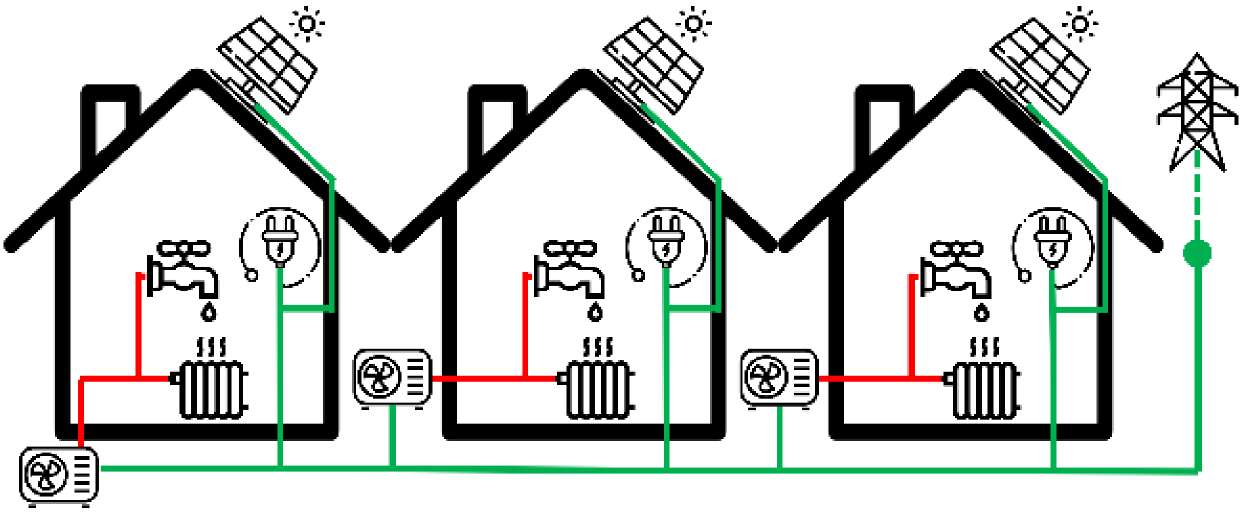

Figure 3: Diagram of the electricity sharing scenario.

In the **energy community scenario**, the benefits of a fully integrated energy community that shares all energy vectors, i.e. heat and electricity, are investigated. In this setup, the individual heat pumps shown in Figure 3 are replaced by a collective air-to-water heat pump and a micro district heating network, as depicted in Figure 4.

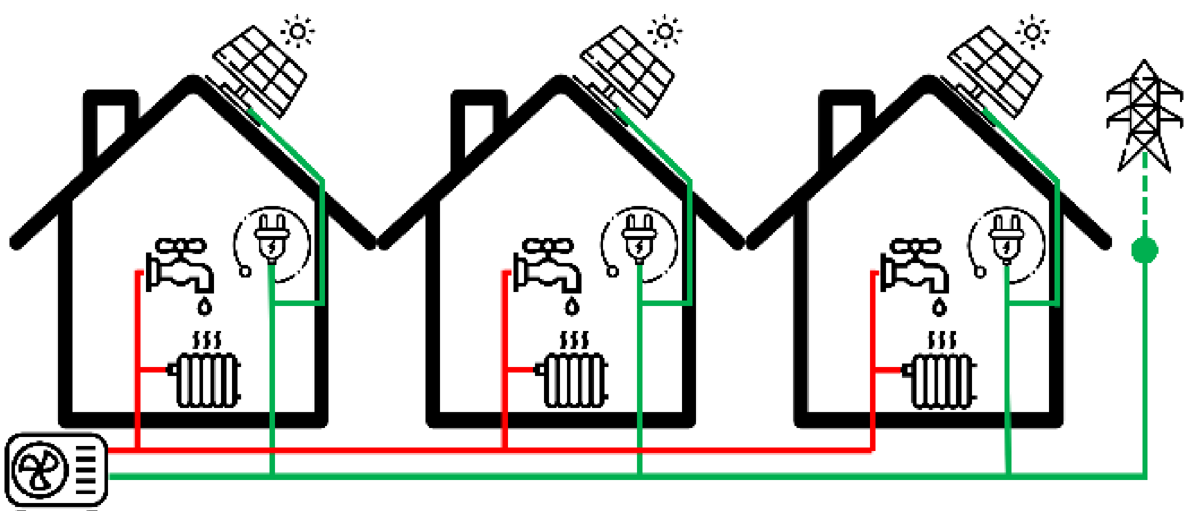

Figure 4: Diagram of the energy community scenario.

Regarding electricity supply, all scenarios include three individual PV installations, with two possible installation sizes (A and B) compared in each scenario. In option A, the PV installation is sized based on the plug load demand in the reference scenario. In option B, the entire roof surface is used for the PV installation. All other energy system components are sized according to established standards. Since both the electricity sharing and energy community scenarios involve energy sharing, they are classified as MECs.

Optimal control

In addition to the energy system design, an appropriate controller acts as the system integrator. The reference scenario employs a simple rule-based on/off control. In contrast, the electrified scenarios use optimal control to fully exploit the non-linear behaviour of the heat pumps and the building's flexibility. The employed optimal controller is an idealized model predictive controller that uses a detailed white-box system model (without model mismatch) and perfect predictions of the boundary conditions such as occupancy, weather data, CO_2 emission intensity, and energy prices, eliminating the need for a feedback loop. All boundary condition data are correlated, time-dependent profiles sourced from 2021 and linked to the city of Leuven (Belgium).

The optimal controller optimizes the control inputs over one year by minimizing a multi-criteria objective function consisting of three criteria: (i) minimization of CO_2 emissions, (ii) minimization of primary energy use (or maximization of energy efficiency), and (iii) minimization of thermal discomfort. Minimizing operational CO_2 emissions primarily targets reducing the climate impact of energy services in the built environment, a key driver for transitioning to energy communities. The operational CO_2 emissions originate from the gas boilers in the reference scenario and the electricity offtake from the distribution grid in all scenarios. Simultaneously, the objective is to maximize thermal comfort while minimizing the use of "primary" energy, thereby enhancing energy efficiency. These criteria ensure that any emission-free electricity generated by the PV installation is used efficiently, avoiding the unnecessary use of resources, including materials. It is important to note that the objective function does not target maximum PV self-consumption or minimum operational costs. Nevertheless, the controller always prioritizes locally generated electricity because electricity generated by the PV installation is emission-free. Moreover, electricity originating from renewable energy sources has a low marginal cost, resulting in a strong correlation between the CO_2 emission intensity and the price of electricity.

Figures 5-6-7-8 present the main results, focusing on (1) the annual electricity balances, (2) the annual operational CO_2 emissions, (3) the annual total costs, and (4) the CO_2 emissions abatement costs.

Annual electricity balance

Figure 5 displays the clusters' total electricity demand (by the bars) and total electricity generation by the PV installations (yellow for option A and green for option B), both represented as positive values. In the reference scenario, there is only an electricity demand for household appliances. The higher electricity demand (≈ 12 MWh) in the electrified scenarios reflects the contribution of the heat pump(s) supplying approximately 54 MWh of heat for SH and DHW. The results show a net positive energy surplus from the clusters in the electrified scenarios when the entire roof surface is used for PV (indicated by the arrow).

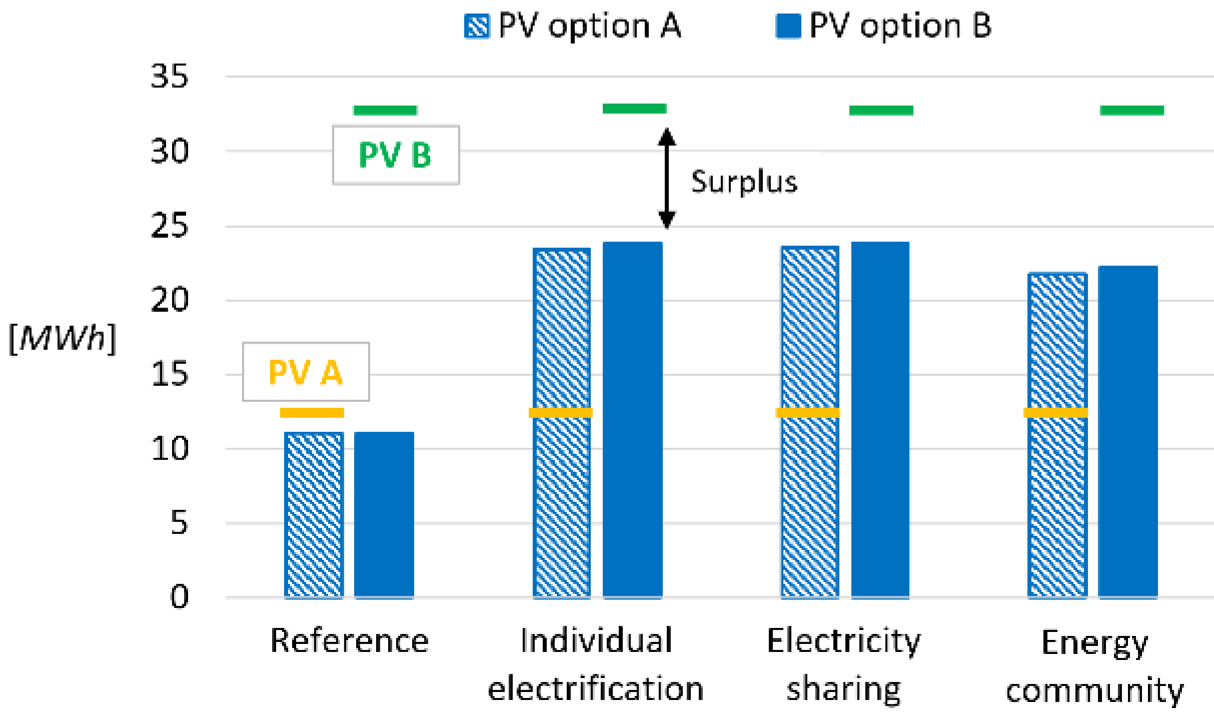

Figure 5: Annual electricity balances.

