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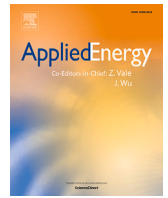
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Optimization of heating curves for heat pumps in operation: Outdoor temperature ranges for energy-efficient heating curve shifts

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HIGHLIGHTS

- Method to derive heating curve optimization guidelines, implementable by residents.
- Study is based on observational data from 3995 air-to-water heat pumps, located in average climate.
- Standard parallel shift of the heating curve is preferable only for $T_{outdoor} \in [2,5]^{\circ}\text{C}$.
- 84.42 % of the heating curves can be improved, reducing yearly energy consumption by 4.02 % on average.
- Significantly reduced number of misconfigured heating curves from 24.01 % to 7.08 %.

ARTICLE INFO

Keywords:

Air-to-water heat pump
Heating curve
Optimization
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ABSTRACT

In the light of global sustainability efforts, heat pumps offer environmental benefits, but their complexity and potential misconfigurations often lead to homeowner dissatisfaction due to inaccurate heating and lower-than-expected efficiency. Among the most important and complex settings is the heating curve and yet there are no easy-to-use methods to optimize it after its initial set-up. This study aims to develop ready-to-use guidelines for optimizing the heating curve with energy-efficient adjustments that improve room comfort and prevent suboptimal user changes, all without requiring additional sensors like room thermostats. Based on interpretable linear models, estimated on 3995 air-to-water heat pumps, located in Central Europe, we select the least energy-intensive heating curve shift for each outdoor temperature, needed to meet room thermal comfort. We find that the standard parallel shift of the heating curve is only the optimal approach when the average outdoor temperature is between 2 °C and 5 °C. Outside this range, the heating curve should be moved at its starting or the endpoint. Simulation shows that by translating user input to the room controller with our proposed changes, 84.42 % of the heating curves can be improved, reducing the share of misconfigured heating curves from 24.01 % to 7.08 %. This leads to an average reduction in yearly energy consumption of 4.02 % and an increase in the seasonal coefficient of performance by 2.59 % on average. By introducing ready-to-use heating curve improvement guidelines, we aim to increase efficiency and confidence in heat pump technology, ensuring its adoption to meet carbon emission targets.

1. Introduction

In the context of global efforts to reduce CO₂ emissions, heat pumps (HPs) stand out as a key technological solution for heating systems, valued for their ability to electrify and decarbonize the heating sector while providing high energy efficiency [1,2]. HPs have seen increased adoption in the building sector in recent years, with nearly 20 million units in operation just in Europe in 2023 [3].

Despite the rapid adoption of HPs, sales growth has begun to plateau [4], raising concerns about meeting installation rates needed to achieve net-zero goals by 2030, with current projections predicting a 58 % shortfall [2]. This slowdown is partly driven by persistently high electricity prices, and declined gas prices, which have made HPs less financially attractive [5]. User dissatisfaction has also played a role, with several studies reporting insufficient heating performance and

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Nomenclature	
α_1	Intercept of a multiple linear regression used to estimate the energy consumption
α_2	Slope of the supply temperature of a multiple linear regression model used to estimate the energy consumption
α_3	Slope of the outdoor temperature of a multiple linear regression model used to estimate the energy consumption
β_1	Intercept of a simple linear regression used to represent a heating curve
β_2	Slope of a simple linear regression used to represent a heating curve
ϵ	Error term of a regression model
ΔT_{room}	Change in room set temperature in degrees Celsius
γ_1	Intercept of a multiple linear regression used to estimate coefficient of performance
γ_2	Slope of the supply temperature of a multiple linear regression model used to estimate coefficient of performance
γ_3	Slope of the outdoor temperature of a multiple linear regression model used to estimate coefficient of performance
CH	Index indicating the change of a heating curve
EP	Index indicating the endpoint
h_j	Annual frequency (in hours) of predefined outdoor temperatures in an average climate, as defined in Table A.2 of the EN 14825 standard
k	Intercept of a simple linear regression used to represent a heating curve
PL	Index indicating the parallel shift
$shift$	Supply temperature
SP	Index indicating the starting point
T_O	Outdoor temperature
T_S	Supply temperature
u_{hp}	Heat pump specific intercept of a multiple linear regression used to estimate coefficient of performance
v_{hp}	Heat pump specific intercept of a multiple linear regression used to estimate the energy consumption
w_i	Weighting factors for predefined outdoor temperatures in average climates, used to calculate SCOP, as defined in the EN 14825 standard
Acronyms	
AWHP	air-water heat pump
COP	coefficient of performance
HP	heat pump
MdAPE	median absolute percentage error
OTD	outdoor temperature-dependent
SCOP	seasonal coefficient of performance

higher-than-expected operational costs [6–8]. Ensuring the efficient operation of HPs is therefore crucial to restoring and sustaining confidence in the technology and sustaining adoption.

Reasons for deviating HP performance lie in the complex nature of HP configurations in comparison to traditional heating systems [9]. They require more parameters to be set [9] and their performance is more sensitive to operating conditions such as supply and outdoor temperatures [10]. Recent field studies have shown that the performance of HPs in both average [11] and cold [12,13] climate zones is often impacted by suboptimal choice of HP control parameters. Therefore, many researchers have explored alternative HP methods to improve upon traditional weather-compensated heating system control. The primary focus has been on dynamically adjusting the supply temperature based on system feedback, incorporating factors such as actual room temperature [14], thermostatic valve positions [15,16], scheduling [16], and model predictive control [17], which optimizes parameters based on predicted system responses.

An alternative approach to supply temperature control is flowrate regulation [18,19]. While flowrate control is commonly used for air-to-air HPs, it is not applicable to hydronic heating systems (that use water as distribution medium) [20]. In these systems, the flowrate is predetermined and optimized through hydraulic balancing for a specific heating system configuration. Additionally, implementing flowrate control requires additional sensors [19,20]. Oshurbekov et al. [21] highlight that effective flowrate control without introducing significant pressure drops or efficiency losses is nearly impossible in single-pump systems. Although these advanced control strategies have demonstrated improvements in thermal comfort and HP coefficient of performance (COP), they are rarely integrated into commercially available HP products. Due to the complexity of implementation and the need for additional sensors, these methods are also rarely used for retrofitting. As a result, weather-compensated control remains the most widely used approach for HP regulation in commercially available systems [22].

For HPs that are adjusted by weather conditions, one of the most important parameters for efficient operation is the heating curve. This parameter defines the supply temperatures that are necessary at different outdoor temperatures to deliver the right amount of heat to the building

for keeping the room temperature within a comfortable range [9,23]. Changing the heating curve has a high influence on energy efficiency, given that a parallel decrease of a heating curve by one degree is reported to increase the COP for HPs by 2.6 %–13 % [24,25]. Moreover, a well-adjusted configuration of the heating curve is the basis for a constant room comfort, which increases users' willingness to adopt energy-saving strategies (e.g., supply temperature reduction during absence, weather-dependent room temperature adjustments, or preheating when energy prices are low), thus, making operation cheaper, more energy-efficient [26], or improving grid stability [27].

Calculating the heating curve parameters for HPs is a complex process that is prone to inaccuracies. This is because it involves numerous household specific variables and assumptions. A study by Weigert [7] revealed that around 60 % of households inspected during an energy consulting session had incorrectly configured heating curve settings. Reasons for inaccurate configurations are diverse: First, numerous parameters such as radiator type and size, room size, house insulation, window sizes, etc. need to be known before the calculations. When lacking such information, e.g., the type of wall insulation, assumptions have to be made, which can lead to errors. Second, based on many collected parameters, complex calculations are involved to prove whether a heating curve would deliver sufficient heat. These calculations are performed iteratively for different supply temperatures and must be repeated if parameters such as occupancy change, making the process labor-intensive [28]. Third, after the calculations, the installers tend to set the heating curve higher than necessary to avoid post-installation adjustments, additional visits, and service calls [11]. This is despite the fact that guidelines suggest setting the heating curve 3–5 degrees lower than calculated and letting the informed user adjust the heating curve when feeling cold [28].

These reasons lead to deviations between the configured heating curve parameters and those actually required to maintain the room comfort temperature for optimal HP efficiency. Several researchers have shown that post-installation optimization of HP parameters, especially those related to the heating curve, offers significant energy savings potential [11,24]. Still, informed post-installation heating curve adjustments by an energy consultant are often not considered worth the effort,

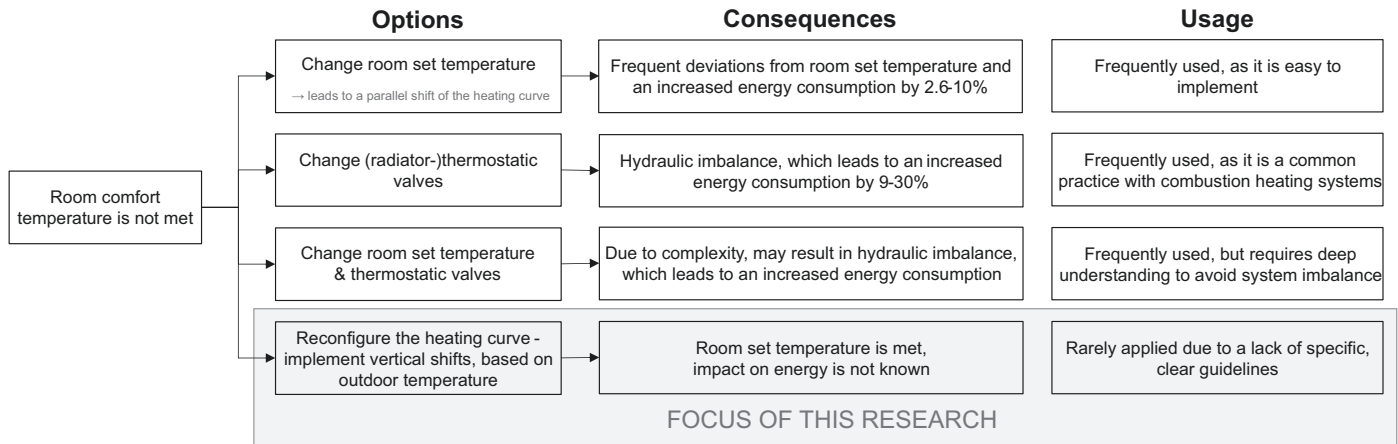


Fig. 1. Overview of available adjustments to maintain comfortable room temperature when deviations occur due to a suboptimal heating curve configuration, highlighting the focus of this study.

as they are labor-intensive due to the need for a full set of heating system context data and on-site presence [11].

Residents can thus choose from four options to address heating curve related issues when experiencing discomfort, as shown in Fig. 1. First, residents can adjust the set room temperature on the room controller, causing a parallel shift in the heating curve [29]; however, this only changes the intercept, not the slope of the heating curve, resulting in subsequent room temperature deviations that would often require further adjustments.

Second, residents typically adjust thermostatic radiator valves to maintain comfort, as they did with conventional combustion systems. However, this reactive approach provides only short-term relief and often reduces the overall efficiency of the HP due to hydraulic imbalance [8,13].

The third option, is to adjust both the heating curve parameters and the radiator valves simultaneously. This method requires a good understanding of the home's hydraulics and is usually attempted after the previously defined strategies have failed. However, if done incorrectly, it can further imbalance and reduce the efficiency of the system [8,13].

The fourth option, recommended in heating system manuals but rarely used in practice, suggests changing the starting- or endpoints of the heating curve, depending on the outdoor temperature at which a resident feels discomfort [29,30]. In this case the slope of the heating curve is changed. However, this approach is rarely applied because existing guidelines lack precision in terms of low and high outdoor temperatures, as well as the size of the adjustments needed, as the concrete values would vary depending on the heating system, climate zone, and specific heating curve parameters.

The first three options discussed are common among users but tend to be inefficient for HPs, failing to address the initial misconfiguration of the heating curve and leading to repeated adjustments throughout the heating season. Consequently, this research aims to establish clear outdoor temperature thresholds for the fourth option, promoting its broader application in the heating industry while using user inputs on the room controller as direct feedback, similarly as proposed by Jayathissa et al. [31], where authors propose a methodology for collecting detailed longitudinal comfort feedback using a smartwatch platform.

The objective of this study is to develop guidelines that help make informed adjustments to the heating curve, ensuring thermal comfort while minimizing energy consumption. Specifically, we propose a method to derive precise outdoor temperature thresholds and corresponding adjustments, based on a large-scale observational field-study, to enhance the practicality of schematic heating curve modifications

currently presented in energy manuals [30,32]. These existing schematics suggest that adjustments at low outdoor temperatures should focus on the heating curve endpoint, while adjustments at warmer temperatures should target the starting point. However, existing schematics for heating curve adjustments lack concrete values for outdoor temperatures and needed shifts. While our proposed method for deriving the guidelines is widely applicable, the estimated guidelines are specifically valid for air-to-water HPs located in Central Europe, as the estimations are based on our specific dataset.

2. Background and research questions

Before introducing the specific research questions, this section provides an overview of the concept of a heating curve and reviews the methods available in the literature for determining their optimal settings.

2.1. Conventional heating curve

The heating curve captures the relationship between supply and outdoor temperature (Fig. 2a), aiming to compensate for weather variances and maintain consistent indoor warmth. The heating curve is most commonly operationalized as a linear function [30]. A linear heating curve is then defined either by its slope and intercept or by specifying two points at different outdoor temperatures. Common practice involves defining the supply temperatures at the starting and endpoints of the curve (Fig. 2a). Heating manuals typically set these points at an outdoor temperature of 20 °C (referred to as the foot-point or heating limit) and -20 °C as the endpoint [30]. Even though HPs often operate in a narrower range of supply temperatures than conventional heating systems and are usually turned off at outdoor temperatures above 15 °C, a conventional heating curve diagram is still used in practice when configuring a heating curve for HPs. We follow this convention in our study.

As the heating curves also need to be set for conventional heating systems [33], deterministic guidelines were investigated by many researchers [23]. The heating curve parameters are calculated based on assumptions during the design phase of the HP, which includes context-specific parameters such as house heating load, heat distributors (radiators or floor heating) and their capacity [34]. Due to multiple parameters and complex calculations, estimations of the heating curve parameters in practice are often based on installers' experience or rough estimations [35]. These reasons make it difficult to verify the settings,

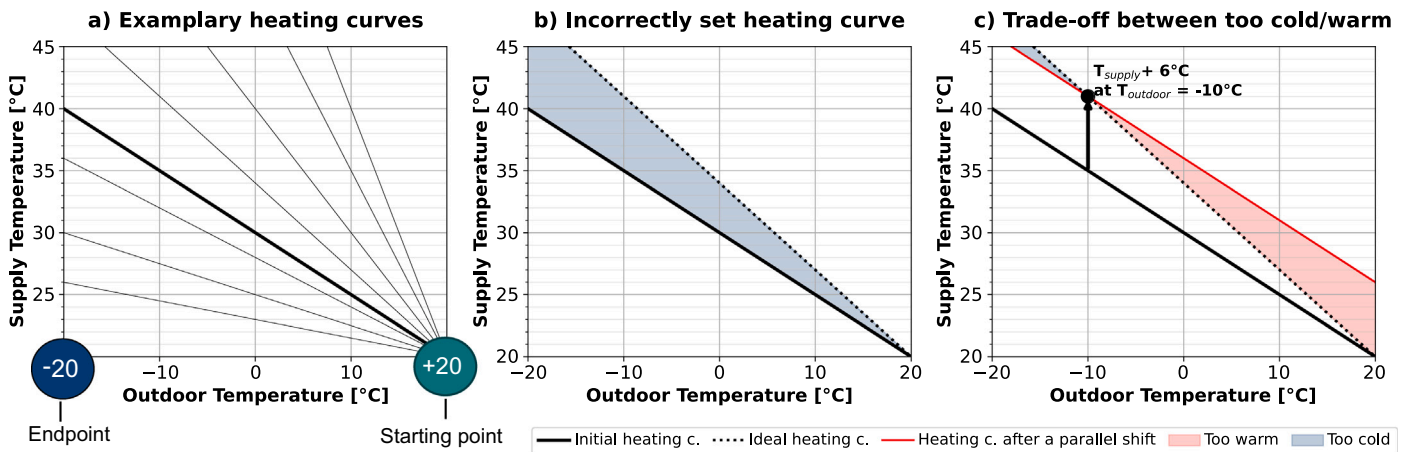


Fig. 2. Starting and endpoints of the heating curve and resulting trade-off, when a non-ideal heating curve is set during the configuration of the HP.

not only for the homeowners, but also for an installer, if the inspection is done remotely.

Methods to ensure that room temperatures are automatically maintained after configuring the conventional heating curve often require additional temperature sensors and thermostats [36,37]. If the room temperature deviates, these devices trigger adjustments by either shifting the heating curve in parallel or modifying the supply water flow rate on the thermostats [37]. However, these methods do not modify the slope of the heating curve and may be inefficient [8,13]. Additionally, room temperature measurements can be inaccurate due to sensor placement, room dynamics (e.g., open windows), and decreasing sensor performance over time. Moreover, separate heating circuits are required for each space, which increases costs of the heating system even further and adds complexity to the system's control.