Annual operational CO_2 emissions

Figure 6 shows the cluster's total operational CO_2 emissions. Moving from the reference scenario to the electrified scenarios results in a reduction of over 93% in CO_2 emissions. Furthermore, shifting from the individual electrification scenario to the energy community scenario reduces the CO_2 emissions by approximately 10%, which increases to about 20% when the entire roof surface is used for PV in the electrified layouts. However, the absolute difference between PV option A and PV option B is relatively small due to the temporal mismatch between the peak demand for residential SH in winter and the peak PV electricity generation in summer. It is important to note that the optimal controller minimises the CO_2 emissions in the electrified scenarios and that the cluster does not receive any CO_2 emissions compensation for injecting emission-free electricity into the grid.

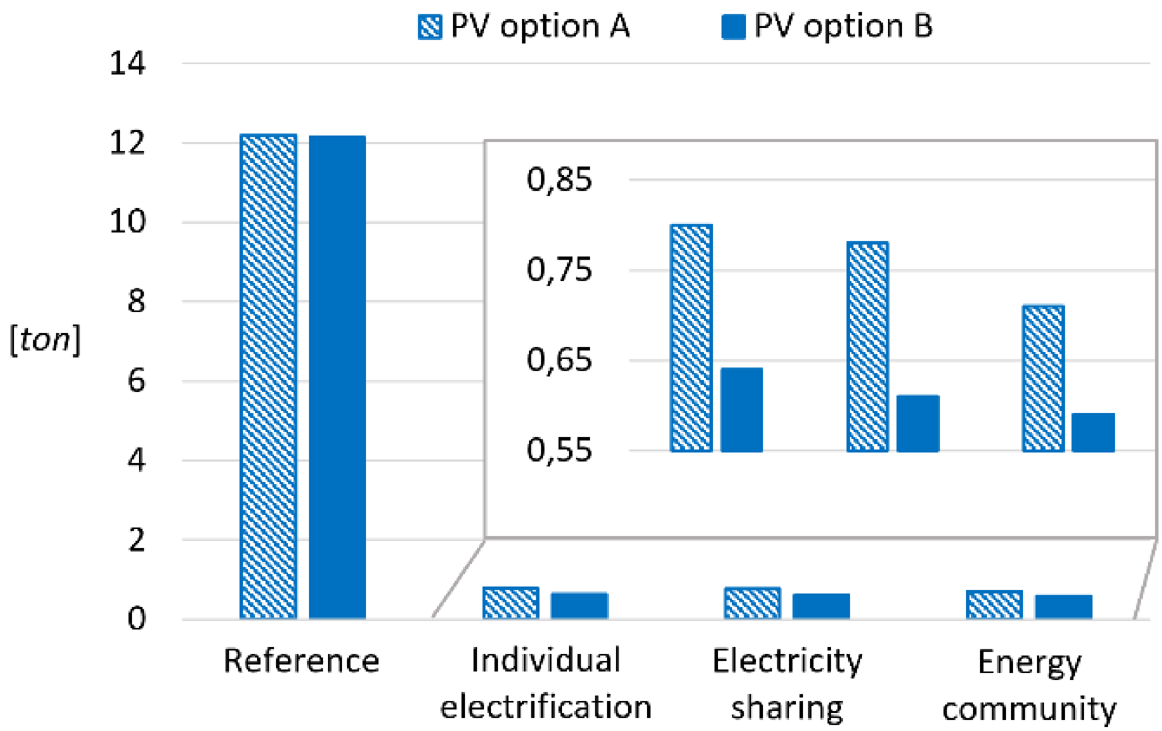

Figure 6: Annual CO_2 emissions.

Annual total costs

Figure 7 presents the annual total costs. These costs comprise annual investment costs (annualized investment costs considering component lifetimes and a discount rate of 7%) along with yearly maintenance costs, which together form the annual fixed costs and yearly operational costs. In the electrified scenarios, the fixed costs are higher compared to the reference scenario, while the operational costs are lower, resulting finally in higher total costs. Installing PV on the entire roof surfaces (PV option B) has a similar effect compared to PV option A, higher fixed cost, lower operational costs and higher total costs. Electricity sharing results in only a limited reduction of approximately €100 (or $107) in operational costs. However, the energy community scenario benefits from a larger, more cost-effective heat pump instead of three smaller ones.

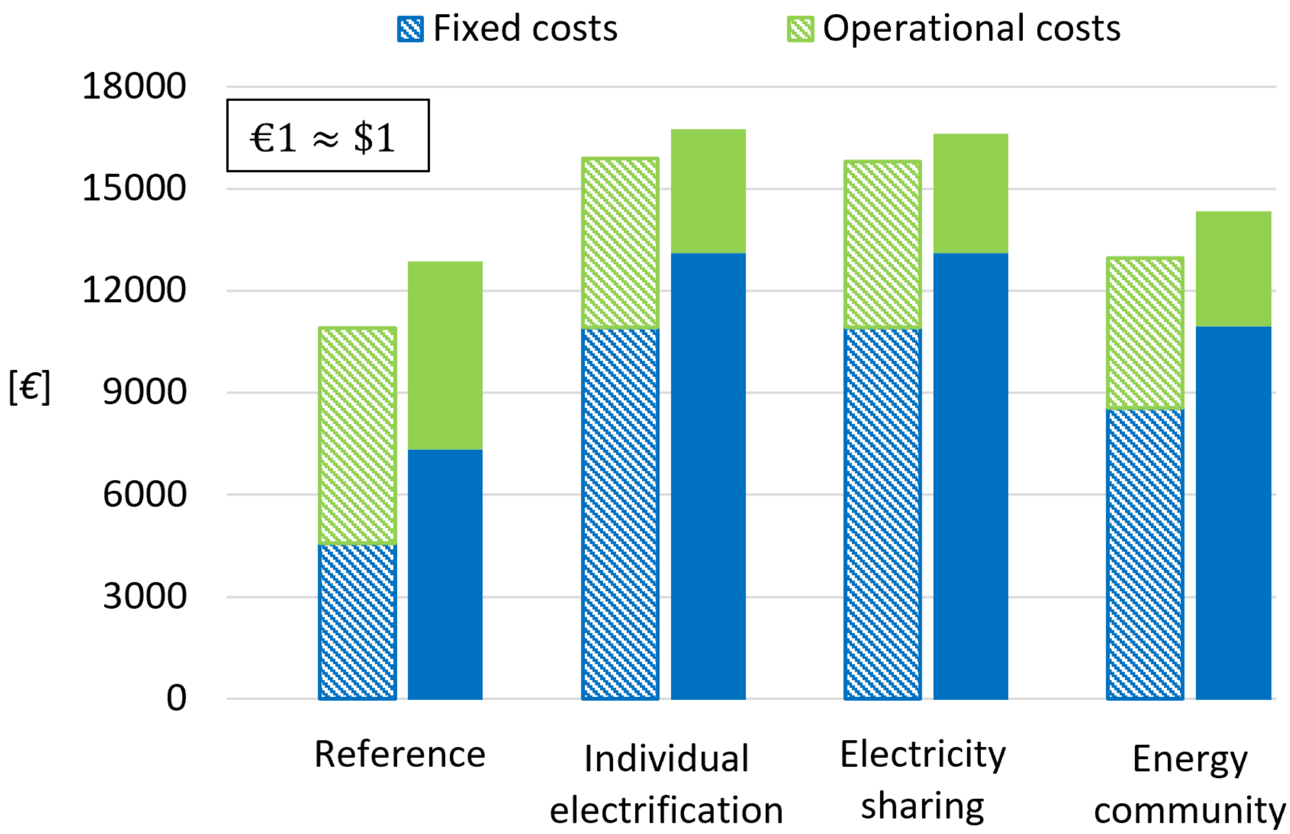

Figure 7: Annual total costs (PV option A: shaded, PV option B: filled).

CO_2 emissions abatement costs

Combining the annual costs from Figure 7 and the annual CO_2 emissions from Figure 6 results in the cost of CO_2 emissions abatement in the electrified scenarios, illustrated in Figure 8. The results indicate that transitioning to a more collective approach lowers the cost of CO_2 emissions abatement. However, installing additional PV capacity (option B) increases the CO_2 emissions abatement cost. In this specific case of a tiny residential cluster, the most effective energy system features a collective heat pump and a PV installation sized according to the plug load demand. This system achieves a 94% reduction in operational CO_2 emissions at a cost of 179 (or $192).

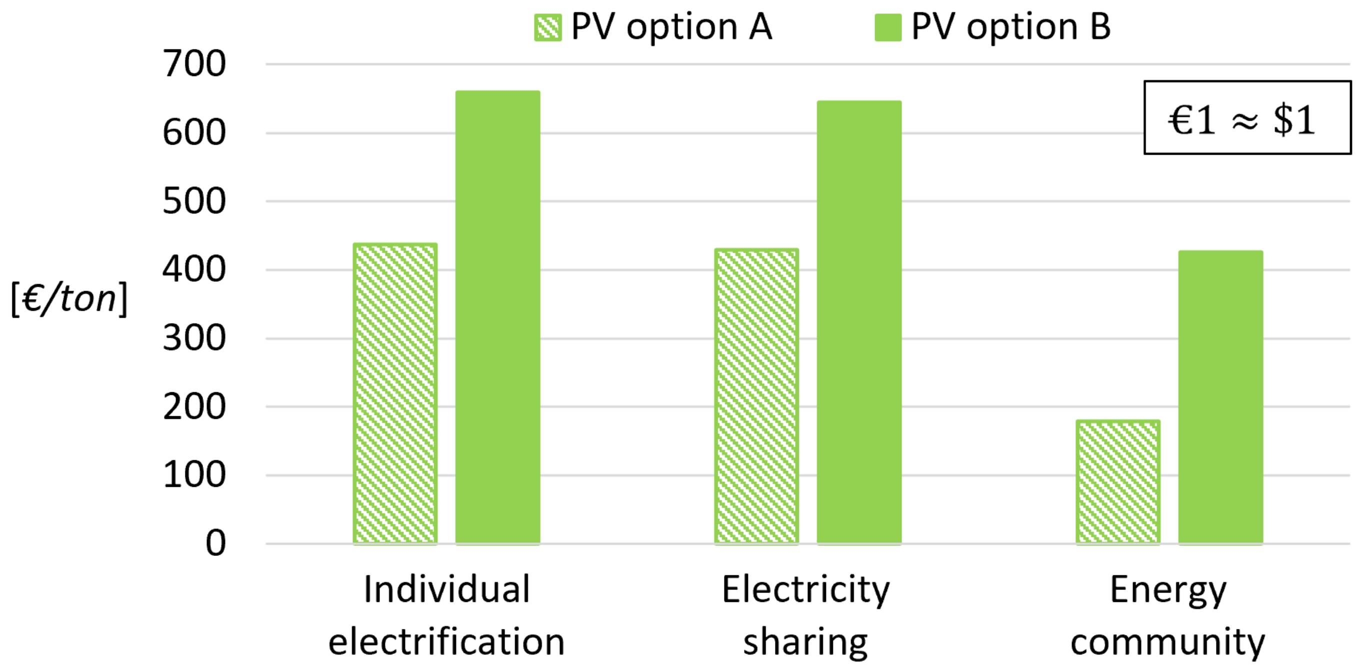

Figure 8: CO_2 emissions abatement costs.

Europe's emission trading system can put these CO_2 emissions abatement costs into perspective. Currently, the EU Emissions Trading System (ETS) is implemented as a cap-and-trade carbon market aimed at reducing Europe's CO_2 emissions in industry and aviation. As an extension, Europe plans to introduce a new emission trading market, ETS 2, in 2027, targeting emissions from fuel combustion in buildings and other sectors. It is projected that the cost of one allowance under EU ETS2 will be €46 per ton of CO_2 at its inception, after which the allowance cost will vary according to the market. In 2021, EU ETS prices fluctuated between €32 and €80 per ton of CO_2. The calculated CO_2 emissions abatement costs within micro energy communities are significantly higher than anticipated future emission taxes, primarily due to high investment costs and a high electricity-to-gas price ratio in Belgium.. This underscores the need for an equitable electricity-to-gas price ratio, which is expected to be more balanced in the future.

Conclusions

This study demonstrates that micro energy communities, where both thermal and electrical energy are shared, can achieve significant CO2 emission reductions compared to fossil fuel-based reference scenarios at a cost of €179 (or $192) per ton of CO2 abated. This cost is significantly higher than the emission taxes that Europe plans to implement in the residential sector in 2027, due to a high electricity-to-gas price ratio in Belgium. However, more balanced and equitable electricity and gas prices are expected towards the future, making these energy community scenarios feasible and cost-effective solutions for structurally reducing CO2 emissions in the built environment, even in clusters of buildings with moderate building envelope qualities. For more details on the methodology and the discussion of the assumptions, we refer to Verleyen et al. (2024).

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Topical Article

Cold Climate Heat Pumps in the US: Updates from the Refrigerant to the Electrical Grid

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The US consists of many diverse climates, ranging from extremely hot to extremely cold, with many regions that experience both over the course of a year. This broad range of temperatures complicates efforts to electrify heating using heat pumps from both a system design and an electric grid standpoint. This article provides an overview of current cold climate heat pump development in the US, ranging from the refrigerants to the electric grid.

The Role of Cold Climate Heat Pumps in Decarbonization

The decarbonization of heating by replacing fossil-fueled boilers and furnaces with electric heat pumps has gained attention rapidly in recent years. This concept is particularly relevant in US homes because space and water heating make up about 40% of US residential energy consumption, up to as much as 60% in cold climates [1]. However, designing efficient heat pumps that use low-Global Warming Potential (GWP) refrigerants is only part of the story. Heat pump integration, both into existing buildings and the electrical grid, is a major challenge. Furthermore, assessing the method of energy production that electrifies a given grid cannot be forgotten. If a large percentage of a given grid is powered by fossil fuels, a heat pump is not necessarily better for the environment than a boiler.

Many heat pumps can function well in ambient temperatures down to or slightly below 0 °C. However, at ambient temperatures well below freezing, vapor compression cycles within a standard heat pump cannot always provide the required heating load and must, therefore, be supplemented by resistance heating. This results in a significant reduction in efficiency and motivates work on heat pumps that are designed to deliver the necessary heat at low ambient temperatures, known as cold climate heat pumps (CCHP). In the US, many heat pumps function on an air-to-air principle. The heat is pumped from the ambient air into central air ducting, which is also where the resistance heater is located. The heating capacity in many single-family US homes is 10 to 18 kW. While progress has been made in CCHP development, broader acceptance within the market has proven to be challenging due to the combination of low natural gas prices and high initial heat pump costs, among other reasons. However, government incentives for CCHP development and implementation are gaining momentum as decarbonization efforts take higher priority in the US.

Based on the climate zones defined by the US Energy Information Administration and the International Energy Conservation Code (IECC), Oak Ridge National Laboratory predicted the size of the Combined Cooling, Heat, and Power (CCHP) market in the US, assuming 4.75% of homeowners replace their heating equipment each year [2]. The primary market was identified as US homes in the cold/very-cold regions that use electrical furnaces and heat pumps, representing approximately 2.6 million homes. The secondary market consists of homes in the cold/very-cold and mixed-humid regions using electric furnaces, propane, or oil for heating, totalling approximately 46 million homes. Therefore, the combined potential of the primary and secondary markets for CCHPs in the US was found to be approximately 123,000 and 2.2 million homes, respectively. To provide a visual for the US climate in the context of heating, Figure 1 shows heating degree days (HDD) relative to 18.3 °C in the US based on data from 2022 [3].

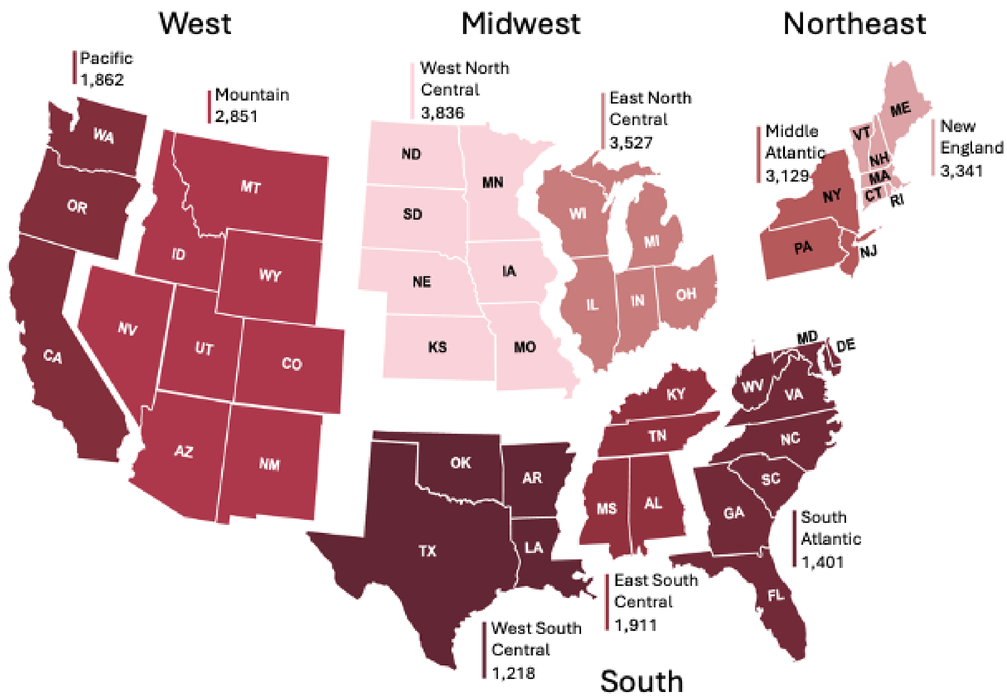

Figure 1: Heating degree days by US census division in 2022 [3].

Heat Pump Design Challenges and Opportunities

To compensate for lacking vapor compression cycle heating capacity at low ambient temperatures, electric resistive heating is often used, leading to reductions in the heat pump Coefficient of Performance (COP). To reduce the amount of resistance heating being used, larger compressors with variable speed capabilities, tandem compressors, multi-stage compression, and vapor injection represent some possible solutions. However, the initial cost and at-scale production of necessary systems and components have been proven to be limiting factors to their acceptance.

To address these challenges in the US, researchers in academia, industry and government roles have been working together to develop CCHP technology for several applications that are scalable and proven in field tests. One example of such an effort is the US Department of Energy (DOE) Residential CCHP Challenge [4], which is an initiative to bring public and private stakeholders together to develop scalable technology to overcome market entry barriers and support large-scale implementation of CCHPs. Launched in 2021, this effort aims at field-tested residential CCHP designs that can provide 100% heating capacity without resistance heating at ambient temperatures down to -15 °C and, in an extreme segment of the competition, -26 °C. The -15 °C performance goals have been achieved by eight major manufacturers in laboratory settings to date, some of which also met the -26 °C performance goals and are now moving towards installing 23 field installations in cold regions in the US.