2.2. Concept of the ideal heating curve

An ideal heating curve ensures that supply water is heated to the optimal temperature to meet heating demands across varying outdoor temperatures. When the configured heating curve is not equivalent to the ideal one, deviations between expected and actual supply temperatures result in unmet room temperatures. Fig. 2b illustrates heating curves, where the supply temperature is ideally aligned only at $T_{outdoor} = 20$ °C. In response to unmet room thermal comfort, users often make adjustments. To mitigate discomfort, modern HP systems allow users to modify room temperatures via controllers or apps, resulting in a parallel shift of the heating curve [29]. An example of this adjustment and the resulting persistent trade-off between periods of overheating and insufficient heating caused by deviations from the ideal heating curve is shown in Fig. 2c. As people are generally more sensitive to feeling too cold than too warm [38], users often set heating curves too high, leading to significantly higher energy consumption compared to actual heating needs [11].

Choosing settings close to the ideal heating curve not only increases user comfort and satisfaction [34] but also improves energy efficiency for several reasons: (1) It prevents users from making adjustments at thermostatic valves, which can be inefficient and cause imbalances within the heating system [8,13]; (2) A reliably functioning heating system increases users' willingness to participate in energy-saving programs, such as temperature setbacks, or cost-saving programs, such as flexible electricity tariffs [26,39]; (3) Since humans are generally insensitive to small temperature variations within the comfort range [38], maintaining stable heat delivery enables the supply temperature to be set closer to the lower boundary of the comfort range, reducing overall energy consumption [39].

2.3. Identification and correction of a non-optimal heating curve

There are several methods on how to identify suboptimal heating curves: by using room temperature sensors [35], by calculating energy consumption deviations from the theoretical building energy signature [13], by tracking user changes to thermostatic valves or to the room set temperature [40] or by directly collecting user feedback [31,41]. In this study, we use adjustments to the room set temperature made by users on their home controllers or via an app as an indicator for identifying days when the desired room temperature is not achieved. This method helps detect a suboptimal heating curve without requiring additional sensors or complex calculations. The room temperature adjustment is then multiplied by the translation factor, set by a technician, which is usually in the range of one to five to translate the set room temperature change to the shift of the heating curve [32].

If the initially set heating curve is non-optimal, several fine-tuning strategies can be employed to adjust it, bringing it closer to the ideal configuration:

- I. Parallel shift of a heating curve;
- II. Heating curve slope and intercept adjustments;
- III. Retrospective adjustments.

The first strategy, a parallel shift of the heating curve, is a standard approach implemented in many room controllers or thermostats [29,32]. The second strategy, which is the focus of this study, involves optimizing the heating curve parameters based on outdoor temperature. Specifically, this approach suggests adjusting the endpoint for discomfort during cold periods and the starting point for discomfort during warmer conditions. The third strategy, adjusting the heating curve based on observed user interventions on the room thermostat after a heating period, is proposed and analyzed in this study as an alternative approach that can also be implemented remotely.

2.4. Schematics of heating curve adjustments

According to energy advisor manuals [30,34], there are three different ways how a heating curve can be adjusted, as illustrated in Fig. 3. A parallel shift (Fig. 3a) is a default strategy, which is applied by the user when feeling too cold or too warm, independent of the outdoor temperature [34]. Vertical shifts at the starting point (Fig. 3b) and vertical shifts at the endpoint (Fig. 3c) are usually conducted by energy experts, installers, or similar professionals, directly on the configuration of the HP, as these parameter changes are more complex and usually have a higher impact on HP operation. Even though these schematic changes are documented in the manuals, there are no specific indicators of when

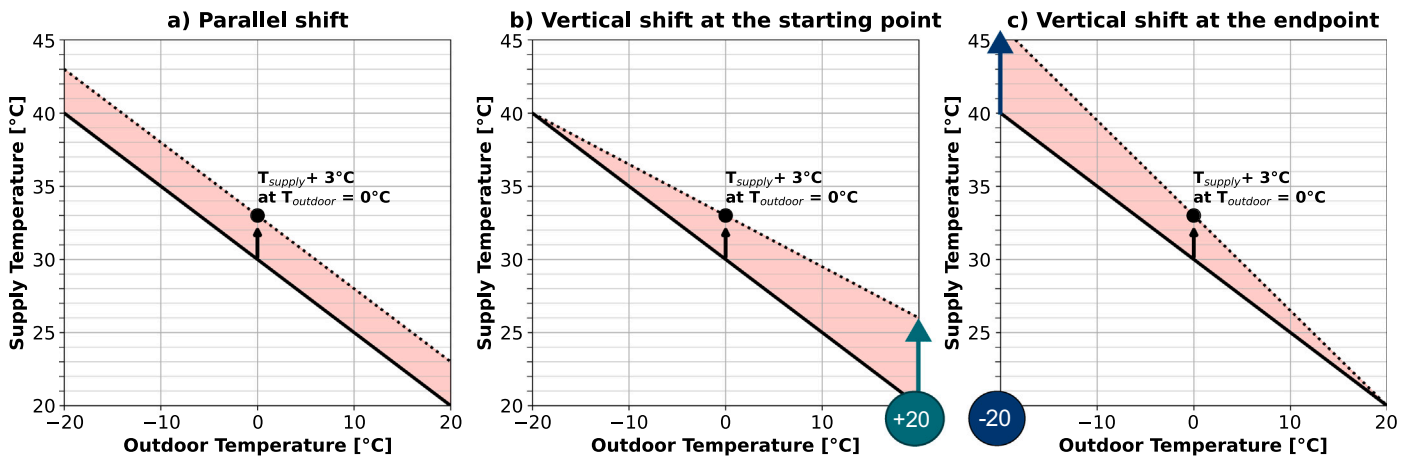


Fig. 3. Schematics of three different heating curve shifts, which all achieve the same desired T_{supply} at $T_{outdoor} = 0^{\circ}\text{C}$.

to use each strategy, making their application rare. This study investigates all three schematic changes of the heating curve and based on most frequent observations defines the outdoor temperatures when and how each of the changes should be used, thereby promoting more widespread and informed use of the existing schematic heating curve optimization guidelines.

2.5. Multiparameter heating curve

To improve thermal comfort and achieve accurate room temperature control in heated spaces, existing research can be divided into two main streams. The first involves incorporating additional parameters, beyond outdoor temperature, to determine the supply temperature. The second approach uses feedback from additional sensors, primarily room temperature measurements, to automatically adjust the heating curve.

Several studies have explored the use of multi-parameter heating curves, recognizing that indoor comfort is influenced by more than just outdoor temperature. These studies aim to better adjust supply temperatures to specific contexts, thereby enhancing the performance of HPs. Potočnik et al. [35] have proposed an off-line optimization method of airwater heat pumps (AWHPs) in residential buildings. The aim of the proposed method was to optimize indoor thermal comfort through an extension of standard outdoor temperature controlled heating curves by considering additional effects, with solar radiation having the strongest effect. Based on simulations, Huchtemann and Müller [23,42] have proposed an algorithm to control supply temperatures based on the heating demand of the rooms, which they indicate based on thermostatic valve positions. Applying their algorithm, savings in annual primary energy demand compared to a standard controlling algorithm are up to 6.8%. This research advances our understanding of heating curves' sensitivity to various temperatures and environmental factors. However, the control of HPs and the temperature sensors are already the most frequent sources of HP faults, and adding parameters such as solar radiation, humidity, room temperature, or valve positions could further exacerbate this issue by increasing system complexity [43,44]. Furthermore, these methods are not applicable to existing HPs that lack the necessary sensors, making widespread implementation challenging.

2.6. Self-optimizing heating curves

Another approach to configure a heating curve, which has not yet been widely adopted in practice, is based on an experimental phase after HP installation, where settings are not configured by an installer but instead are adapted automatically using signals of additional sensor at various positions across the heat distribution system [15,35]. A method for the adaptive parametrization of the heating curve for AWHPs, based

on room temperature sensors, is proposed by Potočnik and Govekar [45]. This approach adjusts the parameters of a standard heating curve with two reference points by minimizing the difference between the set and actual indoor temperatures. It employs a weighting function and recalculates the heating curve on an hourly basis, demonstrating that the heating curve converges to optimal settings within 1 month. A similar lightweight model was proposed by Sun et al. [46], where the parameters were adapted hourly and the algorithm was tested for 7 days in the field. The control strategy reduced the mean supply water temperature by 3.7 °C. A similar approach, incorporating additional parameters such as solar radiation, building heating load, and water flow rate, was proposed by Sun et al. [47]. This method requires 72 hours to parameterize the heating curve, resulting in supply temperatures that are 8.4 °C lower compared to those of a static heating curve.

As the indoor temperature is not only affected by the outdoor temperature, but also by the nonlinear influence of indoor and outdoor multi-parameters [48,49], several researchers have implemented machine learning models for heating curve parametrization, to capture non-linearities. For instance, Sun et al. [50] developed a Modelica-based simulation model for an air-source HP cooling system, using a proportional-integral-derivative control and then developed an optimal water temperature prediction model by using a general regression neural network under varying conditions. Lindelöf et al. [51] created an artificial neural network model to predict indoor temperature changes and adjust water temperature settings accordingly, balancing energy consumption and temperature deviations. Similarly, Hee Kang et al. [52] used a neural network model to optimize water temperature settings for minimal system consumption in an office building's cooling system. Zhang et al. [53] focused on optimizing energy consumption and thermal comfort using reinforcement learning in an EnergyPlus-based model. Brandt et al. [54] applied deep Q-learning to enhance control strategies for water temperatures in air conditioning systems, improving adaptability to different occupancy schedules and temperature needs.

In summary, the research on optimizing the heating curve for HPs can be divided into two streams: setting fixed heating curve parameters that rely on calculations with extensive contextual factors, and automatically estimating heating curve parameters based on additional sensor measurements. In both cases, key challenges hinder practical implementation of discussed research: (1) manual collection of contextual information during installation is labor-intensive and error-prone, leading to increased workload for installers. Given the current shortage of qualified installers, this approach is not a viable option; (2) automatic parametrization methods depend on additional sensors that are often absent in existing systems, and even if installed, it would require advanced controllers for HPs, which are difficult to retrofit; (3) heating

systems usually have a long operational lifespan, and in order to robustly maintain the equipment on a large scale, reduced complexity models are preferred in practice, even for new generation HPs.

2.7. Research questions and study contributions

Given the need to enhance HP efficiency with minimal effort and the absence of existing methods in the literature for heating curve optimization without additional measurement equipment, this study aims to develop a method to identify specific outdoor temperature thresholds where adjusting the heating curve's endpoints and starting points outperforms the standard parallel shift. These adjustments are designed to fine-tune heating curves to residents' needs, ensuring a more efficient delivery of the right amount of heat. In this article, we refer to our enhanced heating curve adjustment schematics, which incorporate specific outdoor temperature ranges and necessary shifts, as the outdoor temperature-dependent (OTD) guidelines. To derive and validate these guidelines, we address the following research questions:

RQ1: Derive guidelines

At which outdoor temperatures should adjusting the starting or endpoint of the heating curve vertically be preferred over a standard parallel shift, in order to minimize yearly energy consumption?

RQ2: Assess guidelines

How does providing users with more targeted guidance for adjusting the heating curve impact the heating curve's quality, and what are the resulting benefits for comfort, yearly energy consumption, and seasonal coefficient of performance (SCOP)?

RQ3: Customize guidelines

How can the required vertical shift at the starting or endpoint of the heating curve be calculated for differently configured HPs, based on outdoor temperature and the desired change in room set temperature?

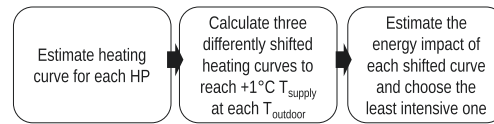
To address these questions, we base our research on operational data of 3995 domestic AHP based in Central Europe. We empirically estimate multivariate linear models for the heating curve, energy consumption and the COP for each HP. We then estimate the impact of heating curve shifts on yearly energy consumption. We observe a pattern where, at certain outdoor temperatures, adjusting the starting or endpoint of the heating curve is systematically more energy efficient than applying a standard parallel shift. This allows us to define specific outdoor temperature ranges for each type of shift. Furthermore, we test whether the continuous application of our proposed outdoor temperature-dependent shifts, instead of a standard parallel shift, improves the quality of the configured heating curve at the end of the heating season.

Our research helps homeowners, technicians, and energy advisors with guidance for informed decision making while adjusting the settings of the heating curve, aiming for precision in HP operation without sacrificing comfort. In addition, we address the lack of clear guidelines in the current literature for applying these strategies by offering individualized feedback on potential energy savings and the specific effects of incremental adjustments to the heating curve. This approach, requiring no contextual information or measurement sensors, promises direct applicability in real-world settings, striving for transparency to motivate homeowners toward energy-efficient practices.

3. Research approach and data

The research approach in this study consists of two main parts, as illustrated in Fig. 4. The first part focuses on establishing OTD guidelines for heating curve adjustments, identifying which changes are less energy-intensive at specific outdoor temperatures. The second part involves assessing the impact of the proposed guidelines. Algorithms for both approaches – to derive and assess the guidelines are also presented as pseudo code in the Appendix A (Algorithms 1 and 2). Both parts

Method to derive outdoor temperature-dependent guidelines



Method to assess the impact of derived outdoor temperature-dependent guidelines

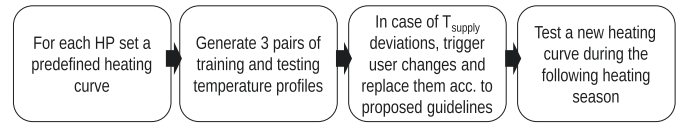


Fig. 4. Overview of the methods used to determine and assess the impact of proposed outdoor-temperature-dependent (OTD) guidelines.

are described in detail in the following sections together with the results. Additionally, in Section 6, we provide the necessary calculations to apply our proposed guidelines for heat pumps that require custom parametrization, different from those used in this study. In the remainder of this section, we describe the data that form the basis of this study.

We use a sample of 3995 domestic AHPs, with thermal power of 3–17 kW, monitored between 2022-10-01 and 2024-04-01 (i.e., for up to 548 days). These HPs operate in residential buildings within 10 Central European nations, predominantly in Germany, which hosts 2551 (63.9 %) of the heat pumps. Other countries are: Austria 468 (11.72 %), Netherlands 410 (10.27 %), Czech Republic 266 (6.66 %), Denmark 89 (2.23 %), Poland 84 (2.1 %) and Sweden 59 (1.48 %), as well as Italy, Spain, Slovenia, Luxembourg and Great-Britain with <1 % of the units. The available variables for the data are listed in Table 1, together with descriptive statistics. All variables are provided on a daily basis.

The average yearly energy consumption for heat pumps with at least 350 days of data per year ($n_{HPs} = 536$) is 6463.7 kWh, with a median of 5149.5 kWh and a standard deviation of 4424 kWh. Comparable values have been reported by other studies for single-family houses: 4993 kWh ($n_{HPs} = 38$) by [55] and 6560 ± 4266.3 kWh ($n_{HPs} = 53$) by [56]. The data analyzed comes from a single manufacturer and includes a wide variety of HP models, buildings, and setups. Each HP is connected to the internet and records several parameters, updating every few seconds. To increase applicability of the proposed guidelines and reduce the complexity of calculations, we use daily aggregates of the measurements: daily averages for supply, outdoor and room set temperatures, and daily sums for electrical energy consumption (which includes the usage of the electric heater and compressor) and thermal energy production. The COP is calculated by dividing the thermal energy output by the electrical energy input.

The calculation of energy input and output relies on internal operational sensors that measure physical parameters such as pressure, volume flow, and power, rather than direct energy metering. This computational approach is widely implemented in contemporary HP systems [6]. The performance indicators presented in this study include the total energy consumption of the compressor, the fan or brine pump, and the electrical auxiliary heater. This methodology aligns with the European standard EN 14825 [57] and follows the H3 system boundary classification as described in [58]. We focus on heating data, including operations such as defrosting, and exclude any operations related to domestic hot water preparations.