From a system and component perspective, a range of cycle modifications have been proposed and investigated numerically and experimentally to overcome three key system-level challenges associated with the high-pressure ratio that compressors need to overcome in CCHP applications:

- High discharge temperatures
- Reduced heating capacities
- Low heating COPs

A conceptual summary of the most common architectures for CCHPs was provided by Bertsch and Groll [5] and shown in Table 1. Experimental investigations of a CCHP for the US residential market were carried out by Oak Ridge National Laboratory [6]. Two single-stage compressors in tandem were utilized to minimize cost and simplify control. Experimental investigations achieved 76% of the heating load delivered at 8.3 °C and a heating COP of 1.94 at -25 °C. When vapor injection was applied using two tandem compressors, 88% of the heating load was delivered at 8.3 °C, and a heating COP of 2.0 at -25 °C were achieved. There are a range of current investigations of CCHPs with both synthetic and natural refrigerants at many research institutions in the US, including Oak Ridge National Labs as well as the Ray W. Herrick Labs.

#	Concept	Preferred Compressor*)	Number heat output steps	Relative Efficiency	Relative Heat output	Discharge temperature
1	1-stage cycle	LT	1	100%	100%	High
2	2-stage w. intercooler	2-stage	1	130%	100%	Acceptable
		Sc, Recip, Rot	3	130%	140%	Acceptable
3	2-stage w. economizer	2-stage	1	130%	100%	Low
		Sc, Recip, Rot	3	130%	150%	Low
4	Cascade cycle	Sc, Recip, Rot	1	140%	140%	Low
5	Refrigerant injection	Sc, Screw	2	Comparable	115%	High
6	Oil cooling	Recip, Rot	1	Comparable	Comparable	Acceptable
7	Mechanical subcooling	LT + Sc	2	110%	120%	High

*) Sc…Scroll, Recip…Reciprocating, Rot…Rotary, LT…Low temperature

Table 1: Comparison of different heat pump cycles in CCHP applications [5].

Legislation surrounding allowable GWP and flammability in the residential sector has currently limited the scope of the most recent CCHP efforts to A2L refrigerants based on blends of Hydrofluorocarbons (HFCs) and Hydrofluoroolefins (HFOs). However, continued

GWP phase downs due to the US EPA AIM Act from 2021, along with concerns regarding the classification of Trifluoroacetic Acid (TFA) as Per- and Fluoroalkyl Substances (PFAS) in some parts of the world, have motivated many manufacturers for heat pumps being sold in the US to keep one eye on R290 (propane) as a possible "future proof" alternative. While the US EPA SNAP regulations have recognized R290 as a viable fluid for window air conditioners, the process to broader acceptance of its use will likely follow a similar path taken for R600a in domestic refrigerators in the US. Dynamic legislation surrounding UL standards 60335-2-40 (residential) and 60335-2-89 (commercial), as well as safety standards (i.e., ASHRAE Standard 15), will have strong influences on the acceptance of hydrocarbon refrigeration and heat pump systems in the US market in the coming years. However, building codes, general EPA regulations, and decentralization of many such decisions to individual US states suggest that the US is still years away from the widespread acceptance of R290 as a working fluid in residential heat pumps.

Cold Climate Heat Pumps and Electrical Infrastructure

In addition to improving thermal comfort and reducing energy bills, CCHPs can reduce strain on electrical infrastructure at the building, distribution, and transmission scales. At the building scale, an inefficient residential air-source heat pump with resistance backup can require currents of 80 Amperes or more in very cold weather. Especially in older homes, currents this high can risk overheating the wires that connect the heating equipment to the main circuit breaker panel, the panel itself, or the wires that connect the panel to the utility's distribution grid. Replacing this building-scale infrastructure can be expensive and slow, as it can require a skilled electrician and approvals from building inspectors or electric utilities. CCHPs, with their higher cold-weather COPs and much lower dependence on resistance backup, can bring required currents down to 30 Amperes or less. In this way, CCHPs can reduce or eliminate the need for electrical work that often accompanies heat pump installation in older homes, lowering a barrier to residential electrification.

At the scale of a medium-voltage distribution network, widespread adoption of inefficient air-source heat pumps with resistance backup could increase electricity demand in cold weather beyond the safe limits of power lines, the distribution transformers that typically serve five to ten homes or the substation transformers that serve whole neighborhoods. Due to supply chain issues and rising demand for transformers, it is not unusual today for US utilities to take two years or longer to upgrade this infrastructure, compared to just a few months in 2020 [7]. Utilities who cannot upgrade infrastructure sufficiently quickly might lobby governments to slow down or halt approvals for electrification projects. On the other hand, utilities who do upgrade infrastructure pass the costs on to ratepayers by raising electricity prices. As transformer costs have risen 60 to 80% since 2020 [7], these infrastructure upgrades could significantly increase electricity prices, weakening economic incentives for adopting heat pumps over fossil-fueled furnaces and boilers. CCHPs' higher cold-weather COPs and reduced dependence on resistance backup could reduce strain on power lines and transformers, mitigating these distribution-scale issues.

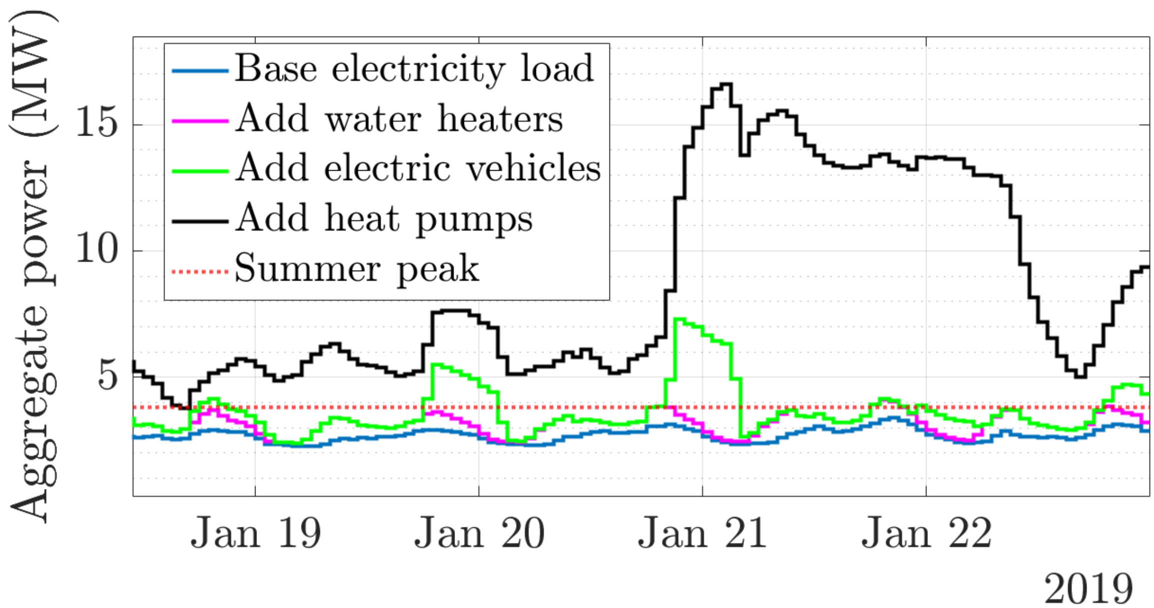

Figure 2: In simulations of 1,000 electrified houses with inefficient air-source heat pumps and resistance backup heat during the coldest week of 2019 in New York, electricity demand peaks at about four times today's summer peak [9].

At the scale of a high-voltage transmission grid, peaks in system-wide electricity demand determine the need to expand transmission and generation capacity. Today, demand in most US power systems peaks during the hottest hours of the year, driven by residential air conditioning. As illustrated in Figure 2, however, widespread adoption of inefficient air-source heat pumps and resistance backup would switch some US power systems from summer- to winter-peaking [8], posing operational challenges. Future winter peaks could greatly exceed today's summer peaks, triggering costly build-out of transmission lines and power plants. The associated costs would ultimately be passed on to ratepayers, weakening economic incentives for further electrification. As at the building and distribution scales, CCHPs could mitigate these transmission-scale issues.

How much money could CCHPs save society by avoiding electrical infrastructure upgrades that inefficient air-source heat pumps with resistance backup might require? The costs are hard to estimate precisely, but joint expansion of distribution, transmission, and generation capacity typically costs at least 1,000 $/kW. At a rough estimate, then, a residential CCHP that reduces peak winter electricity demand by ~10 kW (for example, by saving ~1 kW of compressor power and avoiding ~9 kW of resistance backup) could save on the order of $10,000. Although inexact, this back-of-the-envelope estimate illustrates one justification for CCHP research and development.

Conclusions

The US is a promising market for CCHPs that could improve comfort, save energy, reduce strain on electrical infrastructure, and accelerate decarbonization efforts. CCHP technology to achieve heating COPs of 2.0 at an ambient temperature of -25 °C has been proven, but there are significant legislative, market, and infrastructure-based hurdles to overcome before broad implementation of CCHPs becomes a reality. Initial investments and grid upgrades present significant economic challenges, so economies of scale, government support, and efficient CCHPs are among the next steps necessary to decarbonize residential heating in the US.

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Non-Topical Article

Reducing Capital Cost for Geothermal Heat Pump Systems Through Dynamic Borefield Sizing

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Lone Meertens, Belgium

Geothermal heat pump systems offer a sustainable solution for heating and cooling of buildings, significantly contributing to climate goals by reducing greenhouse gas emissions and achieving carbon neutrality. However, the higher initial costs associated with the borefield pose a barrier to widespread adoption. This article explores how dynamic borehole modeling can optimize borefield sizing, achieving up to a 35% size reduction in the investigated cases, thereby making these systems more cost-effective.