Not all heat pumps had the required measurements recorded. Thus, we reduced the sample to only include those heat pumps with complete data on energy consumption, energy output, outdoor temperature, room set temperature, and supply temperature, resulting in a reduced sample size n_{HPs} . The metrics of the data before and after filtering are summarized in Table 1. The reduction of the available days per heat pump results from two factors. First, as we focus on space heating, data

Table 1
Overview of the heat pump data used in this study, with measurements aggregated to daily values.

	n_{HPs} with records	Availability [days/HP]			Measurement	Daily values			Cumulative values per HP		
		Mean	Median	Std		Mean	Median	Std	Mean	Median	Std
Before filtering	4447	186.74	123.0	164.87	Energy consumption [kWh]	14.91	10.00	19.36	2784.51	1943.00	3016.36
	4449	186.81	123.0	164.93	Energy output [kWh]	48.66	38.00	112.72	9089.81	6648.00	8940.17
	4441	159.47	119.0	131.18	COP [-]	3.55	3.57	1.57	3.64	3.43	2.79
	4449	187.68	124.0	164.81	Outdoor temperature [°C]	9.69	8.98	6.77	n/A	n/A	n/A
	4409	186.51	123.0	164.75	Room set temperature [°C]	20.09	21.0	4.52	n/A	n/A	n/A
	4033	148.58	117.0	122.19	Supply temperature [°C]	37.71	36.7	7.61	n/A	n/A	n/A
After filtering	3995	51.62	46.0	35.13	Energy consumption [kWh]	20.16	15.00	17.04	1040.48	665.00	1168.22
	3995	51.62	46.0	35.13	Energy output [kWh]	65.86	57.00	41.98	3399.64	2366.00	3405.40
	3995	51.62	46.0	35.13	COP [-]	3.72	3.55	1.09	3.63	3.48	0.95
	3995	51.62	46.0	35.13	Outdoor temperature [°C]	6.79	7.42	4.14	n/A	n/A	n/A
	3995	51.62	46.0	35.13	Room set temperature [°C]	21.11	21.00	2.32	n/A	n/A	n/A
	3995	51.62	46.0	35.13	Supply temperature [°C]	38.33	37.63	6.65	n/A	n/A	n/A

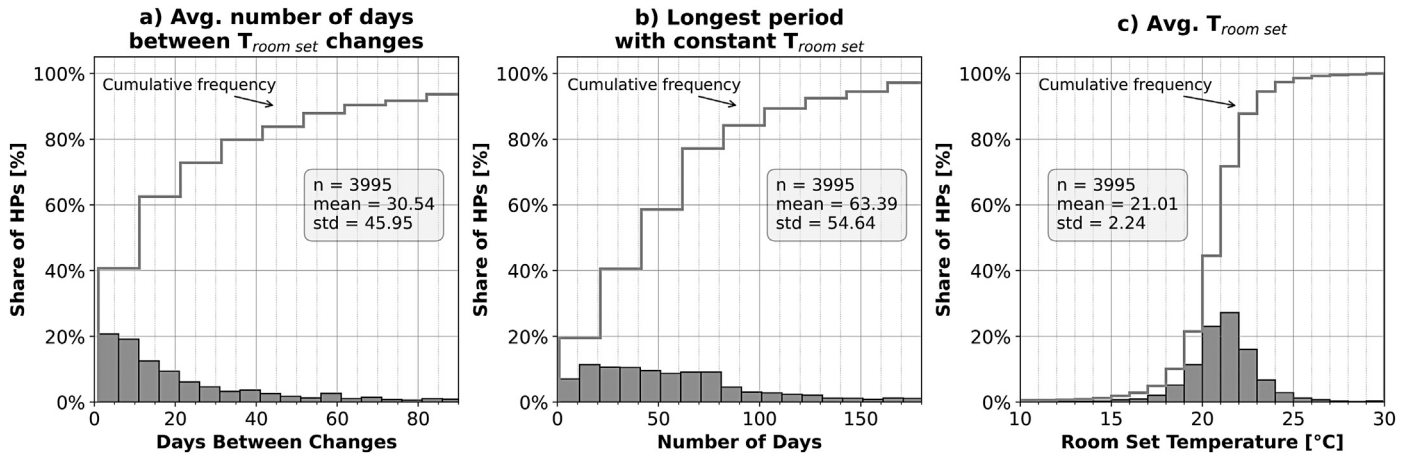


Fig. 5. Observed frequency of changes to room set temperatures and their mean absolute values.

with outdoor temperatures exceeding 20 °C were excluded, as no space heating activities are expected above this threshold. Second, to ensure an accurate estimation of the heating curves, we selected the longest observation period for each system where the average daily room set temperature remained constant. This approach avoids confounding effects from room set temperature adjustments, which directly influence the heating curve, and ensures stability in the data used for analysis.

Fig. 5 characterizes the room set temperature changes made by users and is presented as a histogram with an additional cumulative frequency line. Fig. 5a shows that, on average, occupants change their room set temperature every 30 days, which leads to approximately 5 changes per heating season on average. Fig. 5b reports the longest period the room set temperature is constant, which is 63.39 days on average. In Fig. 5c, the average room set temperature per HP is reported, which is normally distributed around 21 °C. In summary, this means that actively adjusting the room set temperature is a common activity for the observed HPs and also indicates the presence of non-optimally set heating curves in practice.

4. Deriving outdoor temperature-dependent guidelines

4.1. Estimating heat pump specific heating curves

Based on the daily average supply and outdoor temperatures, we estimated the heating curve for each HP individually using Eq. (1).

$$\mathbf{T}_{S, hp} = \begin{bmatrix} 1 & \mathbf{T}_{O, hp} \end{bmatrix} \begin{bmatrix} \beta_{1, hp} \\ \beta_{2, hp} \end{bmatrix} + \epsilon \quad (1)$$

In this equation, $\beta_{1, hp}$ and $\beta_{2, hp}$ represent the heat pump-specific intercept and slope of the heating curve, respectively, with each heat pump identified by its unique ID ($hp = 1; 2; \dots; 3995$). $\mathbf{T}_{O, hp}$ and $\mathbf{T}_{S, hp}$ are vectors of available daily outdoor and supply temperatures for each heat pump hp .

Since some outdoor temperatures occur more frequently and could be overly weighted in a simple linear regression, we used a Gaussian kernel density estimate from `scipy.stats` to weight the outdoor temperature points, and then performed the weighted linear regression using the `statsmodels` package in Python.

4.2. Estimating alternative heating curve changes

Three alternative heating curve adjustments are analyzed, all achieving the same supply temperature at a specified outdoor temperature: a standard parallel shift, a vertical shift at the starting point, and a vertical shift at the endpoint of the curve. The goal is to determine the conditions under which each adjustment is most suitable.

For a parallel shift of the heating curve, we solve Eq. (2) individually for each HP. To derive outdoor temperature-dependent guidelines, we use $shift = 1$ °C, as it can be scaled up if needed, since all models used in this study (heating curve, COP, and energy) are linear. The mathematical reasoning behind the linearity of the heating curve with respect to the shift is discussed in Section 6.2. In Eq. (2) $\beta_{1, PL, hp}$ stands for the new intercept and $\beta_{2, PL, hp}$ is the new slope of the heating curve after the parallel shift (PL), calculated for each heat pump separately. $T_{O, CH}$ is the outdoor temperature, at which the change of the heating curve is taking place, with the values $T_{O, CH} = -20$ °, -19 °C, ..., 20 °C.

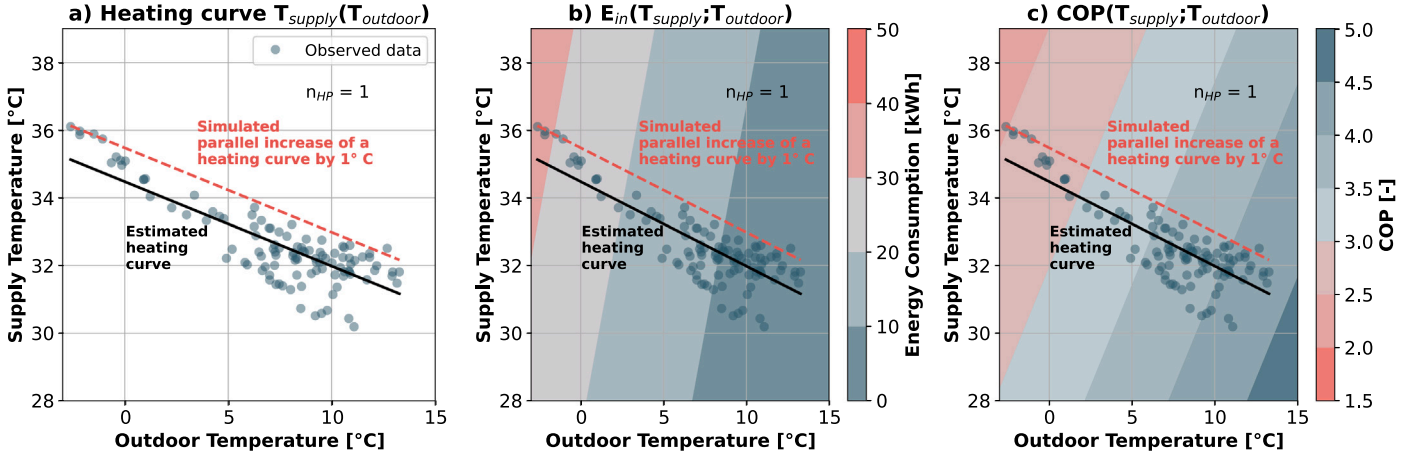


Fig. 6. Example visualization of the heating curve, COP, and energy consumption models fitted in this study, along with the impact of heating curve adjustments on COP and energy consumption.

$$\begin{bmatrix} 1 & T_{O,CH} \end{bmatrix} \begin{bmatrix} \beta_{1,hp} \\ \beta_{2,hp} \end{bmatrix} + \text{shift} = \begin{bmatrix} 1 & T_{O,CH} \end{bmatrix} \begin{bmatrix} \beta_{1,PL,hp} \\ \beta_{2,PL,hp} \end{bmatrix} \quad (2)$$

To identify alternative heating curves that achieve the same supply temperatures at a given $T_{O,CH}$ after the *shift*, Equation System (3) (for shifts at the starting point (SP)) and Equation System (4) (for shifts at the endpoint (EP)) are solved for each $T_{O,CH}$ and *shift* combination.

For the vertical shift at the starting point, Equation System (3) is solved, where $\beta_{1,SP,hp}$ and $\beta_{2,SP,hp}$ are the new intercept and slope parameters of the heating curve of the heat pump hp and $shift_{SP,hp}$ is the needed vertical shift at $T_{O,SP} = 20^\circ\text{C}$.

$$\begin{bmatrix} 1 & -20 \\ 1 & T_{O,CH} \\ 1 & 20 \end{bmatrix} \begin{bmatrix} \beta_{1,hp} \\ \beta_{2,hp} \end{bmatrix} + \begin{bmatrix} 0 \\ \text{shift} \\ \text{shift}_{SP,hp} \end{bmatrix} = \begin{bmatrix} 1 & -20 \\ 1 & T_{O,CH} \\ 1 & 20 \end{bmatrix} \begin{bmatrix} \beta_{1,SP,hp} \\ \beta_{2,SP,hp} \end{bmatrix} \quad (3)$$

For the vertical shift at the endpoint, Equation System (4) is solved, where $\beta_{1,EP,hp}$ and $\beta_{2,EP,hp}$ are the new intercept and slope parameters of the heating curve and $shift_{EP,hp}$ is the needed vertical shift at $T_{O,EP} = -20^\circ\text{C}$.

$$\begin{bmatrix} 1 & -20 \\ 1 & T_{O,CH} \\ 1 & 20 \end{bmatrix} \begin{bmatrix} \beta_{1,hp} \\ \beta_{2,hp} \end{bmatrix} + \begin{bmatrix} \text{shift}_{EP,hp} \\ \text{shift} \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & -20 \\ 1 & T_{O,CH} \\ 1 & 20 \end{bmatrix} \begin{bmatrix} \beta_{1,EP,hp} \\ \beta_{2,EP,hp} \end{bmatrix} \quad (4)$$

All equation systems presented in this section are solved using the Python solver from the SymPy library. By calculating new heating curve parameters, we can compare different heating curve shifts that achieve the same supply temperature at specified outdoor temperatures. In the following, we assess the impact of each heating curve shift on annual energy consumption at various outdoor temperatures to determine which heating curve shift is the least energy intensive.

4.3. Impact of the heating curve on the heat pump performance and energy consumption

To assess the impact of different heating curve shifts on energy consumption and COP, we estimate two multivariate linear models for energy and COP on all data with global parameters (i.e., the same for all HPs) and local parameters (i.e., specific to each HP), as proposed by Brudermueller et al. [25]. For improved interpretability, this study simplifies the model further by constraining the heat pump-specific parameters to a single intercept. Heat pump specific energy consumption $Energy_{hp}$ is modeled according to Eq. (5), where $\alpha_1, \alpha_2, \alpha_3$ are global parameters for intercept and slopes and v_{hp} is a HP specific intercept. T_O

and T_S are vectors of seen outdoor and supply temperatures across all heat pumps.

$$Energy_{hp} = \begin{bmatrix} 1 & T_S & T_O \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} + v_{hp} + \epsilon \quad (5)$$

Heat pump specific COP_p is modeled following the same logic as with Eq. (6), where $\gamma_1, \gamma_2, \gamma_3$ are global parameters for intercept and slopes, and u_{hp} a HP specific intercept.

$$COP_{hp} = \begin{bmatrix} 1 & T_S & T_O \end{bmatrix} \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \end{bmatrix} + u_{hp} + \epsilon \quad (6)$$

Energy consumption and COP models are estimated using the mixedlm function from the statsmodels.formula.api module in Python. Fig. 6 illustrates the course of all three fitted models used in this study. It also shows how HP-specific effects of heating curve shifts on COP and energy consumption can be calculated with these models. By using global parameters as the intercept and slopes for T_O and T_S , and considering only the random intercept for local parameters, the fitted models demonstrate an interpretable pattern similar to Carnot efficiency.

Yearly energy consumption and SCOP

To use available heat pump operational data objectively, we calculate the yearly energy consumption and SCOP according to EN 14825 [57]. These calculations are performed separately for each HP and for all derived heating curves, using Eqs. (2), (3), and (4). To derive the outdoor temperature-dependent guidelines, only the yearly energy consumption estimation is required. However, we also calculate the SCOP, as it is a key performance metric for heat pumps, and understanding the impact of heating curve changes on this metric is of interest. Since the population studied is mainly located in Central Europe, average climate is assumed. Thus, the yearly energy consumption is calculated using Eq. (7), where j is outdoor temperature and h_j is its corresponding frequency per year in hours in average climate, $E_{in,j}$ is the average energy consumption at the outdoor temperature j . The weights (h_j) come from the temperature provided in the norm (see Table A.2 of EN 14825 [57]).

$$Yearly\ Consumption_{hp} = \frac{\sum(h_j \cdot Energy_{hp,j})}{24} \quad (7)$$

considering EN 14825, the heating limit in average climate is 15°C , and days with an average daily temperature of -11°C or below are unlikely

Table 2
Estimated model parameters to simulate heating curve, COP and energy consumption.

Model	Parameter	Coefficient	Std. error	z	P > z	[0.25 0.975]
Heating curve	Intercept	-0.332	0.470	-	-	-
	Outdoor temperature	40.550	8.515	-	-	-
COP	Intercept	2.553	0.007	361.549	0.000	[2.539 2.567]
	Outdoor temperature	0.026	0.000	294.060	0.000	[0.025 0.026]
	Supply temperature	-0.021	0.000	-134.519	0.000	[-0.022 -0.021]
	Group. var.	0.000	0.190	-	-	-
Energy	Intercept	2.549	0.038	66.983	0.000	[2.474 2.624]
	Outdoor temperature	-0.205	0.000	-443.928	0.000	[-0.206 -0.204]
	Supply temperature	0.077	0.001	90.918	0.000	[0.075 0.079]
	Group. var.	0.000	1.050	-	-	-

Table 3
Mean and standard deviation metrics for models of this study. The numbers provided in the columns related to P-values refer to the percentage of heat pumps falling under each category.

Sample	Model type	R ² score	RMSE	MAE	MAPE	MdAPE	P < 0.1, P < 0.05, P < 0.01
Train	Heating curve	0.4 (0.85)	0.99 (0.83)	0.76 (0.63)	2.0 (1.59)	1.63 (1.43)	82.13 %, 78.86 %, 72.51 %
	COP	0.42 (0.64)	0.4 (0.46)	0.31 (0.35)	7.71 (7.76)	6.15 (5.07)	81.58 %, 78.81 %, 72.99 %
	Energy consumption	0.46 (0.95)	4.41 (4.11)	2.94 (2.67)	22.72 (18.5)	13.92 (8.96)	90.2 %, 88.49 %, 83.67 %
	Heating curve and COP	0.38 (0.74)	0.41 (0.45)	0.32 (0.35)	7.98 (7.74)	6.4 (5.18)	81.27 %, 78.15 %, 72.0 %
	Heating curve and energy cons.	0.46 (0.85)	4.5 (4.17)	3.0 (2.72)	22.97 (17.88)	14.1 (8.9)	90.18 %, 88.41 %, 83.52 %
Test	Heating curve	-0.32 (3.54)	1.03 (0.94)	0.83 (0.75)	2.19 (1.92)	1.87 (1.73)	61.22 %, 53.87 %, 41.57 %
	COP	0.04 (1.84)	0.4 (0.53)	0.33 (0.45)	8.01 (7.7)	6.74 (6.76)	54.6 %, 48.9 %, 38.9 %
	Energy consumption	0.2 (1.85)	4.25 (4.33)	3.06 (2.89)	22.71 (24.45)	15.19 (11.84)	63.72 %, 57.8 %, 46.18 %
	Heating curve and COP	-0.05 (2.04)	0.42 (0.53)	0.34 (0.45)	8.31 (7.59)	7.07 (6.99)	53.47 %, 47.59 %, 37.52 %
	Heating curve and energy cons.	0.15 (2.0)	4.33 (4.36)	3.11 (2.85)	22.96 (24.27)	15.52 (12.12)	63.7 %, 57.62 %, 45.75 %

in this climate. As a result, weighting factors (h_j) for temperatures outside this range are zero. This means that the impact of the heating curve on energy consumption during these days is not considered.