Introduction

The building HVAC sector's energy use has garnered increasing attention as a critical component in achieving environmental, energy, and climate goals. Geothermal heat pump systems (GHPS) are gaining prominence due to their potential for significant energy use reduction. These systems exploit the ground as a heat source and consist of two main components: the heat pump system and the borefield. Unlike air-to-water heat pump systems, GHPS (if properly sized) benefit from more stable soil temperatures, offering consistently higher efficiency even in very cold climates. However, the higher initial investment due to the borefield remains a barrier to widespread adoption. To reduce capital cost, it is essential to use a borehole model that is sufficiently accurate to predict heat transfer within and around boreholes, preventing oversizing.

Understanding geothermal heat pumps

GHPS extract heat or cold from the ground (a source of renewable energy) to provide thermal comfort in a building. When heating a building, the GHPS extracts heat from the ground and releases it into the space to be heated. GHPS are most efficient when the temperature difference between the ground and the supply water to the building is small. Therefore, buildings that use a GHPS are usually equipped with a low-temperature (or, for cooling, a high-temperature) emission system such as underfloor heating or Thermally Activated Building Structures (TABS).

GHPS are becoming increasingly important due to their potential to reduce energy use, especially when there is both heat and cold demand. Their high energy efficiency is attributed to three main factors. First, GHPS can provide passive cooling, which requires only circulation pump energy and contributes to the ground thermal balance (when there is heating demand in another season). Second, the coefficient of performance (COP) of the heat pump in GHPS is higher than that of air-to-water heat pump systems because the ground temperature remains relatively constant, resulting in a smaller temperature difference to bridge, especially in time periods when the heat demand is the highest. Finally, this technology also has the advantage of seasonal storage (when the borefield is designed for that purpose), where the stored heat from cooling in summer can be released in winter and vice versa.

Overall, GHPS leverage the earth's temperature to enhance heating and cooling efficiency, making them increasingly attractive for both residential and commercial applications.

The Importance of borefield sizing

Determining the optimal size of the borefield is one of the biggest challenges in GHPS. Due to the significant investment cost, minimizing the borefield size is crucial for economic feasibility. However, the borefield must be large enough to ensure that the heat transfer fluid (HTF) does not exceed predefined temperature limits: at the upper side to allow passive cooling and at the lower side to avoid freezing.

Accurately predicting the HTF temperatures throughout the entire range of borefield operation is thus essential for designing GHPS. For example, a borefield may be dominated by long-term heat buildup or affected by short-term peak loads. In the latter case, fluid temperatures inside the borefield may rise rapidly, with fluctuations of 5-10°C occurring over one to two hours. This emphasizes the importance of accurately determining fluid temperatures, as they directly influence the required length of the borefield and associated investment costs.

In practice, it often happens that a borefield is oversized, which is a result of sizing with a steady-state model that neglects the dynamic behavior of the fluid, the pipe, and especially the grout. Heat is then transferred immediately (without any delay) from the fluid to the ground, leading to an overestimation of heat injection into (or extraction from) the ground. In contrast, a dynamic model accounts for the thermal mass of the materials between the fluid and the ground, introducing inertia and resulting in transient heat transfer processes. Consequently, the borefield size can be reduced while still meeting the predetermined temperature constraints, significantly lowering investment costs.

Advancements in dynamic borehole modeling

Dynamic borehole modeling considers the short-term thermal interactions within the borefield, accounting for the thermal inertia of the fluid, pipes, and grout. By incorporating these transient effects, a more accurate prediction of the system's performance is provided, allowing for a reduction in borefield size without compromising efficiency.

Most software tools currently used, such as EED, GHEtool, and the DTS model used in the TRNSYS sizing tool, rely on Finite Line Source (FLS)-generated g-functions for heat transfer outside the borehole combined with an equivalent thermal resistance method for heat transfer inside the borehole. These methods represent the boreholes as finite lines and assume steady-state heat transfer inside, neglecting the thermal capacities of the materials making up the borehole. As a result, these sizing tools are not accurate for short-term heat transfer estimation and often lead to oversizing.

This article presents the impact of incorporating short-term dynamic effects into the basic model and examines whether the relevance of these effects depends on the chosen load profile. Two main improvements are made to the basic model to better describe heat transfer in borefields. First, the finite line is transformed into an infinite hollow cylinder, introducing a realistic borehole geometry and incorporating an accurate heat exchange surface between the borehole and the ground. Second, a dynamic model is introduced to replace the steady-state equivalent thermal resistance method, accounting for the transient heat transfer inside the borehole. These effects are modeled in GHEtool, an open-source Python package that includes all functionalities needed for borefield sizing and temperature evolution evaluation [1]. A comparison between the basic model and the newly introduced model, including the two short-term dynamic effects, has shown a significant impact on sizing [2].

Relationship between load profiles and borefield size reduction

To understand the impact of different load profiles on borefield sizing, three load profiles with varying characteristics were carefully selected. The two main load characteristics considered were the variability in peak load and the imbalance between heating and cooling demands. These profiles enabled the evaluation of the relevance of including the short-term dynamic effects under different scenarios. Table 1 gives the yearly demand and peak demand for the three investigated buildings. The hourly building loads employed for sizing are converted to primary geothermal loads using a SCOP of 4 and a SEER of 20 and are shown in Figures 1-3.

Table 1: Yearly demand [MWh] and peak demand [kW] for the three different buildings

		Auditorium	Office	Swimming pool
Yearly	Heating	38.3	117.6	1965
	Cooling	3.86	118.3	41.89
Peak	Heating	32	214	540
	Cooling	90	371	106

Profile 1: High Variability in Peak Load

The first load profile represents an auditorium building with significant fluctuations in heating and cooling demand throughout the day. This high variability in peak load makes it an ideal candidate for dynamic borehole modeling. Traditional steady-state models tend to oversize the borefield for such buildings, as they do not account for the short-term thermal capacity of the system, which will flatten out the depicted load peaks.

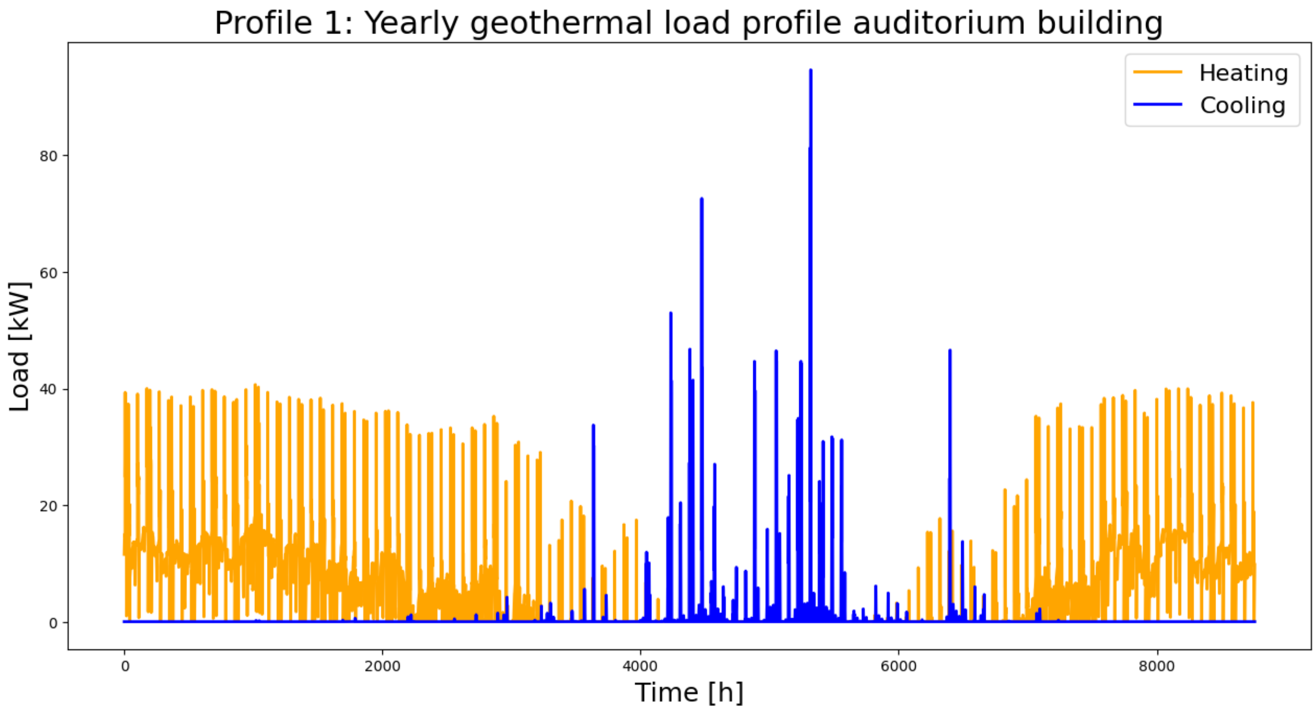

Figure 1: Yearly primary geothermal load profile of the auditorium building in kW.

Dynamic borehole modeling for this profile showed a substantial reduction in borefield size, as the model accurately captured the thermal inertia effects, allowing the system to handle peak loads more efficiently. Figure 4 illustrates that the required borehole length can be reduced by 35% for this building, achieved through dynamic borehole modeling.

Profile 2: Balanced Load with Moderate Variability in Peak Load

The second load profile pertains to an office building characterized by a balanced heating and cooling demand with moderate peak load variability.