According to EN 14825 standards [57] SCOP, is calculated similarly to the yearly energy consumption, given by a weighted average of sampled COP values at fixed outdoor temperatures $i = (-7, 2, 7, 12)$ in °C and with predefined weights $w = (24, 320, 326, 169)$ that represent the temperature distribution of average Central-European climate conditions:

$$SCOP_{hp} = \frac{\sum w_i \cdot COP_{hp,i}}{\sum w_i} \tag{8}$$

When deciding between three alternative heating curve shifts (parallel shift, vertical shift at the starting point, and vertical shift at the endpoint) for each HP at each outdoor temperature, the heating curve shift with the lowest yearly energy consumption is chosen. The outdoor temperature-dependent guidelines are derived for positive heating curve changes (increasing the supply temperature). For negative changes (lowering the heating curve), values in proposed guidelines are multiplied by a minus.

4.4. Resulting outdoor temperature-dependent guidelines

Outdoor temperature-dependent guidelines are based on the heating curves' impact on the annual energy consumption. To assess it, separate models for the heating curve, energy, and COP are estimated for each HP and resulting parameters are reported in Table 2.

Statistical metrics that are typically used to evaluate the fit of regressions are presented in Table 3, where the numbers represent the mean and the numbers in brackets represent standard deviations of the individual scores for each HP. The median absolute percentage error (MdAPE) for the combined COP model (heating curve and COP) is 6.51 ± 5.72 %, and for the combined energy model (heating curve and energy consumption) a value of 14.51 ± 13.27 %.

By employing these models, yearly metrics for each heat pump were calculated and their distributions are shown in Fig. 7. On average, HPs

are operating at rather low supply temperatures of 35.88 ± 7.33 °C, which would mean that the HPs are installed in rather renovated buildings, with modern heat distribution systems. SCOP is 3.61 ± 0.97 . In our data set, yearly energy consumption has a rather long tail distribution, with an average of 4755.5 ± 2642.79 kWh. Fig. 7f shows that systems with lower supply temperatures achieve higher SCOP values and thus have a lower yearly energy consumption, consistent with the physical principles of HPs.

The heating curve parameters of 3995 AWHPs are shown in Fig. 7d and e. These parameters are later used for testing the proposed OTD guidelines.

In order to find which one of the heating curve shifts (parallel shift, vertical shift at the starting point or vertical shift at the endpoint) is the least energy intensive at each outdoor temperature, for each heating curve, we calculate the impact of each shift on the yearly energy consumption. Results for each HP are displayed in Fig. 8a. It shows that a parallel shift of the heating curve by 1 °C results in an annual energy consumption increase of 153.59 ± 40.01 kWh, corresponding to a relative increase of 3.72 ± 1.09 %. Alternative heating curve shifts are nevertheless systematically less energy intensive, as shown in Fig. 8b and c. For outdoor temperatures below 2 °C, the vertical shift at the endpoint is preferable for all 3995 HPs. Similarly, for outdoor temperatures above 5 °C, the vertical shift at the starting point proves to be less energy-intensive for all HPs. Since within the range between 2 °C and 5 °C, the preferable shift depends on the heat pump, we decided that the standard parallel shift should be used in this range in order to derive generally applicable guidelines that are not HP specific to avoid system misconfiguration.

As an example, a parallel shift of 1 °C increases annual energy consumption by 3.72 ± 1.09 % on average. If a person experiences discomfort and wants to raise the supply temperature by 1 °C when the outdoor temperature is -10 °C, an alternative adjustment – such as the vertical shift at the endpoint by 1.3 °C – would result in a less intensive 1.87 ± 0.56 % increase in yearly energy consumption. The required shift of 1.3 °C is the same for all systems and is further elaborated in Section 6.

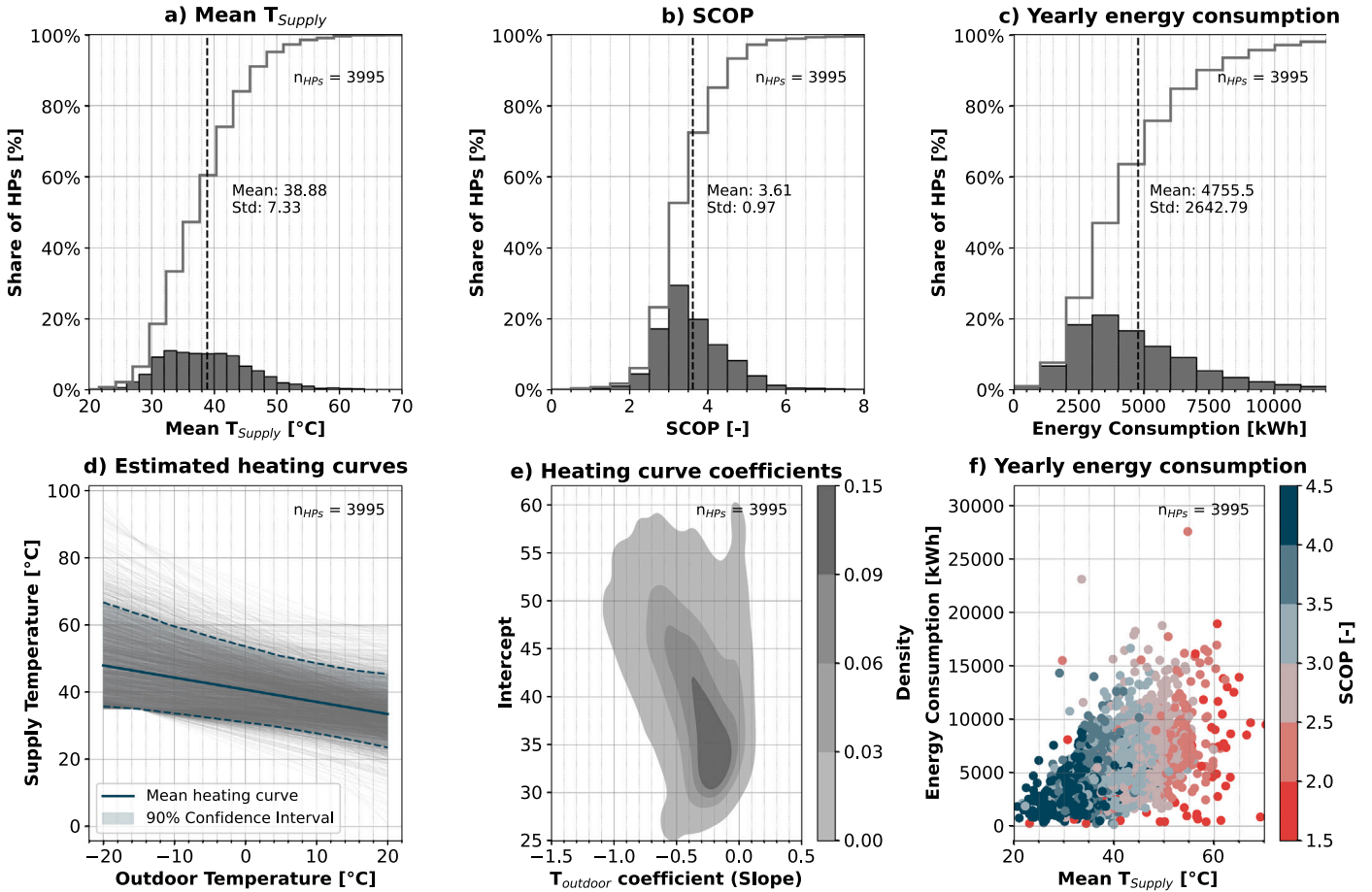


Fig. 7. Resulting distributions of yearly metrics and heating curve parameters.

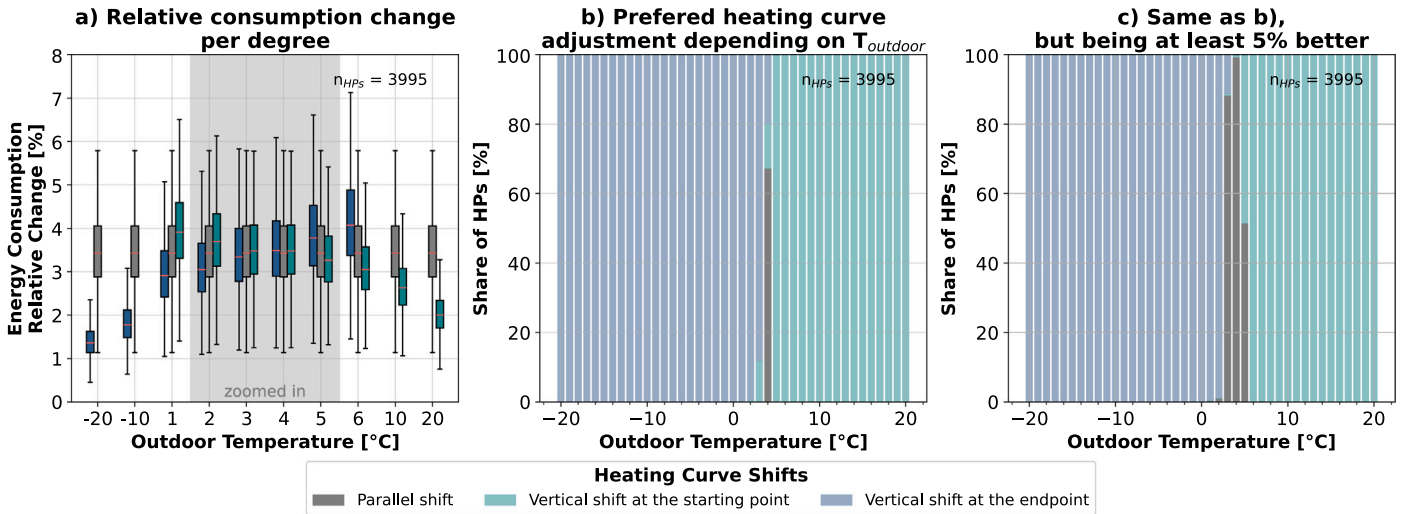


Fig. 8. Impact of different heating curve shifts on yearly energy consumption, dependent on the outdoor temperature when the shift of heating curve was undertaken.

In summary, the guidelines suggest using a vertical shift at the endpoint for outdoor temperatures below 2 °C, a vertical shift at the starting point for temperatures above 5 °C, and a standard parallel shift for temperatures between 2 °C and 5 °C. The required magnitudes of these vertical shifts are presented in Table A.1 and discussed further in Section 6.

5. Assessing the impact of the derived outdoor temperature-dependent guidelines

To improve the quality of a heating curve, the standard parallel shift can be replaced with adjustments based on derived outdoor temperature guidelines. In this section, we evaluate whether continuously applying

proposed temperature-dependent guidelines throughout a heating season enhances the heating curve with respect to user needs. This section begins by presenting metrics to evaluate fine-tuning strategies and heating curve quality, followed by a method to simulate continuous user adjustments when the room thermal comfort is not achieved. At the end, results and the impact of the fine-tuned heating curves are reported.

5.1. Metrics to evaluate the fine-tuning strategy and the quality of a heating curve

The evaluation of the fine-tuning strategy and heating curve quality relies on three key metrics. The first metric is the number of user inputs required during the fine-tuning period, which spans one heating season. A user input is triggered whenever the actual supply temperature deviates too much from the required supply temperature. The range of user comfort limits is presented in the following section. The second metric assesses the quality of the heating curve after the fine-tuning period. This is done by counting the number of days during an unseen heating period when the actual supply temperatures exceed predefined limits compared to the required supply temperatures. This metric captures the ability of the adjusted heating curve to maintain consistent performance under new conditions. The third metric is the maximum possible reduction of the heating curve that still ensures all days remain within the predefined thermal comfort range. Together, these metrics provide a comprehensive assessment of the effectiveness and efficiency of the proposed fine-tuning strategy and its impact on the heating curve's quality.

5.2. Method to simulate the usage of the fine-tuning guidelines

The evaluation procedure involves (1) simulating incorrectly set heating curves for each household, (2) applying continuous user adjustments throughout the heating season when the supply temperature limits are exceeded, and (3) simulation of three different heating curve adjustment strategies, where we aim to compare our proposal with a current standard.

Ideal and simulated initial heating curves for each household

The heating curves that we obtained with Eq. (1) using ordinary least squares estimation represent ideal heating curves for the particular households, meaning that the curve can always provide the desired room temperature. To estimate the impact of using the proposed guidelines, we assume that installers set the same deterministically defined heating curve for each household, which results in the following linear regression, fitted on all available data:

$$T_S = 40.76 - 0.36 \cdot T_O \quad (9)$$

where T_O and T_S are all observed outdoor and supply temperature combinations for 3995 heat pumps.

Triggering user adjustments throughout the fine-tuning period

HPs in our dataset use Eq. (10) to determine the required increase in supply temperature to achieve the desired room temperature increase [32]. This yields the following equation:

$$shift = \Delta T_{room} \cdot k \quad (10)$$

where $shift$ represents the change in supply temperature, ΔT_{room} denotes the change in room temperature, and k is the translation factor – a constant set by the installer on the heat pump controller, typically ranging from one to five in practice [32]. Since the translation factor is unknown to us, we assume that users adjust the heating curve settings when the supply temperature deviates by more than 5 % below or 7 % above the ideal heating curve. During the heating season, user interventions are

Table 4

Three different heating curve fine-tuning strategies, tested in this study.

Fine-tuning strategy	User action if it is too cold or too warm
Parallel shift	Parallel shift
OTD*	Acc. to proposed OTD table*
Retrospective	Parallel shift and an additional recalculation at the end of the season, based on user changes

* OTD – heating curve fine-tuning strategy, based on proposed outdoor temperature-dependent (OTD) guidelines.

triggered if these limits are exceeded. This approach aligns with thermal comfort guidelines, specifically ASHRAE 55 [38] and ISO 7730 [59], which emphasize that perceived thermal comfort depends on outdoor temperature. Greater sensitivity to cold than to heat is reflected in the larger allowable deviation toward higher temperatures (7 %) compared to lower ones (5 %).

For the continuous temperature profiles, we sample the average daily outdoor temperatures in Germany for years 2019–2023 (from October 01 to March 30, to represent a full heating period), using the data provided by the German Weather Service [60], as the majority (63.9 %) of heat pumps in our dataset are located in Germany.

Additionally, we include a 30 % uncertainty in all user-initiated changes to the supply temperature to better reflect real-world practices. For instance, when residents feel too cold and want to raise the room temperature, the exact increase needed might be 2 °C, but the residents may not know this precisely. Instead, they might anticipate and choose to increase the room set temperature by 3 °C. This approach accounts for the natural variability in how temperature changes are perceived and adjusted.

Three strategies to fine-tune the heating curve

In order to determine which changes lead to the heating curve deviating least from the ideal curve at the end of the season, we test three different options on how a user can modify the heating curve: by a parallel shift, according to our proposed OTD guidelines or by making retrospective adjustments, as summarized in Table 4.

Although this study focuses on the proposed outdoor temperature-dependent guidelines as an alternative to the standard parallel shift for addressing room comfort deviations, retrospective adjustments to the heating curve were also tested, as they represent a practical use case for the industry. New parameters for a heating curve are calculated, following Eq. (11), after three or more observed heating curve changes. $T_{S,new,i}$ stands for a supply temperature after the room set temperature change and $T_{O,i}$ for the outdoor temperature when the change occurred. A new heating curve can only be calculated if there are three or more changes by the user during the season. Fewer points are not feasible for the estimation of a linear model, because of the measurement uncertainties.

$$\begin{bmatrix} T_{S,new,1} \\ T_{S,new,2} \\ T_{S,new,3} \\ \vdots \end{bmatrix} = \begin{bmatrix} 1 & T_{O,1} \\ 1 & T_{O,2} \\ 1 & T_{O,3} \\ \vdots & \vdots \end{bmatrix} \begin{bmatrix} \beta_{1,new} \\ \beta_{2,new} \end{bmatrix} + \epsilon \quad (11)$$

We assess the number of user inputs, days outside the comfort range, and the maximum possible setback of heating curves for differently fine-tuned heating curves: users using the standard parallel shift and users following our proposed outdoor temperature-dependent guidelines. This method evaluates whether our guidelines enable more effective fine-tuning of the heating curve compared to the standard approach.