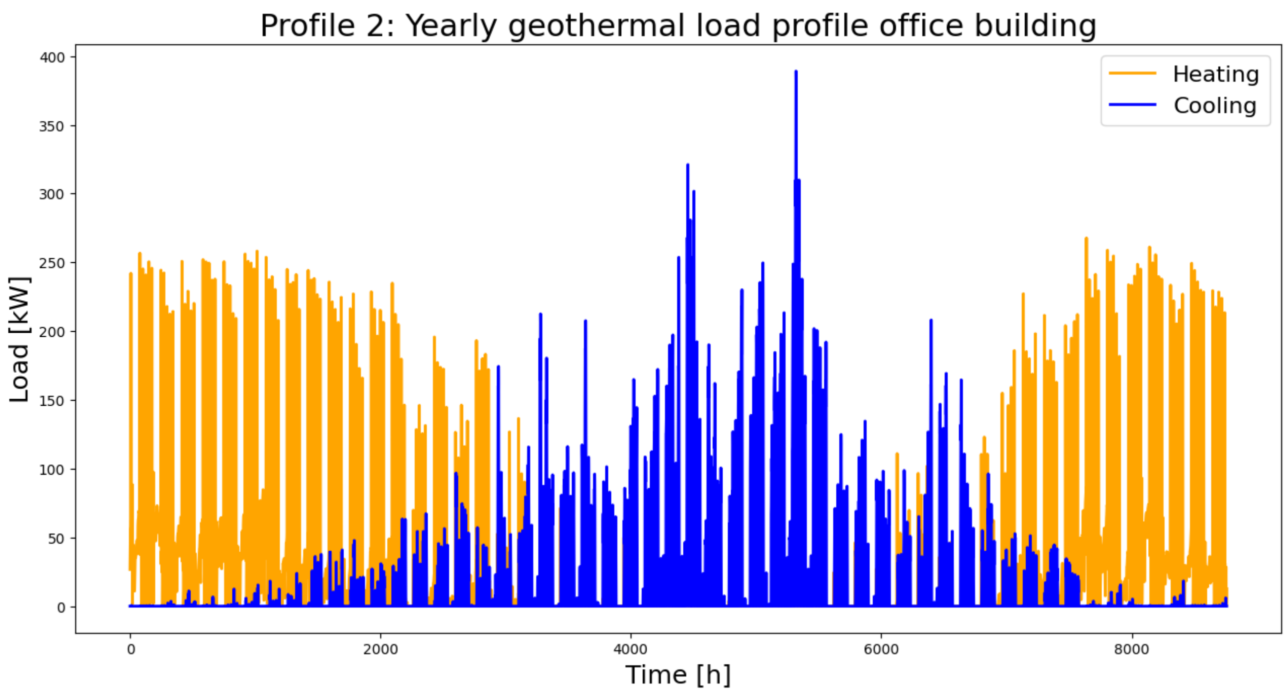

Figure 2: Yearly primary geothermal load profile of the office building in kW.

The results indicate that even with moderate peak load variability, dynamic borehole modeling can achieve significant cost savings. The sizing is primarily influenced by temperature peaks because there is no significant imbalance between heating and cooling demands over the year. Accurate estimation of the HTF temperature during peak hours results in a more precise borefield size. For this specific case, the required borefield size can be reduced by 11%, as shown in Figure 4.

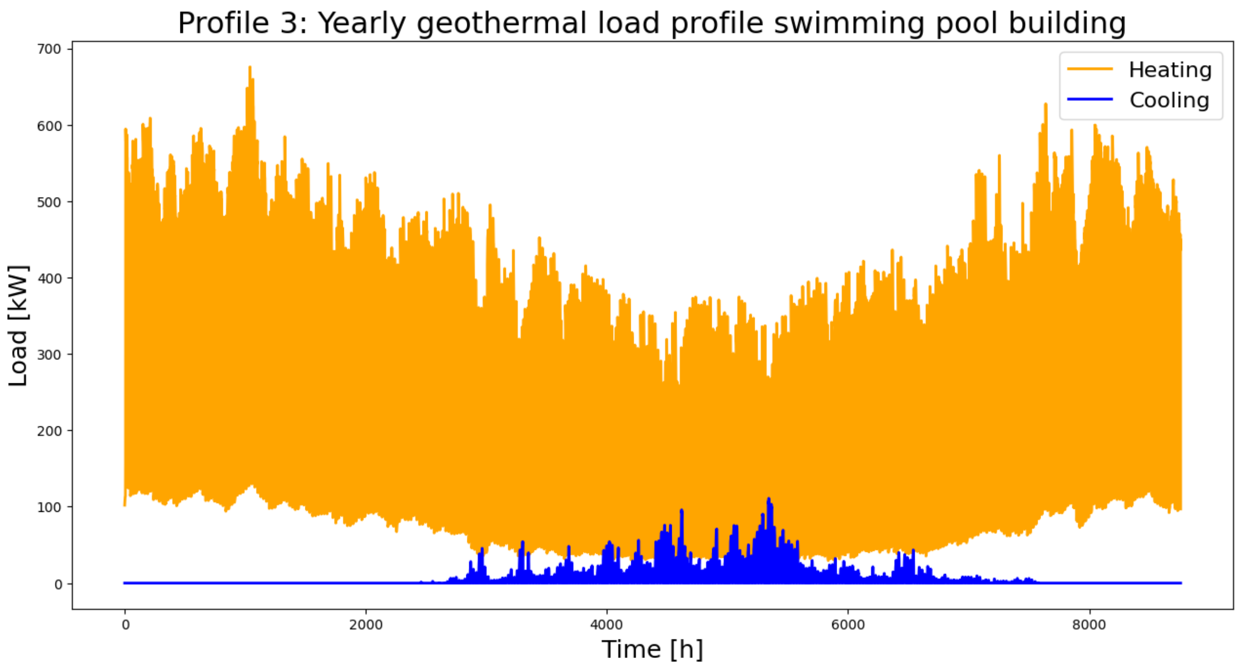

Figure 3: Yearly primary geothermal load profile of the swimming pool building in kW.

Profile 3: Highly Imbalanced Stable Load

The third load profile focuses on a swimming pool building, which has stable heating and cooling demands but a significant imbalance between both. This imbalance means that the building requires more heating than cooling, or vice versa, over the course of the year, as shown in Figure 3. This substantial load imbalance causes the ground temperature around the borefield to cool down year after year since more heat is extracted than injected. Consequently, the HTF temperature decreases annually until it hits the lower temperature limit at the end of the exploitation period. This constraint is considered during the sizing process, and thus, the sizing is dominated by this large imbalance. The dynamic borehole model, which accounts for short-term effects, does not alter the steady-state behavior in the long term. This explains why, for this specific case, incorporating short-term dynamic effects does not offer the potential for size reduction.

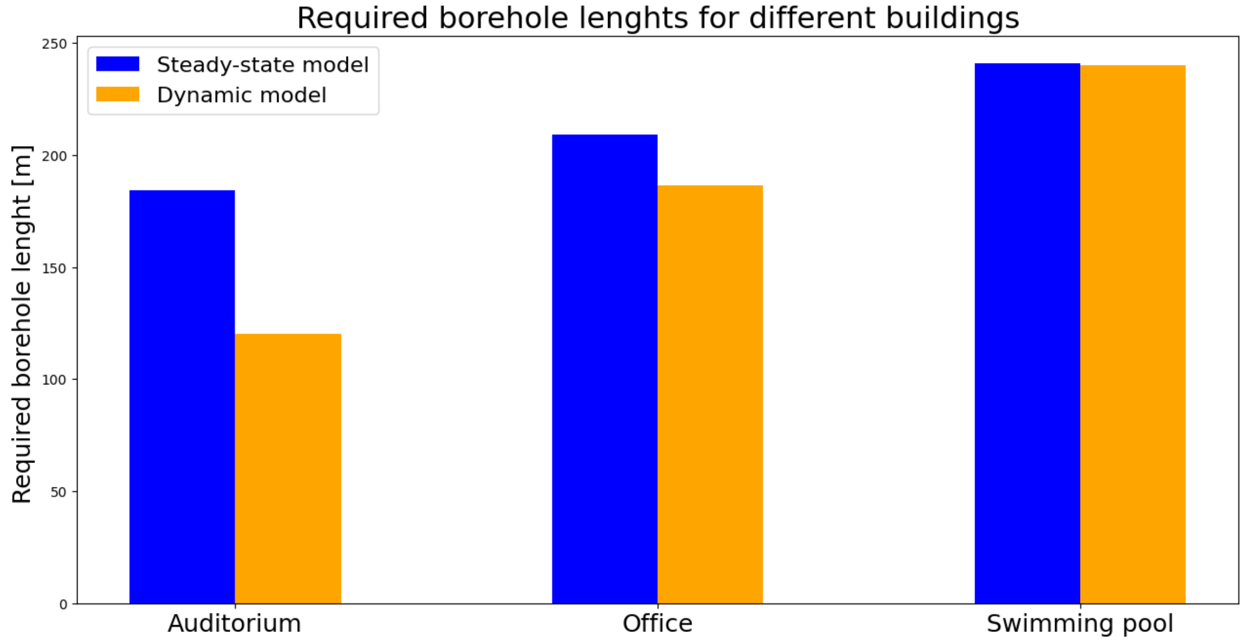

Figure 4: Required borehole lengths for the different buildings and different borehole models

Benefits for Reaching Climate Goals

The enhanced efficiency and reduced costs of GHPS directly contribute to global climate goals. By decreasing reliance on fossil fuels for heating and cooling, GHPS reduce greenhouse gas emissions. Additionally, their long lifespan and low maintenance requirements make them a sustainable choice for the future.