5.3. Impact assessment results

The simulation results comparing the standard parallel shift with our proposed outdoor temperature-dependent fine-tuning strategy are

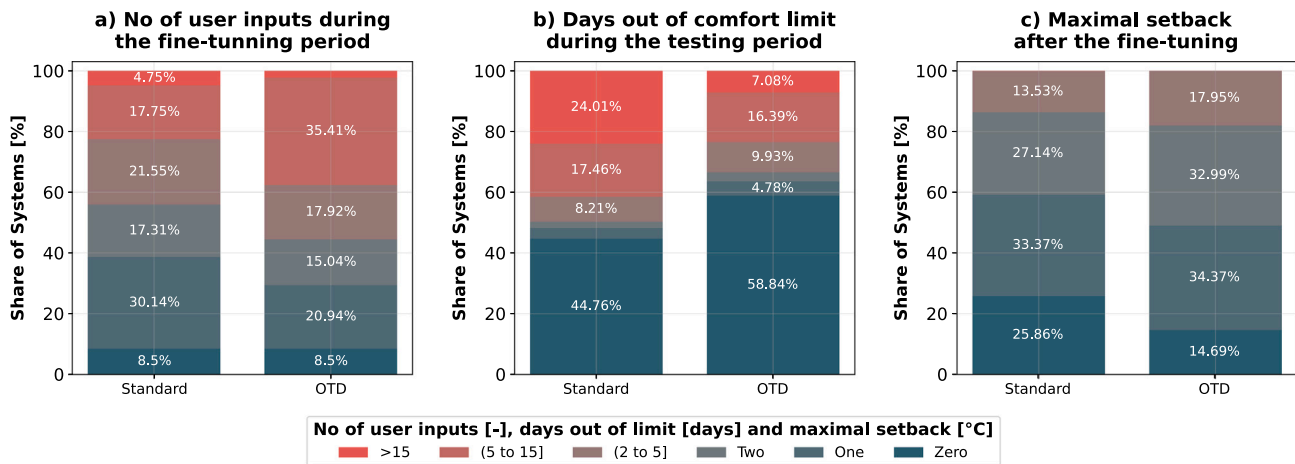


Fig. 9. Comparison of strategies for optimizing the heating curve during the fine-tuning period, which is one heating season.

summarized in Fig. 9. In Fig. 9a, the number of user inputs during the fine-tuning period is reported. For users, using a standard parallel shift to adapt the heating curve when the room comfort is met, 4.39 ± 6.88 changes per heating season were triggered on average. For users, following our proposed outdoor temperature-dependent guidelines, 4.92 ± 4.62 changes per heating season were triggered on average. Even though the difference between these groups is significant ($P = 0.0000$, tested with Wilcoxon Signed-Rank Test), the effect size is small (effect = 0.0905, tested using Cohen’s D).

Fig. 9b reports the results of testing the fine tuned heating curves on an unseen heating season, by calculating the number of days, which are out of limit. The differences between the groups are significant with $P = 0.0000$ (tested with Wilcoxon Signed-Rank Test) with a medium effect size of -0.5346 (Cohen’s D). It can be seen that the proportion of systems with an ideal heating curve (i.e., not exceeding comfort limits on any day) is higher among households that followed our proposed guidelines compared to those that did not (58.84 % vs. 44.76 %). The number of systems failing to achieve sufficient heating curve parametrization (with more than 15 days outside comfort limits per heating season) is significantly reduced when our proposed OTD guidelines are used: 7.08 % compared to 24.01 %. Additionally, households that used our proposed approach have 3.42 ± 6.21 (median = 0.0) days out of thermal comfort limit during the testing period, and the households, which have followed the standard parallel shift approach have significantly higher on average 13.51 ± 25.95 (median = 2.0) days out of limit during the testing period. In total, 84.42 % of the heating curves could be improved using the proposed guidelines. This percentage accounts for the 100 % total, minus 8.5 % of heating curves that were already optimal and 7.08 % that exceeded the comfort limit for more than 15 days during the testing period.

Retrospective adjustment was applied to 44.05 % of the systems. The remaining systems had two or fewer adjustments during the observation period, which was considered insufficient to fit a new heating curve due to measurement uncertainties. Nevertheless, heating curves, after the retrospective adjustments show the highest quality, where only 4.17 % of the systems are out of limit for more than 5 days per season.

5.4. Efficiency increase due to a fine-tuned heating curve

A fine-tuned heating curve provides a more accurate heat supply. Less intensive deviations from the ideal heating curve offer an opportunity to more strongly off-set a curve without notable loss in comfort.

In Fig. 9c, the maximal resulting setback for each household after the fine-tuning is summarized. On average, the median reduction (setback) of the heating curve after the fine-tuning is as follows: 0.52 ± 2.02 °C

after fine-tuning with the standard parallel shift, 1.08 ± 1.04 °C using proposed OTD guidelines, and 1.49 ± 0.72 °C for the retrospectively improved heating curve. This means that mean savings per household, with improved heating curve are 4.02 ± 5.05 % on average if proposed OTD fine-tuning is used. Additionally, the percentage of the systems with a maximum temperature reduction greater than 1 °C is 40.67 % after the standard parallel shift and 50.94 % after the OTD heating curve adjustments.

Example ranges for heating curve setbacks are illustrated in Fig. 10. In both Fig. 10a and b, the initial and ideal heating curves belong to the same system, fine-tuned using different methods (standard parallel shift and our OTD guidelines) over the same time period. For this system, the heating curve fine-tuned using our proposed guidelines achieved higher accuracy, leading to smaller deviations from the ideal heating curve and significantly greater flexibility for applying a setback. A maximum reduction of supply temperatures (setback) after the fine-tuning with the standard parallel shift is 1 °C, where the maximum setback after the OTD fine-tuning is 4.5 °C. The savings from a parallel shift of the heating curve in our study include a 2.4 % increase in SCOP and a 3.72 % reduction in yearly energy consumption per 1 °C decrease. This leads to a 10.8 % increase in SCOP and a 16.65 % reduction in yearly energy consumption. These findings align with values reported in the literature [24,25].

In summary, the impact assessment highlights the benefits of the proposed heating curve optimization guidelines. Compared to the standard parallel shift method, these guidelines reduce the likelihood of failing to achieve an optimal heating curve from 24.01 % to 7.08 %, requiring a comparable number of user adjustments during the fine-tuning period with lower standard distribution (4.39 ± 6.88 changes for the standard method vs. 4.92 ± 4.62 for the proposed guidelines). Simulation shows that during the testing period, households using the proposed approach experienced significantly fewer days outside the comfort range (3.42 ± 6.21 days, median = 0.0) compared to those following the standard method (13.51 ± 25.95 days, median = 2.0). Additionally, optimized heating curves allowed supply temperatures to be lowered by an average of 1.08 ± 1.04 °C to the lower comfort limits, reducing annual energy consumption by 4.02 % and increasing SCOP by 2.59 % on average.

6. Customizing proposed guidelines

The heating curve is a key factor for efficient heat pump operation, but setting the heating curve correctly is still challenging, partially due to the lack of standardization across different heat pump brands. To address this, we provide equations that enable the application of our proposed guidelines to various equipment configurations. These equations

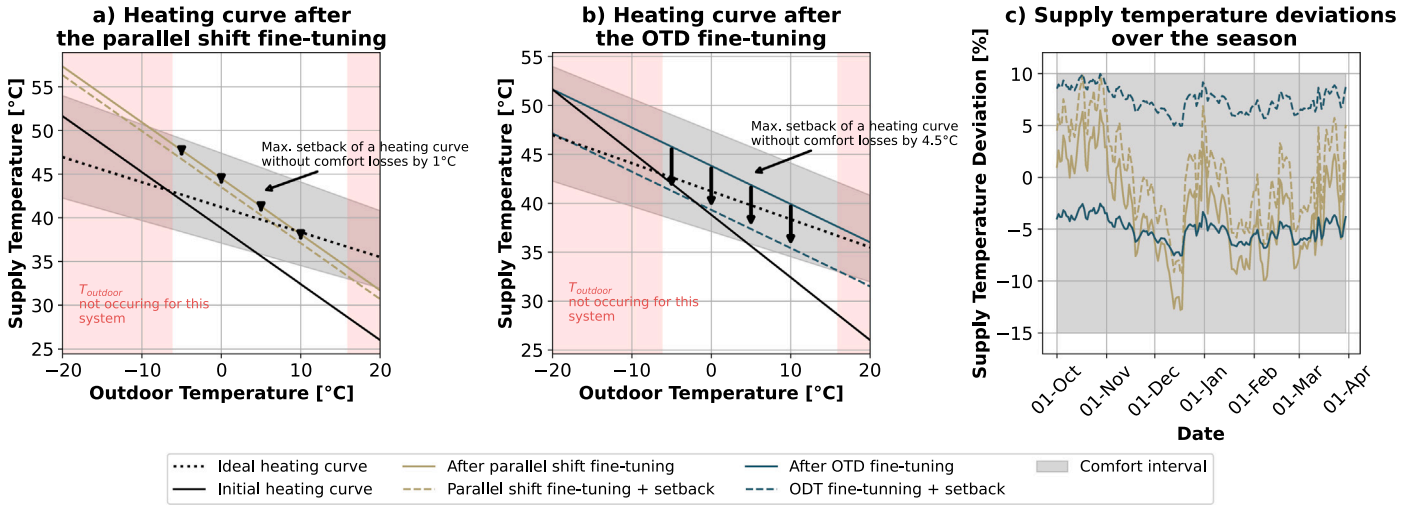


Fig. 10. Visualization of heating curves after different fine-tuning approaches: evaluating the maximum supply temperature reduction achieved through improved heating curve quality. For visualization purposes, comfort limits are set to be between -15% and 10% .

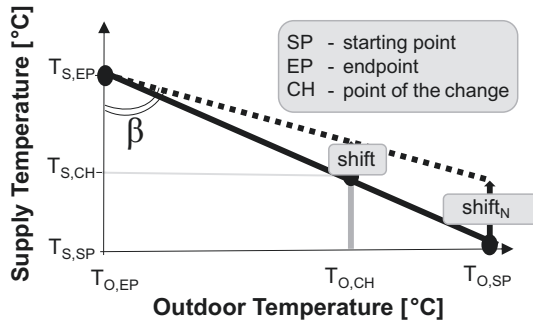


Fig. 11. Calculation of needed shift for the proposed outdoor temperature-dependent guidelines. Example schematics, when the vertical shift of the heating curve is done on the starting point.

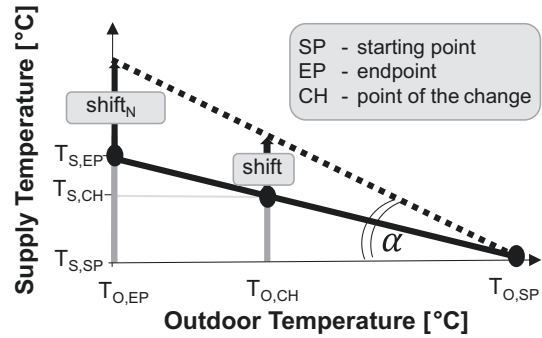


Fig. 12. Calculation of needed shift for the proposed outdoor temperature-dependent guidelines. Example schematics, when the vertical shift of the heating curve is done on the endpoint.

also help determine the magnitude of required vertical shifts at custom outdoor temperature points or when the heating curve is defined by intercept and slope instead of specific outdoor temperature points.

6.1. Translating supply to room temperature for easier interpretability

The proposed OTD guidelines are derived with supply temperature change as the dependent variable, as the translation factor k in Eq. (10) is unknown to the researchers. However, if this factor is known – such as in the case of installers who configure the heat pump – the interpretability of the proposed OTD guidelines can be further improved by dividing the derived supply temperature shifts by k . Exemplary OTD guidelines for $k = 1$ are provided in Table A.1.

6.2. Calculating needed size of the vertical shifts

In our proposed OTD guidelines, we provide the required vertical shift size at the endpoints, defined as $T_{O,EP} = -20\text{ °C}$ for the endpoint and $T_{O,SP} = 20\text{ °C}$ for the starting point of the heating curve. Based on trigonometric solution (Figs. 11 and 12), we see that the resulting needed shift is independent from the parameters of a heating curve and can be directly calculated from the outdoor temperatures with Eqs. (12) and (13). This explains why the calculated needed shift at each outdoor temperature remains the same across all heat pumps.

Eq. (12) should be solved to find needed shift, if the changes should be made on the starting point of the heating curve.

$$\frac{T_{O,SP} - T_{O,EP}}{(T_{S,EP} - T_{S,SP}) - shift_N} = \frac{T_{O,CH} - T_{O,EP}}{(T_{S,EP} - T_{S,CH}) - shift} = \tan(\beta) \tag{12}$$

$$\rightarrow shift_N = \frac{T_{O,SP} - T_{O,EP}}{T_{O,CH} - T_{O,EP}} \cdot shift$$

Based on schematics in Fig. 12, Eq. (13) should be solved to find needed shift, if the changes should be made on the endpoint of the heating curve.

$$\frac{(T_{S,EP} - T_{S,SP}) + shift_N}{T_{O,SP} + T_{O,EP}} = \frac{(T_{S,CH} - T_{S,SP}) + shift}{T_{O,SP} - T_{O,CH}} = \tan(\alpha) \tag{13}$$

$$\rightarrow shift_N = \frac{T_{O,SP} - T_{O,EP}}{T_{O,SP} - T_{O,CH}} \cdot shift$$

6.3. Calculations if the predefined starting and endpoints are not at 20 °C and -20 °C

In this study we have used -20 °C and 20 °C as end- and starting points of a heating curve, as these are the thresholds in currently used heating system manuals. Nevertheless, the calculation with values other than these may be needed, depending on the specific HP model or its

configuration. The same Eqs. (12) and (13) can be used to calculate our guidelines with custom starting and endpoints.

6.4. Recalculations, if the heating curve input parameters are slope and intercept rather than starting and endpoints

In some cases, the heating curve is configured using slope and intercept parameters rather than separate points. The following equations outline the necessary recalculations. Eq. (14) represents a new heating curve, with intercept $\beta_{1,new}$ and slope $\beta_{2,new}$ parameters we aim to determine.

$$\mathbf{T}_{S_{new}} = \begin{bmatrix} 1 & \mathbf{T}_O \end{bmatrix} \begin{bmatrix} \beta_{1,new} \\ \beta_{2,new} \end{bmatrix} \quad (14)$$

If the outdoor temperature is >5 °C, at the point when the user wants to change the heating curve, the vertical shift at the starting point should be chosen and a new heating curve calculated by solving Equation System (15), which is an equivalent to previously discussed Eq. (3).

$$\begin{bmatrix} 1 & -20 \\ 1 & T_{O,CH} \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \text{shift} \end{bmatrix} = \begin{bmatrix} 1 & -20 \\ 1 & T_{O,CH} \end{bmatrix} \begin{bmatrix} \beta_{1,new} \\ \beta_{2,new} \end{bmatrix} \quad (15)$$

If the outdoor temperature is <2 °C, meaning that the shift at the endpoint should be used, Equation System (16), which is similar to Eq. (4), should be solved for the new intercept and slope parameters.

$$\begin{bmatrix} 1 & T_{O,CH} \\ 1 & 20 \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} + \begin{bmatrix} \text{shift} \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & T_{O,CH} \\ 1 & 20 \end{bmatrix} \begin{bmatrix} \beta_{1,new} \\ \beta_{2,new} \end{bmatrix} \quad (16)$$

In these equations, same as before, *shift* stands for a wished shift of the supply temperature at outdoor temperature $T_{O,CH}$, where β_1 and β_2 are the old intercept and slope parameters of the heating curve.

7. Discussion

In the following section we firstly highlight the contributions and the benefits of our research. Additionally we provide concepts, how our proposed guidelines could be implemented, for a better transfer into practice. Finally, we discuss the limitations of our approach and outline directions for future work.

7.1. Contributions and benefits of our approach

The central challenge addressed by this research is the complexity and unfamiliarity associated with adjusting the heating curve of HPs. Unlike traditional combustion-based heating systems, HPs require precise calibration to operate efficiently and deliver the desired amount of heat [7,61]. Most homeowners and installers struggle with this fine-tuning process, partly due to the relative novelty of heat pumps in the market [7,62]. As heat pumps are modular technologies with significant installation-specific cost components, the expected reduction in installation or advisory costs has not materialized as anticipated [63]. Furthermore, the absence of specialized guidelines for optimizing heating curves for heat pumps leaves users without adequate support to fine-tune their systems effectively.

This study aims to provide guidelines based on which users can universally adjust their HP settings, or manufacturers can implement new "fine-tuning" programs. The goal is for more HPs to have ideally set heating curves that enhance room comfort, minimize inefficient user input, and on average contribute with 4.02 % decrease in HP's yearly energy consumption and average increase in SCOP of 2.59 %.

Additionally, optimizing the heating curve enhances room comfort, reducing customer dissatisfaction and the likelihood of manual adjustments to thermostatic valves, which may significantly degrade heat

pump performance due to hydraulic imbalance [8,13]. Hydraulic imbalance not only affects system stability but also disrupts the heat exchange process. When return temperatures fall below the designed levels, the required temperature lift may exceed the capacity of the heat exchanger due to size and mass flow limitations. As a result, higher primary cycle temperatures are needed, which in turn increases compressor utilization and overall power consumption. Since heat pumps are designed to operate efficiently within predefined conditions – such as an optimal temperature lift – any deviation from these conditions can lead to sub-optimal performance and accelerated wear on compressor components [64].

Our proposed method for modeling energy consumption and COP based solely on the daily averages of supply and outdoor temperatures offers the advantage of interpretability. It has been tested on a significant number of heat pumps operating in the field and shows an interpretable, comparable course of the target variables, similar to the Carnot efficiency, allowing relatively robust extrapolation. The error achieved with our method is comparable to that of other energy [65] and COP [66,67] modeling approaches available in the literature. However, our approach does not account for the cycling behavior of the heat pump, which may lead to non-linear energy consumption and COP behavior at warm outdoor temperatures.