The International Energy Agency's (IEA) Tracking Clean Energy Progress 2023 report highlights the crucial role of geothermal energy in the transition to a net-zero emissions world [3]. GHPS, being a mature and reliable technology, are well-positioned to aid this transition by offering a renewable and efficient alternative to conventional heating and cooling systems.

By optimizing borefield sizing through dynamic borehole modeling, GHPS become more cost-effective, encouraging broader adoption. This not only makes the technology more accessible to a wider range of users but also accelerates its impact on reducing carbon footprints and advancing energy sustainability.

Conclusions

Geothermal heat pump systems are a powerful technology in the fight against climate change. By optimizing borefield sizing through dynamic borehole modeling, these systems can become more accessible and cost-effective, thus accelerating their adoption. As the world transitions towards a sustainable energy future, GHPS will play a crucial role in reducing emissions and promoting energy efficiency.

This article describes a method to enhance the commonly used steady-state borehole models for borefield sizing by incorporating short-term dynamic effects. These improvements introduce a more realistic cylindrical geometry and consider the thermal capacities of the borehole components. This approach flattens out the heat transfer peaks, allowing for a smaller borefield size while still meeting the predefined temperature constraints of the HTF. For buildings with high variations in peak thermal demand, dynamic borehole modeling can significantly reduce borefield size and installation costs. The investigated cases demonstrated a size reduction of up to 35%.

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National Market

France: Heat Pump Market Report

DOI: 10.23697/x102-cy46

Pedro JORQUERA FERRAT, CETIAT, France

In recent years, the thermodynamical systems market in France has been influenced by economic challenges and technological advancements, and sales have increased in the last decade. The economic situation, international context, and evolving government policies have resulted in heat pump sales slowing down in 2023, especially in new buildings. However, government objectives and a focus on energy efficiency provide support. Technological innovations in these systems continue, and future growth is anticipated.

Introduction

The market for thermodynamical systems in France has experienced significant shifts due to various economic, political, and technological factors. Over a long period of time, the Heat Pump (HP) market in France saw an important evolution, specially in 2008, 2013-2014, and 2021, due to the global energy crisis, energy performance of building regulation (RT2012), and post-Covid boom. The reader is advised to refer to the issue No.2/2018 of the HPT Magazine, pages 18-21, for interesting insight on the Heat Pump Market in France from 2008 to 2018 [1].

This document explores the current state of the market, the impact of recent economic conditions, technological advancements, and the outlook for future growth.

Market Overview and Trends

The French market for thermodynamical systems has been notably impacted by economic challenges. High inflation rates, decreased purchasing power, and rising loan rates have led to a slowdown in the new building sector, consequently reducing the demand for new HPs and other thermodynamical systems. Despite these challenges, the market is driven by a strong focus on energy efficiency and sustainability.

On the one hand, inflation and high interest rates have significantly impacted the market for new constructions, leading to a reduction in the installation of new thermodynamical systems. This phenomenon is also fueled by the implementation of energy performance and environmental regulation RE2020, a strict regulatory framework that leads to increases in construction costs. In 2023, the construction of new housing in France fell by 22% compared to the previous year, while building permits granted dropped by 24% during the same period. On top of this, according to the forecasts, construction starts should decline by 16% year-on-year in 2024, while building permits issued would decrease by 12% [2].

On the other hand, the renovation market is facing challenges due to evolutions in support schemes.

Some of the French Government Incentives and Support Schemes are:

- MaPrimeRénov'
- Eco-PTZ (Eco-Loan at Zero Interest)
- Local and Regional Grants
- Heating Boost (*"Coup de pouce chauffage"):* Boost to replace old fossil boilers, frame of Energy Savings Certificates (CEE)
- The energy check for low-income families
- VAT Reduction: Reduced VAT rates for energy renovation works

In 2023, evolutions on MaPrimeRénov have had a negative impact on the heat pump market: the scheme that aims at existing buildings used to target comprehensive as well as single upgrades. But in 2023 it has shifted focus towards comprehensive energy renovation projects, leaving small room for the sole replacement of the heating and hot water production system. Additionally, higher-income households have seen reduced or eliminated eligibility for certain grants, further shrinking the market base.

This market report shows in numbers the actual situation of HP sales in France. The information has been compiled from Uniclima's Press Release of 2016, 2019, 2021 and 2023 [3].

Air-to-water heat pumps

Air-to-water heat pumps have seen significant advancements aimed at improving efficiency and reducing environmental impact. They are favoured for their easier installation, especially in France, where hydronic heating is widespread.

As seen in Figure 1, the air-to-water heat pumps market has seen an important evolution in recent years, with a peak of 355,000 units sold in 2022. The important increase of AWHP sales observed in 2019 was notably the consequence of financial incentives from the government and energy suppliers as part of the renovation of old heating systems with a more efficient system and/or using renewable energy (Heating Boost scheme).

After the market stability observed between 2019 and 2020 linked to the Covid health crisis, the market was strongly boosted by financial aids in energy renovation (Heating Boost and MaPrimeRenov') and the promotion of HPs in the new residential market, mainly in individual housing. Indeed, 2020 marked the beginning of the MaPrimRenov' scheme, subsiding up to 90% of the total operation cost for lower-income families.

In 2023, sales of air-to-water heat pumps are 14% down compared to 2022. However, they remain at a higher level than 2021.

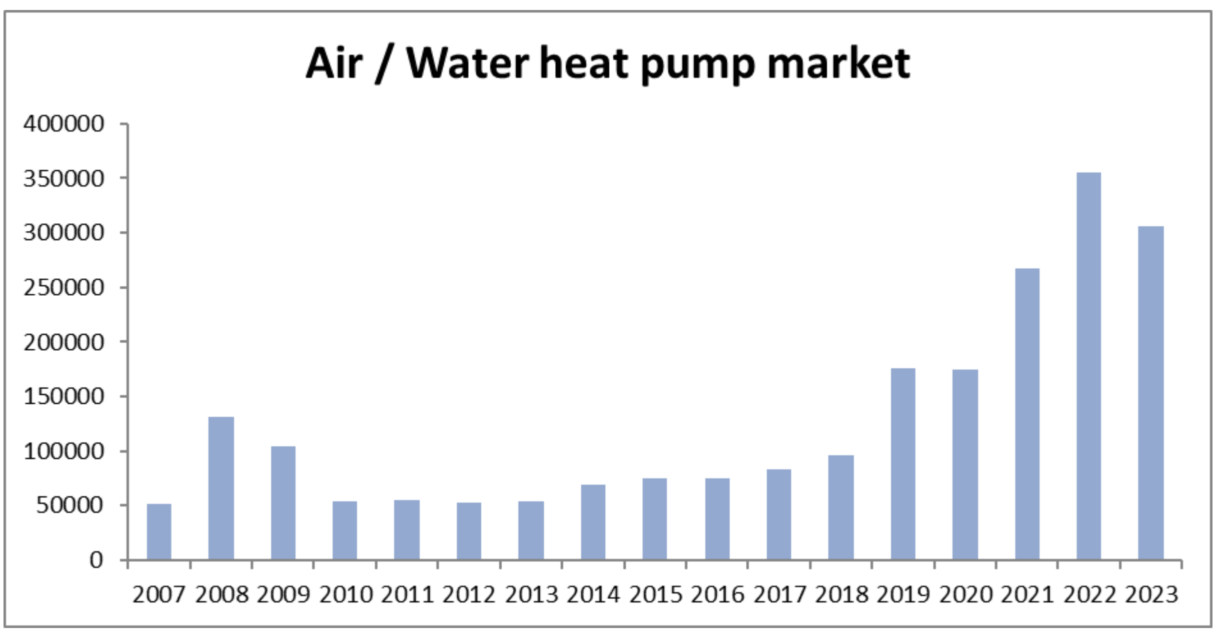

Figure 1: Sales of air to water heat pumps (in number of units).

Ground source heat pumps
Figure 2 depicts how this segment has been slowing down since 2008 due to alternatives with a lower initial investment. However, in 2019 a shift was observed in the tendency, probably due to the promotion of this technology by the government, professional unions, associations, and manufacturers.

In 2023, with 3,500 units sold (+18% compared to 2022), water/water-type heat pumps remain a small market in France. However, this market has not seen such a level since 2013. It benefits from recalibrated public aid like the evolutions on the Heating Boost scheme ("*Coup de pouce chauffage*"). Manufacturers note that all power segments are progressing, specially ground source HP of 20 to 30 kW (+47%).

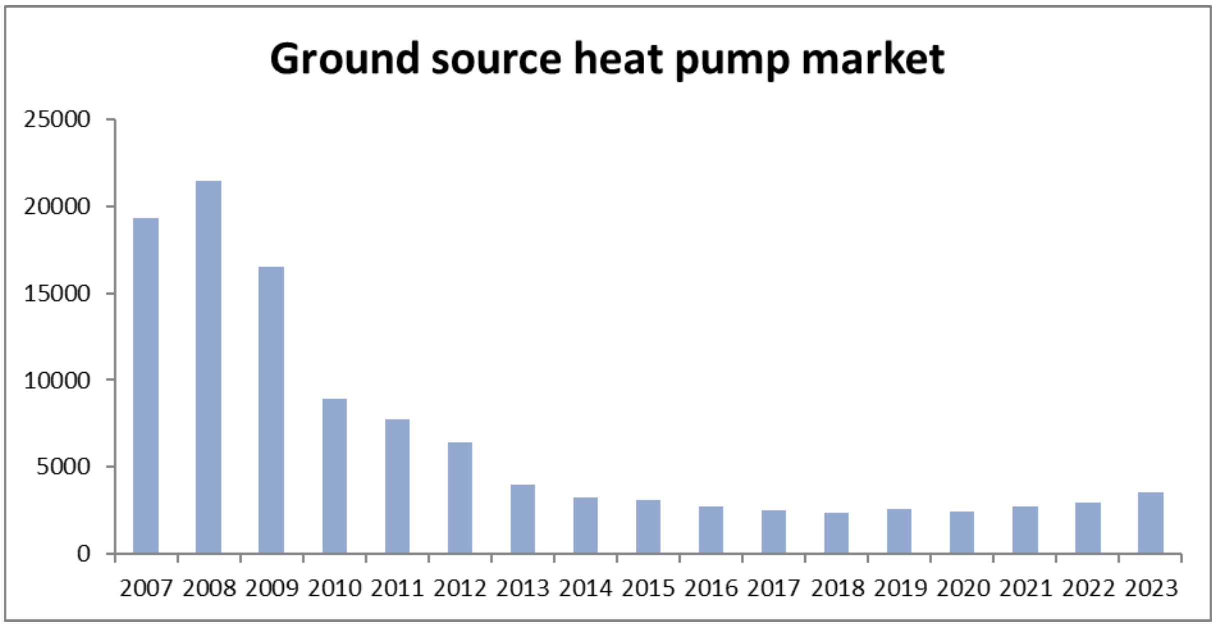

Figure 2: sales of ground source heat pumps (in number of units).

Air-to-air heat pumps
Air/air heat pumps confirm their relevance in terms of energy efficiency and decarbonization.[1] In new buildings and renovations, particularly in replacing Joule heating systems, the requirements of French building regulation RE2020 must be met. Although a stabilization in recent years is observed, as shown in Figure 3, the outlook remains good for this equipment as distribution stock seems to correspond to trends in the installation market, and public aid has a relatively small impact on sales.

[1] In France, electricity production is 92% decarbonized [4].

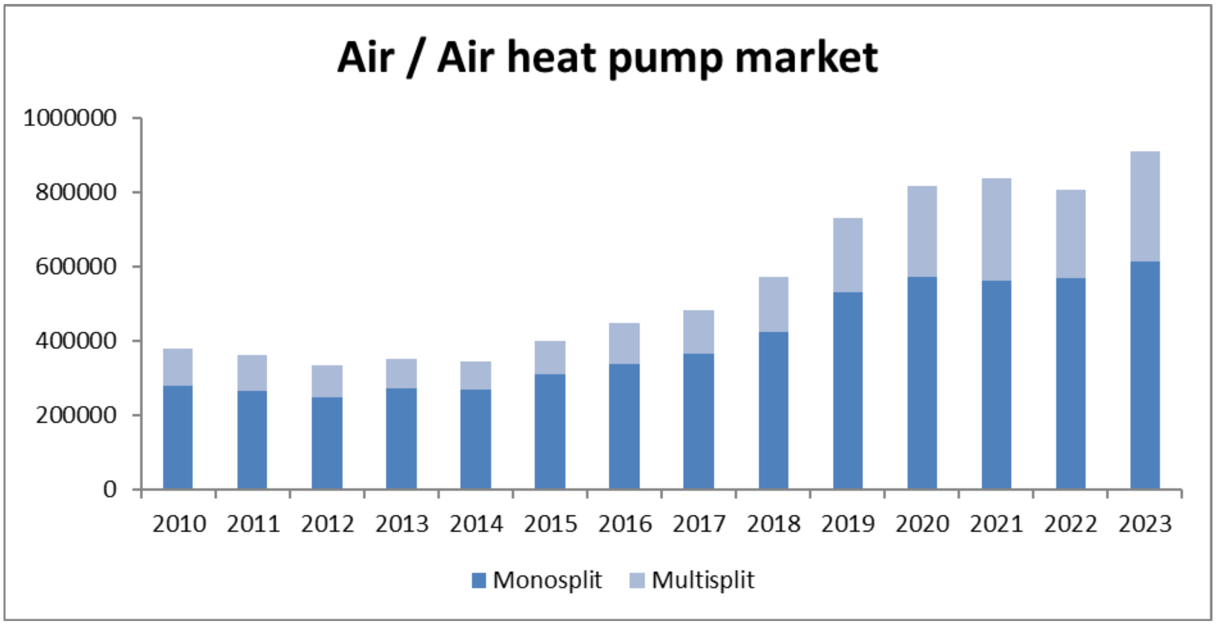

Figure 3: Sales of air-to-air heat pumps (in number of units).

Heat Pump Domestic Water Heaters

Heat pump water heaters are increasingly preferred due to their high efficiency and reduced environmental impact. They offer substantial energy savings over traditional electric water heaters.

Figure 4 shows that in 2021, the market grew 29% compared to 2019, which is the consequence of a catch-up effect in deliveries of individual houses (a consequence of delays accumulated in 2019 and 2020 during lockdown periods).

Recent growth in this market segment is supported by government incentives promoting renewable energy in residential settings.

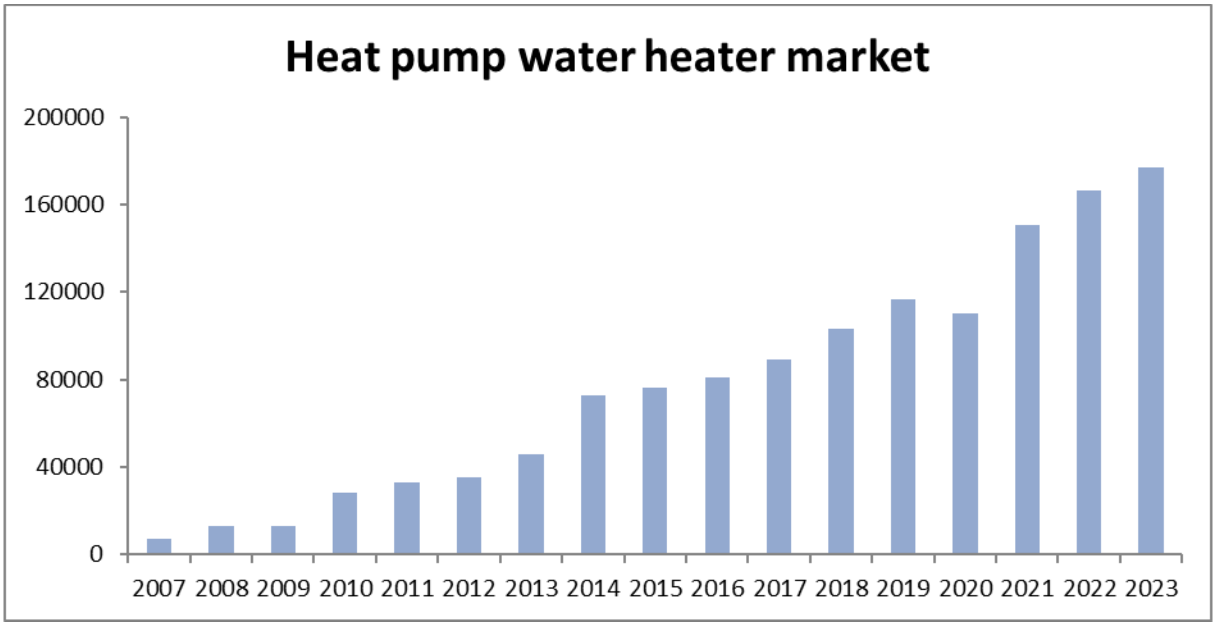

Figure 4: Sales of heat pump water heaters (in number of units).

Perspectives

Manufacturers estimate that the decline in new construction is only starting to be felt in 2023 but is expected to increase in 2024. It is, therefore, the renovation market that has decreased in 2023 due to the economic situation and the vagueness and complexity of public aid for renovation.

The scheme MaPrimeRenov' is going through additional evolutions: the government recently re-accepted single upgrades as well as comprehensive projects, at least until the end of 2024. Moreover, in April this year, the government has announced that the scheme will be reserved to European heat pump systems from 2025 [5].

Although political instability could change in the near future, the French government is committed to its energy transition goals. For instance, on April 15, 2024, the French Government unveiled the action plan aimed at producing 1 million heat pumps by 2027 in order to reduce France's dependency on fossil fuels.

Conclusions

While the Heat Pump market in new buildings will face slow progression or maybe even stagnation in the following years, the priority must be given to the renovation market. But this market requires simplicity and stability regarding the renovation support systems and schemes which hasn't been the case in France.

In conclusion, the French thermodynamical systems market is navigating a complex landscape shaped by economic challenges, regulation requirements, technological innovations, and ever-evolving government policies. By leveraging government incentives and promoting the benefits of these systems, stakeholders can foster greater adoption and contribute to France's environmental and energy efficiency goals.

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International Energy Agency
The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among its participating countries, to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development.

Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) International collaboration for energy efficient heating, refrigeration, and air-conditioning.

Vision
Heat pumping technologies are the Cornerstone for a secure, affordable, high-efficiency, clean and net-zero emission energy system for heating, cooling and refrigeration. We are the key worldwide independent actor to achieve this vision across multiple applications and contexts.

We generate and communicate information, expertise and knowledge related to heat pumping technologies as well as enhance international collaboration.

Mission
To accelerate the transformation to an efficient, renewable, clean and secure energy sector in our member countries and beyond by performing collaborative research, demonstration and data collection and enabling innovations and deployment within the area of heat pumping technologies.

Heat Pump Centre
A central role within the HPT TCP is played by the Heat Pump Centre (HPC).
The HPC contributes to the general aim of the HPT TCP, through information exchange and promotion. In the member countries, activities are coordinated by National Teams. For further information on HPC products and activities, or for general enquiries on heat pumps and the HPT TCP, contact your National Team at www.heatpumpingtechnologies.org/contact-us/
The Heat Pump Centre is operated by RISE Research Institutes of Sweden.

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