The relevance of more transparent guidelines to reduce the complexity and unfamiliarity with HP technology has been emphasized by many researchers [7,68]. These methods must be specifically designed to tackle practical challenges, including the absence of contextual information, handling inaccurate measurements and data disruptions, and addressing privacy concerns. Accelerating the development of such methods can significantly speed up the implementation of digital monitoring solutions for HPs. This, in turn, would substantially contribute to enhancing energy efficiency in buildings, fostering user confidence in the technology, and facilitating the widespread adoption of HP installations. Urgent action is imperative, as both aspects are essential for meeting climate targets: improving energy efficiency in buildings and deploying a significantly higher number of HPs in the field [2,69]. Additionally, the user feedback, collected via room temperature controllers may substitute the need for additional temperature sensors or software applications for data collection [31,41]. The advantage of the application of the proposed OTD table is that only the outdoor temperature needs to be known, so even HPs that are not connected to the internet can be optimized, making it suitable for scalable energy efficiency services at low costs, which are currently missing.

7.2. Proposal on how to implement proposed outdoor temperature-dependent guidelines

The proposed heating curve fine-tuning strategies, particularly those based on OTD guidelines, can be implemented in various ways. These are summarized in Table 5. Firstly, a well informed resident could adapt the HP settings by himself, following the proposed guidelines. In this case we propose that installers provide customized OTD guidelines after the HP installation, so that the customer does not need to recalculate the starting and endpoint as well as the room temperature into supply temperatures. This customization can be done in a simple spreadsheet. Secondly, an energy advisor, after asking the resident about perceived room comfort on cold, medium and warm days, may rely on our OTD guidelines to make more informed decisions. Third, the manufacturer could implement a fine-tuning mode directly on the heat pump's controller, which would be activated for a period of 3–6 months after installation. Customers should be informed about this mode and advised to carefully adjust their room set temperature. This fine-tuning mode could be developed by the equipment manufacturer and deployed as a software update for already installed, connected heat pumps. While the implementation requires minimal investment, field trials and edge

Table 5
Use-cases on how a fine-tuning of a heating curve can be implemented.

Implementation by	Required daily mean values	Based on
Resident, on the HP settings	T_o	OTD table
Energy advisor or similar, on the HP settings	T_o	OTD table
Manufacturer implements fine-tuning program	T_o	OTD table
Manufacturer implements fine-tuning program	T_o, T_s	Retrospective calculation
Resident keeps a log of changes	T_o, T_s	Retrospective calculation

case testing may be necessary to validate its effectiveness and ensure the robustness of the heating system under various conditions. For manufacturers, this fine-tuning mode serves as an additional feature that provides direct insights into user thermal comfort while also allowing for optimization of heat pump operation efficiency. This option is particularly beneficial for users who are responsible for operating costs, especially if the potential energy savings are made transparent. For the three proposals above, only the daily average temperature is needed. For the following two options, additionally the average daily supply temperature should be known on the day when the room set temperature change takes place, as these options are based on the retrospective calculation of the heating curve and the implementation of the improved heating curve is a one-time event, after enough observations are collected. The retrospective calculation of a new heating curve can be implemented by the manufacturer, who possesses operational data of the HP. A new heating curve and a potential efficiency benefits could be proposed on the app for the user or for the installer, who could implement the curve remotely or during the yearly HP inspection. The costs and benefits of implementing heating curve adjustments, based on retrospective calculations, are comparable to those of implementing the proposed OTD guidelines, as discussed above, with similar advantages and challenges. Alternatively, a resident could keep a log of changes, which he makes on the room set temperature, the resulting average daily supply temperature and the average daily outdoor temperature on the next day after the changes are made and calculate a new heating curve after enough observations according to the previously presented Eq. (11).

While retrospective heating curve optimization can improve heating curves slightly better, it remains a post-hoc strategy applicable only to internet-connected heat pumps or cases where the resident has maintained a precise log of changes, including supply and outdoor temperatures at the time of adjustments. Although this approach has significant potential for manufacturer implementation in heat pump monitoring or remote reconfiguration, its reliance on connected equipment underscores the continued need for our proposed outdoor temperature-dependent heating curve fine-tuning guidelines.

7.3. Limitations and future work

This study analyzes data from AWHPs installed in Central Europe, which falls within an average climate zone. Although the proposed method for deriving guidelines is universally applicable to different climates, the resulting OTD guidelines would vary across climates. This variation is primarily due to differences in estimated energy consumption models and the weighting of the heating curve, as provided in Table A.2 of the EN 14825 standard.

The primary criterion for selecting the heating curve shifts based on outdoor temperature in this research is the estimated energy consumption model, which depends only on supply and outdoor temperatures. The availability of large-scale data enabled a robust estimation of both global and local parameters for this multivariate regression model. However, access to such extensive proprietary datasets is not always possible for all researchers. For those aiming to develop comparable outdoor-temperature-dependent heating curve optimization guidelines for heat pumps in different climate zones – or similar guidelines for alternative heating systems controlled by heating curves – alternative modeling approaches should be considered. If large datasets are

unavailable, researchers may need to explore other techniques beyond the multivariate linear model used in this study, such as physics-based models, smaller-scale empirical studies, or experimental data generation, to ensure reliable results.

We have assumed that the house has only one room controller, further research may focus on the interplay of several of them. Furthermore, additional heating curve, such as bivalent point and heating limit, were not investigated in this study, but are known to have a high impact on the HPs' operation and could also make implementation of the proposed guidelines more complex. We assume linear models for the heating curve, COP, and energy consumption, as these sufficiently represent the physics and typical operation of heat pumps. However, in practice, heat pumps may exhibit non-linear behavior under certain operating conditions. These conditions could be examined separately in future work to capture any deviations from linearity and their impact on our derived guidelines more accurately. Data was collected for domestic HPs with a power range of 3–17 kW of one manufacturer, this could lead to biased results. Additionally, our simulations do not account for individual resident behaviors, such as personal thermal preferences or manual adjustments for day/night or absence schedules, which can vary significantly across individuals. Additionally, the OTD table relies on daily average outdoor temperatures. In practice, calculating these averages may introduce uncertainties that are not accounted for in the guidelines. Nonetheless, this study shows the great potential inherent in digital monitoring solutions, as well as a stand-alone guideline for improving the comfort and energy efficiency of HPs in residential buildings in a scalable manner.

Setting a deterministically predefined heating curve as the initial configuration for all households in our simulation study was chosen for several reasons. Firstly, installers often rely on predefined parameters or their own experience to simplify and speed up the heat pump configuration process [7,11]. Secondly, using predefined heating curves in our simulation tests the ability of fine-tuning strategies to correct misconfigurations caused by non-customized initial setups. Future work could explore more tailored initial heating curves by clustering households based on the type of energy distributors, as this information was not available for the dataset used in this study.

8. Conclusion

This study aims to propose a method and derive universal guidelines on how the heating curve of heat pumps can be optimized depending on the outdoor temperature, aiming to enable users to improve the heat pump efficiency, of already installed heat pumps, without need of additional investments. An optimized heating curve improves comfort, reducing the need for inefficient practices such as frequent thermostatic valve adjustments. It also reduces the annual energy consumption of the heat pump by an average of 4.02 % and provides a basis for additional energy-saving strategies, such as reducing temperature during residents' absence or utilizing dynamic electricity pricing. The findings of this study can be summarized as follows.

Methodological contribution We propose a method to derive outdoor temperature ranges where specific heating curve adjustments outperform standard parallel shifts, enhancing heating curve quality.

This method can be used for heat pumps located in other climate zone, as well as for alternative heating systems. Additionally, this study proposes a method to retrospectively calculate an optimized heating curve from operational data, using room temperature changes as feedback to assess initial heating curve's effectiveness.

RQ1: Derive guidelines

Derived outdoor temperature-dependent guidelines suggest using a parallel shift of the heating curve only for outdoor temperatures $T_o \in [2, 5] \text{ }^\circ\text{C}$. For higher temperatures, adjustments to the starting point, and for lower temperatures, vertical changes at the endpoint are more energy-efficient when the HP is located in an average climate zone. These findings are based on the largest HP field study to date (3995 AWHPs), additionally demonstrating that a $1 \text{ }^\circ\text{C}$ parallel shift increases yearly energy consumption by 153.59 kWh (3.72 %) and decreases the COP by 2.4 %.

RQ2: Assess guidelines

Our simulation study demonstrates that translating user input according to our proposed guidelines significantly reduces the number of suboptimal heating curves, decreasing insufficient configurations from 24.01 % to 7.08 % compared to standard parallel shift adjustments. Furthermore, heating curves optimized with our guidelines result in significantly fewer days exceeding user's thermal comfort limits, averaging 3.42 ± 6.21 days per heating season, compared to 13.51 ± 25.95 days for households using standard parallel shift adjustments. This indicates that proposed guidelines can also help to correct heating curve configuration errors to some extent. Finally, our optimized heating curves allow for an average reduction of $1.08 \pm 1.04 \text{ }^\circ\text{C}$ in supply temperature while maintaining user comfort. This leads to an average yearly energy consumption reduction of 4.02 % and a 2.59 % improvement in SCOP.

RQ3: Customize guidelines

By considering different heating curve parametrization options available in practice we provide recalculation methods, so that our guidelines can be directly implemented in the practice by heat pump users and installers.

CRedit authorship contribution statement

Ugne Potthoff: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tobias Brudermueller:** Writing – review & editing, Visualization, Data curation. **Konstantin Hopf:** Writing – review & editing. **Felix Wortmann:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors used AI-based tools in order to improve readability and language. However, these tools were not used to write paragraphs of text. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ugne Potthoff reports financial support was provided by Robert Bosch GmbH. Felix Wortmann reports financial support was provided by Robert Bosch GmbH. Ugne Potthoff reports a relationship with Robert Bosch GmbH that includes: funding grants. Felix Wortmann reports a relationship with Robert Bosch GmbH that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A. Appendix

A.1. Impact of different heating curve shifts on yearly energy consumption and SCOP

In Section 4 in order to determine outdoor temperature-dependent guidelines, three different approaches for how a heating curve can be changed (parallel shift, vertical shift at starting point and vertical shift at endpoint) were presented. In Figs. A.1 and A.2 impact of these changes on the yearly energy consumption and SCOP is reported, where the values on the x-axis stand for the heating curve shifts according to the schematics reported in previously presented Fig. 3.

It is seen that the consequences of energy consumption and SCOP per degree are higher for the standard parallel shift than for the alternative vertical shifts at the starting point and the endpoint. Generally, it can be said, that an increase by 1 degree leads on average to an increase in energy consumption of $159.59 \pm 92 \text{ kWh}$, which is a $3.72 \pm 2.5 \%$ relative increase and a relative increase of $2.4 \pm 2 \%$ of SCOP for the standard parallel shift. For the vertical shift at the starting point, every increase by $1 \text{ }^\circ\text{C}$ leads to $89 \pm 5 \text{ kWh}$ ($2.13 \pm 5 \%$) for the energy consumption and $1.53 \pm 5 \%$ relative decrease of SCOP. For the vertical shift at the endpoint, an increase of $1 \text{ }^\circ\text{C}$ leads to $59 \pm 5 \text{ kWh}$ ($1.44 \pm 5 \%$) for the energy consumption and $0.81 \pm 0.5 \%$ relative increase of SCOP. It is also seen, that there is a slight difference between the direction of the adjustments of the heating curve. The increase of the supply temperature has a higher impact on energy consumption than the decrease in the supply temperature.

A.2. Outdoor temperature-dependent guidelines

The core of this study is the development of the OTD guidelines, which are detailed in Table A.1. These guidelines are estimated for a starting point at $T_{\text{outdoor}} = 20 \text{ }^\circ\text{C}$ and an endpoint at $T_{\text{outdoor}} = -20 \text{ }^\circ\text{C}$. If different values for the starting or endpoints are needed, recalculations should be performed using the equations provided in Section 6. Non-rounded values are provided to allow for more precise calculations, especially for adjustments larger than those currently given. This also enables manufacturers to implement more accurate heating curve adjustments in automatic fine-tuning modes, rather than being limited to degree increments.

The following example serves to better understand how to use this table. If the supply temperature needs to be increased by $4 \text{ }^\circ\text{C}$ and the average daily outdoor temperature is $-10 \text{ }^\circ\text{C}$, the standard parallel shift of $4 \text{ }^\circ\text{C}$ should instead be replaced by a vertical adjustment of $5 \text{ }^\circ\text{C}$ at the endpoint. As shown in Fig. A.1, this increase in supply temperature would lead to an average yearly energy consumption increase of $4 \cdot 3.72 = 14.88 \%$ if a parallel shift is used, whereas it would result in only a $5 \cdot 1.44 = 7.20 \%$ increase on average if the vertical adjustment is applied.

A.3. Evaluation of different strategies to fine-tune the heating curve

In Section 5.3, we evaluated various heating curve fine-tuning strategies: the standard parallel shift, our proposed OTD guidelines, and a retrospective approach. As shown in Fig. A.3, no significant differences

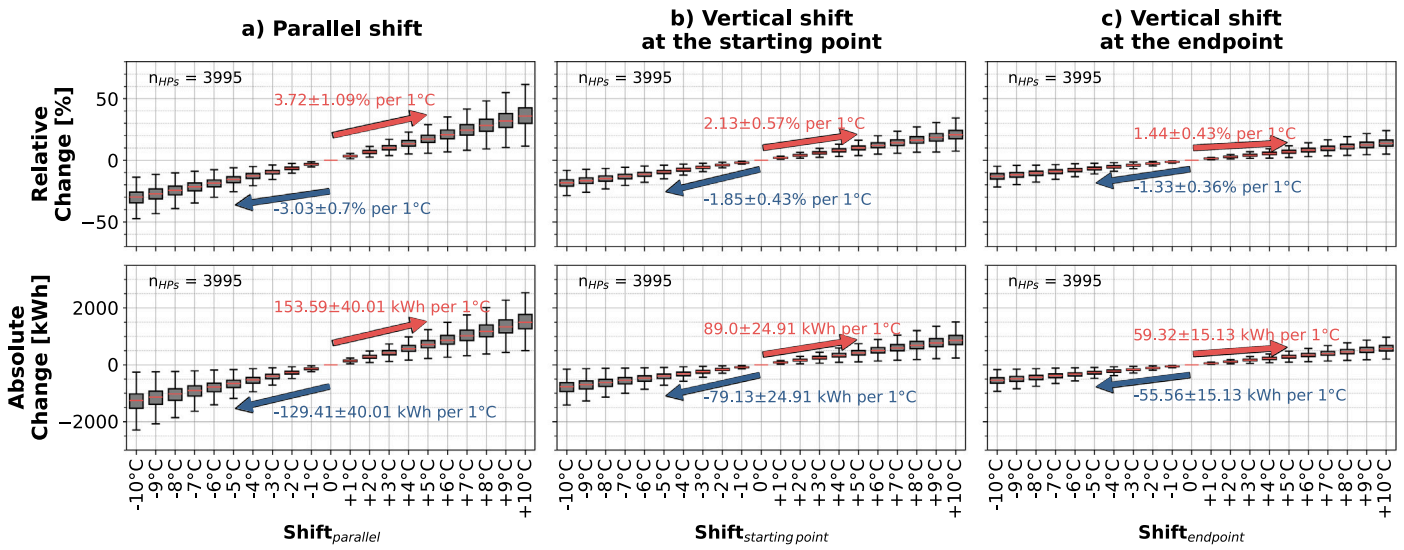


Fig. A.1. Changes in yearly energy consumption resulting from incremental adjustments to the heating curve, using three different heating curve shift approaches.

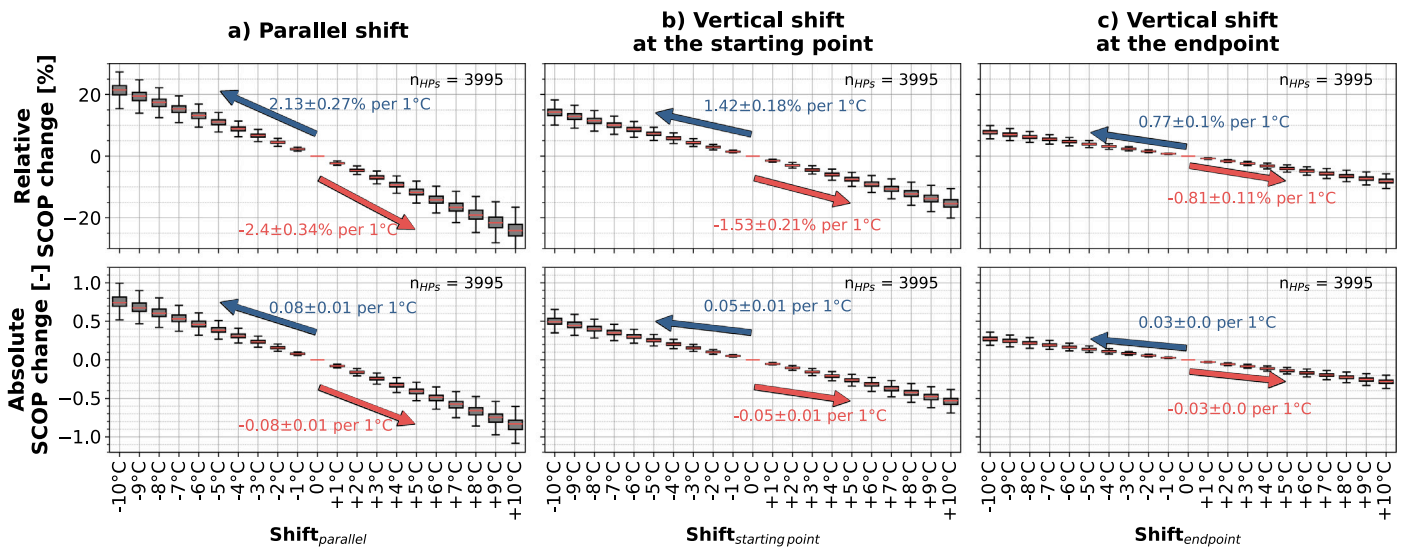


Fig. A.2. Changes in SCOP resulting from incremental adjustments to the heating curve, using three different heating curve shift approaches.

in the yearly metrics were observed among these strategies. This is primarily because our proposed method focuses on achieving an ideal heating curve that consistently delivers comfort, rather than optimizing energy consumption or heat pump performance. Energy savings and performance improvements are realized after implementing increased setbacks for users with optimized heating curves. Additional savings are achieved by avoiding manual adjustments to thermostatic valves and so preventing hydraulic imbalance.

Nevertheless, a positive trend is evident in all the reported yearly metrics in Section 5.3 for both the training and testing data. The proportion of systems with higher-than-needed supply temperatures is systematically lower when using the proposed heating curve fine-tuning strategies, as compared to the standard parallel shift. For instance, the percentage of systems with a yearly mean supply temperature more

than 5 % higher than necessary is 25.43 % when the heating curves are fine-tuned using the standard parallel shift. In contrast, this percentage decreases to 21.74 % for systems fine-tuned according to the proposed OTD guidelines and to 19.48 % for systems fine-tuned using the retrospective approach. Similar trends are observed for SCOP and yearly energy consumption.

A.4. Algorithms to derive and test outdoor temperature-dependent guidelines

Steps needed to derive proposed outdoor temperature-dependent guidelines are summarized as Algorithm 1. The steps to test the guidelines over a time period are summarized as Algorithm 2.

Table A.1

Exemplary outdoor temperature-dependent (OTD) guidelines, if the heating curve is configured to have the translation factor $k = 1$ ($\Delta T_{supply} = \text{Translation}_{factor} \cdot \Delta T_{room\ set}$), the endpoint at $T_{outdoor} = -20\text{ }^\circ\text{C}$ and the starting point at $T_{outdoor} = 20\text{ }^\circ\text{C}$. The necessary adjustments are provided for five different room temperature adjustments. An example, highlighted in gray, shows that if a resident wants to raise the room temperature by $4\text{ }^\circ\text{C}$ when the outdoor temperature is $-10\text{ }^\circ\text{C}$, the recommended approach is to increase the supply temperature at the endpoint of the heating curve by $5\text{ }^\circ\text{C}$.

$T_{outdoor}$	Recommended shift of the heating curve	Wanted increase of $T_{room\ set}$ by					
		Rounded values					Not rounded
		1°C	2°C	3°C	4°C	5°C	1°C
-20°C	Vertical shift at the endpoint	1.0	2.0	3.0	4.0	5.0	1.0000
-19°C	Vertical shift at the endpoint	1.0	2.0	3.0	4.0	5.0	1.0256
-18°C	Vertical shift at the endpoint	1.0	2.0	3.0	4.0	6.0	1.0526
-17°C	Vertical shift at the endpoint	1.0	2.0	3.0	5.0	6.0	1.0811
-16°C	Vertical shift at the endpoint	1.0	2.0	4.0	5.0	6.0	1.1111
-15°C	Vertical shift at the endpoint	1.0	2.0	3.0	5.0	6.0	1.1429
-14°C	Vertical shift at the endpoint	1.0	2.0	4.0	5.0	6.0	1.1765
-13°C	Vertical shift at the endpoint	1.0	2.0	4.0	5.0	6.0	1.2121
-12°C	Vertical shift at the endpoint	1.0	2.0	4.0	5.0	6.0	1.2500
-11°C	Vertical shift at the endpoint	1.0	3.0	4.0	5.0	6.0	1.2903
-10°C	Vertical shift at the endpoint	1.0	3.0	4.0	5.0	7.0	1.3333
-9°C	Vertical shift at the endpoint	1.0	3.0	4.0	6.0	7.0	1.3793
-8°C	Vertical shift at the endpoint	1.0	3.0	4.0	6.0	7.0	1.4286
-7°C	Vertical shift at the endpoint	1.0	3.0	4.0	6.0	7.0	1.4815
-6°C	Vertical shift at the endpoint	2.0	3.0	5.0	6.0	8.0	1.5386
-5°C	Vertical shift at the endpoint	2.0	3.0	5.0	6.0	8.0	1.6000
-4°C	Vertical shift at the endpoint	2.0	3.0	5.0	7.0	8.0	1.6667
-3°C	Vertical shift at the endpoint	2.0	3.0	5.0	7.0	9.0	1.7391
-2°C	Vertical shift at the endpoint	2.0	4.0	5.0	7.0	9.0	1.8182
-1°C	Vertical shift at the endpoint	2.0	4.0	6.0	8.0	10.0	1.9048
0°C	Vertical shift at the endpoint	2.0	4.0	6.0	8.0	10.0	2.0000
1°C	Vertical shift at the endpoint	2.0	4.0	6.0	8.0	11.0	2.1053
2°C	Parallel shift	1.0	2.0	3.0	4.0	5.0	1.0000
3°C	Parallel shift	1.0	2.0	3.0	4.0	5.0	1.0000
4°C	Parallel shift	1.0	2.0	3.0	4.0	5.0	1.0000
5°C	Parallel shift	1.0	2.0	3.0	4.0	5.0	1.0000
6°C	Vertical shift at the starting point	2.0	3.0	5.0	6.0	8.0	1.5385
7°C	Vertical shift at the starting point	1.0	3.0	4.0	6.0	7.0	1.4815
8°C	Vertical shift at the starting point	1.0	3.0	4.0	6.0	7.0	1.4286
9°C	Vertical shift at the starting point	1.0	3.0	4.0	6.0	7.0	1.3793
10°C	Vertical shift at the starting point	1.0	3.0	4.0	5.0	7.0	1.3333
11°C	Vertical shift at the starting point	1.0	3.0	4.0	5.0	6.0	1.2903
12°C	Vertical shift at the starting point	1.0	2.0	4.0	5.0	6.0	1.2500
13°C	Vertical shift at the starting point	1.0	2.0	4.0	5.0	6.0	1.2121
14°C	Vertical shift at the starting point	1.0	2.0	4.0	5.0	6.0	1.1765
15°C	Vertical shift at the starting point	1.0	2.0	3.0	5.0	6.0	1.1429
16°C	Vertical shift at the starting point	1.0	2.0	3.0	4.0	6.0	1.1111
17°C	Vertical shift at the starting point	1.0	2.0	3.0	4.0	5.0	1.0811
18°C	Vertical shift at the starting point	1.0	2.0	3.0	4.0	5.0	1.0526
19°C	Vertical shift at the starting point	1.0	2.0	3.0	4.0	5.0	1.0256
20°C	Vertical shift at the starting point	1.0	2.0	3.0	4.0	5.0	1.0000

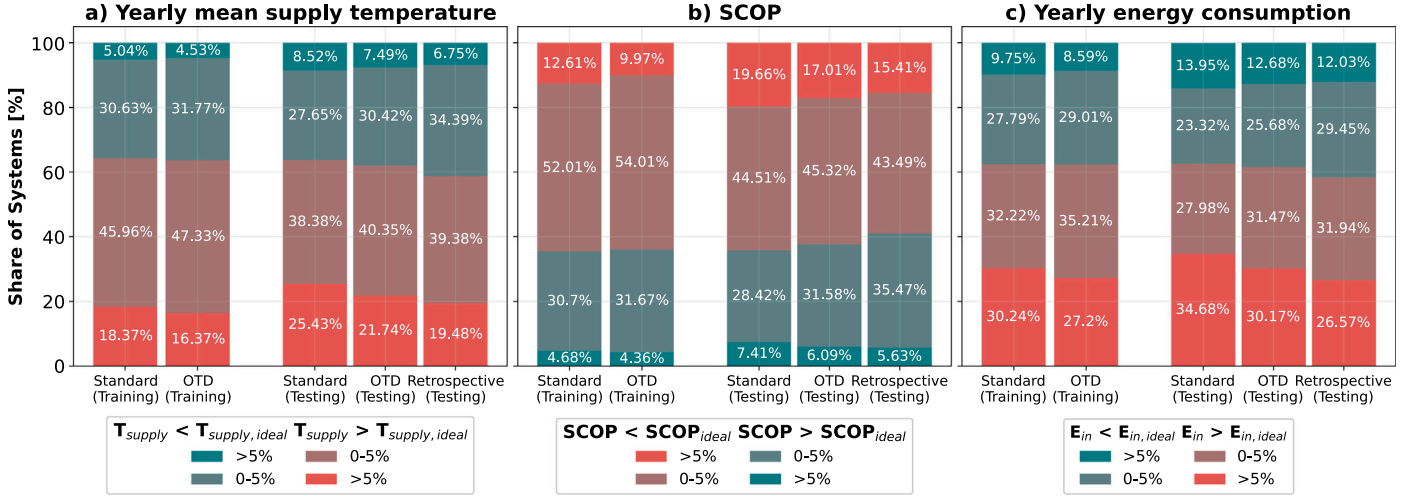


Fig. A.3. Evaluation of different strategies to fine-tune the heating curve, based on yearly metrics.

Algorithm 1 Algorithm to derive outdoor temperature-dependent guidelines.

```

 $T_{\text{outdoor, HP}} \leftarrow$  vector of HP specific observed daily average outdoor temperatures
 $T_{\text{supply, HP}} \leftarrow$  vector of HP specific observed daily average supply temperatures
 $shift \leftarrow 1$  °C, increase in supply temperature
 $\alpha_1, \alpha_2, \alpha_3 \leftarrow$  global parameters for energy model, estimated with Eq. (6)
 $v_{HP} \leftarrow$  HP specific parameter for energy model, estimated with Eq. (6)
 $OTD\_table \leftarrow \{ \}$ 

for each  $t_{\text{outd}} \in [-20; 20]$  °C do
    for each HP  $\in$  all HPs do
         $\beta_1, \beta_2 \leftarrow \text{LinearRegression}(T_{\text{outdoor, HP}}, T_{\text{supply, HP}})$ 
        for each strategy  $\in$  [parallel; starting point; endpoint] do
            if strategy = parallel then
                 $\beta_{1,\text{new}} \leftarrow \beta_1 + shift$ 
                 $\beta_{2,\text{new}} \leftarrow \beta_2$ 
                 $shift_{\text{needed}} \leftarrow shift$ 
            else if strategy = starting point then
                 $\beta_{1,\text{new}}, \beta_{2,\text{new}}, shift_{\text{needed}} \leftarrow \text{Solve Eq. (3)}$ 
            else if strategy = endpoint then
                 $\beta_{1,\text{new}}, \beta_{2,\text{new}}, shift_{\text{needed}} \leftarrow \text{Solve Eq. (4)}$ 
            end if
            for  $t \in [-20; 15]$  °C do
                 $h_t \leftarrow$  frequency per year in hours in average climate for  $t$  from EN 14825
                 $\Delta T_{\text{supply},t} \leftarrow (\beta_1 + \beta_2 \cdot t) - (\beta_{1,\text{new}} + \beta_{2,\text{new}} \cdot t)$ 
                 $\Delta E_{\text{in},t} \leftarrow \alpha_1 + \alpha_2 \cdot \Delta T_{\text{supply},t} + \alpha_3 \cdot t + v_{HP}$ 
                 $\Delta \text{Yearly Consumption} \leftarrow \Delta \text{Yearly Consumption} + (\frac{h_t}{24} \cdot \Delta E_{\text{in},t})$ 
            end for
            if  $\Delta \text{Yearly Consumption} < \text{min\_energy}$  then
                 $\text{min\_energy} \leftarrow \Delta \text{Yearly Consumption}$ 
                 $\text{best\_strategies}[HP] \leftarrow (\text{strategy}, shift_{\text{needed}})$ 
            end if
        end for
    end for
end for
if length(unique(best_strategies.strategy)) = 1 then
     $OTD\_table[t_{\text{outd}}].strategy \leftarrow \text{unique}(best\_strategies.strategy)$ 
     $OTD\_table[t_{\text{outd}}].shift \leftarrow \text{mean}(best\_strategies.shift)$ 
else
     $OTD\_table[t_{\text{outd}}].strategy \leftarrow \text{parallel}$ 
     $OTD\_table[t_{\text{outd}}].shift \leftarrow shift$ 
end if
end if
Return  $OTD\_table$ 

```

▷ Initialize dictionary to store selected strategy for each t_{outd}
 ▷ Simulate a shift at different t_{outd}
 ▷ Heating curve's initial intercept and slope, (indep. of t_{outd})
 ▷ Reach a shift with different strategies
 ▷ Calculate yearly energy consumption change
 ▷ Update minimum energy if current is lower
 ▷ Store the strategy associated with min energy
 ▷ Choose the unique strategy
 ▷ Choose parallel if multiple unique strategies exist
 ▷ Output selected strategies and corresponding shifts for each outdoor temperature

Algorithm 2 Algorithm for heating curve fine-tuning based on outdoor temperature-dependent guidelines and subsequent testing.

```

all_heating_curves ← dictionary, that stores all initial heating curves for each HP
T_outdoor,2019, T_outdoor,2020, T_outdoor,2021, T_outdoor,2022, T_outdoor,2023 ← vectors of continuous daily average outdoor
temperatures in Germany during the heating seasons 2019–23

for each HP ∈ all HPs do
    β1, β2 ← all_heating_curves[HP]                                ▷ Heating curve's initial intercept and slope
    β1,i, β2,i ← 40.76, -0.36                                       ▷ Initially set heating curve
    for each year ∈ [2019, 2022, 2021, 2022] do                       ▷ Fine-tune the heating curve during different years
        for each toutd ∈ T_outdoor, year do
            Tsupply,should ← β1 + β2 · toutd
            Tsupply,reached ← β1,i + β2,i · toutd
            ΔTsupply ← 100 % · (Tsupply,should - Tsupply,reached) / Tsupply,should
            uncertainty ← 1 + random(-0.3, 0.3)                       ▷ Random uncertainty, to represent user input
            shiftneeded ← round((Tsupply,should - Tsupply,reached) · uncertainty)
            if ΔTsupply ≤ -7 % or ΔTsupply ≥ 5 % then                 ▷ Changes are triggered, if limits are exceeded
                if toutd < 2°C then
                    β1,i, β2,i ← Solve Eq. (16) with shiftendpoint from OTD table
                else if toutd > 5 °C then
                    β1,i, β2,i ← Solve Eq. (15) with shiftstarting point from OTD table
                else if 2 ≤ toutd ≤ 5 °C then
                    β1,i, β2,i ← β1,i - shift, β2,i
                end if
            end if
        end if
    end for
    for each toutd ∈ T_outdoor, year+1 do
        Tsupply,should ← β1 + β2 · toutd
        Tsupply,reached ← β1,i + β2,i · toutd
        ΔTsupply ← 100 % · (Tsupply,should - Tsupply,reached) / Tsupply,should
        if ΔTsupply ≤ -7 % or ΔTsupply ≥ 5 % then
            days_out_of_limit[HP][i][year + 1] ← days_out_of_limit[HP][i][year + 1] + 1
        end if
    end for
end for
end for

```

Data availability

The raw data is not publicly available due to privacy and other restrictions. However, we provide data to enable the reconstruction of key figures (Figs. 5 and 7–9) under <https://data.mendeley.com/datasets/2xc7nkchp7/1>. Figs. 7–9 present simulated data from the study and were not directly measured. It is important to note that the provided data does not allow for a direct evaluation of the manufacturer or the heat pumps, as the measurements and simulations were not conducted within a controlled experimental framework. Additional materials are available upon reasonable request.

References

- [1] Kou X, Wang R, Shuai D, Zhenyuan X, Zhu X. Heat pump assists in energy transition: challenges and approaches. *DeCarbon* 2024;3:100033. doi:<https://doi.org/10.1016/j.decarb.2023.100033>.
- [2] Rosenow J, Gibb D, Nowak T, Lowes R. Heating up the global heat pump market. *Nat Energy* 2022;7(10):901–4. doi:<https://doi.org/10.1038/s41560-022-01104-8>.
- [3] Lyons L, Lecomte E, Georgakaki A, Letout S, Mountraki A. Clean energy technology observatory: heat pumps in the European Union - 2023 status report on technology development, trends, value chains and markets; 2023. <https://publications.jrc.ec.europa.eu/repository/handle/JRC134991>.
- [4] European Heat Pump Association. Heat pump sales fall by 5% while eu delays action; 2023. <https://www.ehpa.org/news-and-resources/news/heat-pump-sales-fall-by-5-while-eu-delays-action/> [Accessed 30.05.2024].
- [5] European Heat Pump Association (EHPA). Pump it down: why heat pump sales dropped in 2023; Apr 2024. https://www.ehpa.org/wp-content/uploads/2024/04/Pump-it-down-why-heat-pump-sales-dropped-in-2023_EHPA_April-2024.pdf.
- [6] Nolting L, Steiger S, Praktiknjo A. Assessing the validity of European labels for energy efficiency of heat pumps. *J Build Eng* 2018;18:476–86. doi:<https://doi.org/10.1016/j.jobe.2018.02.013>.
- [7] Weigert A. Identification and classification of heat pump problems in the field and their implication for a user-centric problem recognition. *Energy Inform* 5(1):2022. doi:<https://doi.org/10.1186/s42162-022-00250-3>.
- [8] Che Z, Sun J, Hongming N, Yuan Y, Qiu Z, Tao D. A novel method for intelligent heating: on-demand optimized regulation of hydraulic balance for secondary networks. *Energy* 2023;282:128900. doi:<https://doi.org/10.1016/j.energy.2023.128900>.
- [9] Tejada A, Milu A, Riviere P, Marchio D. Energy consequences of non-optimal heat pump parameterization. In: International High Performance Buildings Conference; 2014. <https://api.semanticscholar.org/CorpusID:9906298>.
- [10] Oltarzewska A, Krawczyk D. Analysis of heat pumps efficiency in selected locations - a case study. *Environ Clim Technol* 2022;26:648–57. doi:<https://doi.org/10.2478/rtuect-2022-0049>.
- [11] Weigert A, Hopf K, Günther SA, Staake T. Heat pump inspections result in large energy savings when a pre-selection of households is performed: a promising use case of smart meter data. *Energy Policy* 2022;169:113156. doi:<https://doi.org/10.1016/j.enpol.2022.113156>.
- [12] Winkler J, Ramaraj S. Field validation of air-source heat pumps for cold climates. National Renewable Energy Laboratory (NREL); 2023. doi:<https://doi.org/10.2172/1973090>.
- [13] Deng J, Wei Q, Liang M, Shi H, Zhang H. Does heat pumps perform energy efficiently as we expected: field tests and evaluations on various kinds of heat pump systems for space heating. *Energy Build* 2019;182:172–86. doi:<https://doi.org/10.1016/j.enbuild.2018.10.014>.
- [14] Schulz M, Kemmler T, Kumm J, Hufendiek K, Thomas B. A more realistic heat pump control approach by application of an integrated two-part control. *Energies* 2020;13:2752. doi:<https://doi.org/10.3390/en13112752>.
- [15] Huchtemann K, Streblov R, Müller D. Adaptive supply temperature control for domestic heat generators. In: Proceedings of BS 2013: 13th conference of the international building performance simulation association; Aug 2013. doi:<https://doi.org/10.26868/25222708.2013.1416>.
- [16] Ruelens F, Iacovella S, Claessens BJ, Belmans R. Learning agent for a heat-pump thermostat with a set-back strategy using model-free reinforcement learning. *Energies* 2015;8:8300–18. doi:<https://doi.org/10.3390/en8088300>.
- [17] Thorsteinsson S, Jensen S, Bendtsen J. Model predictive control of heat pump based on a regression model fitted to data measured in accordance to ehpa regulation. In: E3S web of conferences; vol. 246; 2021. p. 11008. doi:<https://doi.org/10.1051/e3sconf/202124611008>.
- [18] Edwards KC, Finn DP. Generalised water flow rate control strategy for optimal part load operation of ground source heat pump systems. *Appl Energy* 2015;150:50–60. doi:<https://doi.org/10.1016/j.apenergy.2015.03.134>.
- [19] Wang S, Burnett J. Online adaptive control for optimizing variable-speed pumps of indirect water-cooled chilling systems. *Appl Therm Eng* 2001;21(11):1083–103. doi:[https://doi.org/10.1016/S1359-4311\(00\)00109-5](https://doi.org/10.1016/S1359-4311(00)00109-5).

- [20] Karlsson F, Fahlén P. Capacity-controlled ground source heat pumps in hydronic heating systems. *Int J Refrig* 2007;30(2):221–9. doi:<https://doi.org/10.1016/j.ijrefrig.2006.08.008>.
- [21] Oshurbekov S, Kazakbaev V, Prakhit V, Dmitrievskii V, Gevorkov L. Energy consumption comparison of a single variable-speed pump and a system of two pumps: variable-speed and fixed-speed. *Appl Sci* 2020;10:8820. doi:<https://doi.org/10.3390/app10248820>.
- [22] Thibault QP, Salom J, Costa-Castelló R. Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings. *J Process Control* 2019;74:35–49. doi:<https://doi.org/10.1016/j.jprocont.2018.03.006>. Efficient energy management.
- [23] Huchtemann K. Supply temperature control concepts in heat pump heating systems [PhD thesis]. RWTH Aachen; 2015. https://www.researchgate.net/publication/284878878_Supply_temperature_control_concepts_in_heat_pump_heating_systems.
- [24] Hoogmartens J, Helsen L. Influence of control parameters on the system performance of ground coupled heat pump systems: a simulation study. In: *Proceedings of building simulation 2011: 12th conference of international building performance simulation association*; 2011. https://publications.ibpsa.org/proceedings/bs/2011/papers/bs2011_1200.pdf.
- [25] Brudermueller T, Potthoff U, Fleisch E, Wortmann F, Staake T. Estimation of energy efficiency of heat pumps in residential buildings using real operation data. *Nat Commun* 2025;16(1):2834. doi: <https://doi.org/10.1038/s41467-025-58014-y>.
- [26] Thorsteinsson S, Arash Sand Kalae A, Vogler-Finck P, Lund Stærnrose H, Katic I, Dimon Bendtsen J. Long-term experimental study of price responsive predictive control in a real occupied single-family house with heat pump. *Appl Energy* 2023;347:121398. doi:<https://doi.org/10.1016/j.apenergy.2023.121398>.
- [27] You Z, Dirk Lumpp S, Doepfert M, Tzscheutschler P, Goebel C. Leveraging flexibility of residential heat pumps through local energy markets. *Appl Energy* 2024;355:122269. doi:<https://doi.org/10.1016/j.apenergy.2023.122269>.
- [28] Verein Deutscher Ingenieure. VDI 4645 Blatt 1: heating systems with heat pumps in single- and multi-family houses - planning, construction, operation - trainings, examinations, certifications of qualification. VDI Standard; 2023.
- [29] Junkers. Installationsanleitung für den Fachmann: Bedieneinheit CR 400 | CW 400 | CW 800; 2014. <https://junkers-de-de.csbchtt-documents.com/download/file/file/6720894052.pdf>.
- [30] Energie Schweiz. Operational optimisation - heating: set the heating curve correctly. Swiss Federal Office of Energy; 2022. <https://pubdb.bfe.admin.ch/en/publication/download/9982> [Accessed 30.10.2024].
- [31] Jayathissa P, Quintana M, Abdelrahman M, Miller C. Humans-as-a-sensor for buildings—intensive longitudinal indoor comfort models. *Buildings* 2020;10(10). ISSN 2075-5309. doi:<https://doi.org/10.3390/buildings10100174>.
- [32] Bosch Home Comfort. Installationsanleitung für die Fachkraft. Bedieneinheit CR 120. EN: Installation instructions for the specialist. CR 120 control unit. Bosch Home Comfort; 2024. <https://www.bosch-homecomfort.com/web-etk/documents/doc?id=513207>.
- [33] Justyna Werner-Juszczak A, Siuta-Olcha A. Assessment of the impact of setting the heating curve on reducing gas consumption in a residential building while ensuring thermal comfort. *J Build Eng* 2024;94:110032. doi:<https://doi.org/10.1016/j.job.2024.110032>.
- [34] Albers K-J. Taschenbuch für Heizung und Klimatechnik 2019/2020: einschließl.ich Trinkwasser-und Kältetechnik sowie Energiekonzepte. Deutscher Industrie-Verlag; 2018. https://ezb.ur.de/detail.phtml?jour_id=239615&bibid=SLUB.
- [35] Potočník P, Vidrih B, Kitanovski A, Govekar E. Analysis and optimization of thermal comfort in residential buildings by means of a weather-controlled air-to-water heat pump. *Build Environ* 2018;140:68–79. doi:<https://doi.org/10.1016/j.buildenv.2018.05.044>.
- [36] Peeters LF, Van der Veken J, Hens H, Helsen L, D'Haeseleer W. Control of heating systems in residential buildings: current practice. *Energy Build* 2008;40(8):1446–55. doi:<https://doi.org/10.1016/j.enbuild.2008.02.016>.
- [37] Schäuble D, Marian A, Cremonese L. Conditions for a cost-effective application of smart thermostat systems in residential buildings. *Appl Energy* 2020;262:114526. doi:<https://doi.org/10.1016/j.apenergy.2020.114526>.
- [38] ASHRAE Standard. Thermal environmental conditions for human occupancy. ASHRAE; 2017. <https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy>.
- [39] Rutz AL, Moran MJ. Rule-based thermostat design for night setback of heat pumps. *Energy* 1990;15(11):935–41. doi:[https://doi.org/10.1016/0360-5442\(90\)90018-W](https://doi.org/10.1016/0360-5442(90)90018-W).
- [40] Burak Gunay IB-MH, O'Brien W, Bursill J. Development and implementation of a thermostat learning algorithm. *Sci Technol Built Environ* 2018;24(1):43–56. doi:<https://doi.org/10.1080/23744731.2017.1328956>.
- [41] Jayathissa P, Quintana M, Sood T, Nazarian N, Miller C. Is your clock-face cozie? A smartwatch methodology for the in-situ collection of occupant comfort data. *J Phys Conf Ser* 1343 2019 Nov; 1:012145. doi:<https://doi.org/10.1088/1742-6596/1343/1/012145>.
- [42] Huchtemann K, Müller D. Simulation study on supply temperature optimization in domestic heat pump systems. *Build Environ* 2013;59:327–35. doi:<https://doi.org/10.1016/j.buildenv.2012.08.030>.
- [43] Madani H, Roccatello E. A comprehensive study on the important faults in heat pump system during the warranty period. *Int J Refrig* 2014;48:19–25. doi:<https://doi.org/10.1016/j.ijrefrig.2014.08.007>.
- [44] Madani H. The common and costly faults in heat pump systems. *Energy Procedia* 2014;61:1803–6. doi:<https://doi.org/10.1016/j.egypro.2014.12.217>. International Conference on Applied Energy, ICAE2014.
- [45] Potočník P, Govekar E. Adaptive optimization of heating curves in buildings heated by a weather-compensated heat pump. *Sci Technol Built Environ* 2019;25(10):1380–93. doi:<https://doi.org/10.1080/23744731.2019.1616984>.
- [46] Sun Y, Xintian L, Wei W, Xue H, Wang W, Deng S. Development of a variable water temperature control method for air source heat pump based on the supply-demand balance. *Sustain Energy Technol Assess* 52:2022. doi:<https://doi.org/10.1016/j.seta.2022.102366>.
- [47] Sun Y, Chen X, Shangjiang W, Wei W, Wang W, Deng S. Performance analysis of air source heat pump space heating system with an adaptive control for supply water temperature. *Appl Therm Eng* 211:2022. doi:<https://doi.org/10.1016/j.applthermaleng.2022.118401>.
- [48] Mofidi F, Akbari H. Intelligent buildings: an overview. *Energy Build* 2020;223:110192. doi:<https://doi.org/10.1016/j.enbuild.2020.110192>.
- [49] Serale G, Fiorentini M, Capozzoli A, Bernardini D, Bemporad A. Model predictive control (MPC) for enhancing building and HVAC system energy efficiency: problem formulation, applications and opportunities. *Energies* 2018;11(3):631. doi:<https://doi.org/10.3390/en11030631>.
- [50] Sun Y, Xue H, Wang W, Shangjiang W, Yong W, Hong Y, et al. Development of an optimal control method of chilled water temperature for constant-speed air-cooled water chiller air conditioning systems. *Appl Therm Eng* 2020;180:115802. doi:<https://doi.org/10.1016/j.applthermaleng.2020.115802>.
- [51] Lindelöf D, Afshari H, Alisafaei M, Biswas J, Caban M, Moccellini X, et al. Field tests of an adaptive, model-predictive heating controller for residential buildings. *Energy Build* 2015;99:292–302. doi:<https://doi.org/10.1016/j.enbuild.2015.04.029>.
- [52] Hee Kang W, Yoon Y, Hyeon Lee J, Woo Song K, Tae Chae Y, Ho Lee K. In-situ application of an ANN algorithm for optimized chilled and condenser water temperatures set-point during cooling operation. *Energy Build* 2021;233:110666. doi:<https://doi.org/10.1016/j.enbuild.2020.110666>.
- [53] Zhang Z, Chong A, Pan Y, Zhang C, Poh Lam K. Whole building energy model for HVAC optimal control: a practical framework based on deep reinforcement learning. *Energy Build* 2019;199:472–90. doi:<https://doi.org/10.1016/j.enbuild.2019.07.029>.
- [54] Brandi S, Savino Piscitelli M, Martellacci M, Capozzoli A. Deep reinforcement learning to optimise indoor temperature control and heating energy consumption in buildings. *Energy Build* 2020;224:110225. doi:<https://doi.org/10.1016/j.enbuild.2020.110225>.
- [55] Schlemminger M, Ohrdes T, Schneider E, Knoop M. Dataset on electrical single-family house and heat pump load profiles in Germany. *Sci Data* 2022 Feb; 9(1):56. ISSN 2052-4463. doi:<https://doi.org/10.1038/s41597-022-01156-1>.
- [56] Fraunhofer Institute for Solar Energy Systems ISE. WPsmart im Bestand: Schlussbericht. Technical Report. Freiburg, Germany: Fraunhofer Institute for Solar Energy Systems ISE; July 2022. Available online at: https://wp-monitoring.ise.fraunhofer.de/wp-smart-im-bestand/download/Berichte/BMWi-03ET1272A-WPsmart_im_Bestand-Schlussbericht.pdf.
- [57] European Committee for Standardization. EN 14825: 2022: air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling – testing and rating at part load conditions and calculation of seasonal performance. Technical Report. Brussels, Belgium: European Committee for Standardization (CEN); 2022. <https://standards.cen.eu>.
- [58] O'Hegarty R, Kinnane O, Lennon D, Colclough S. Air-to-water heat pumps: review and analysis of the performance gap between in-use and product rated performance. *Renew Sustain Energy Rev* 2022;155:111887. doi:<https://doi.org/10.1016/j.rser.2021.111887>.
- [59] International Organization for Standardization. Ergonomics of the thermal environment – analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. International Standard; 2005. <https://www.iso.org/standard/39155.html>.
- [60] Deutscher Wetterdienst (DWD). DWD climate data center (CDC); 2024. <https://www.dwd.de/DE/leistungen/opendata/opendata.html> [Accessed 07.01.2024].
- [61] Caird S, Roy R, Potter S. Domestic heat pumps in the UK: user behaviour, satisfaction and performance. *Energy Effic* 2012;5(3):283–301. doi:<https://doi.org/10.1007/s12053-012-9146-x>.
- [62] Oikonomou E, Zimmermann N, Davies M, Oreszczyn T. Behavioural change as a domestic heat pump performance driver: insights on the influence of feedback systems from multiple case studies in the UK. *Sustainability* 2022;14(24):16799. doi:<https://doi.org/10.3390/su142416799>.
- [63] Winkler M, Heptonstall P, Gross R. Reducing heat pump installed costs: reviewing historic trends and assessing future prospects. *Appl Energy* 2024;375:124014. doi:<https://doi.org/10.1016/j.apenergy.2024.124014>.
- [64] Szreder M, Miara M. Impact of compressor drive system efficiency on air source heat pump performance for heating hot water. *Sustainability* 2020;12:10521. doi:<https://doi.org/10.3390/su122410521>.
- [65] Semmelmann L, Hertel M, Kircher KJ, Mikut R, Hagenmeyer V, Weinhardt C. The impact of heat pumps on day-ahead energy community load forecasting. *Appl Energy* 2024;368:123364. doi:<https://doi.org/10.1016/j.apenergy.2024.123364>.
- [66] Evens M, Arteconi A. Heat pump digital twin: an accurate neural network model for heat pump behaviour prediction. *Appl Energy* 2025;378:124816. doi:<https://doi.org/10.1016/j.apenergy.2024.124816>.
- [67] Fischer D, Wolf T, Wapler J, Hollinger R, Madani H. Model-based flexibility assessment of a residential heat pump pool. *Energy* 2017;118:853–64. doi:<https://doi.org/10.1016/j.energy.2016.10.111>.
- [68] Narayanaswamy B, Balaji B, Gupta R, Agarwal Y. Data driven investigation of faults in HVAC systems with model, cluster and compare (MCC). In: *Proceedings of the 1st ACM conference on embedded systems for energy-efficient buildings, BuildSys '14*; New York, NY, USA: Association for Computing Machinery; 2014. p. 50–9. doi:<https://doi.org/10.1145/2674061.2674067>.
- [69] Levesque A, Osorio S, Herkel S, Pahle M. Rethinking the role of efficiency for the decarbonization of buildings is essential. *Joule* 2023;7(6):1087–92. doi:<https://doi.org/10.1016/j.joule.2023.05.011>.