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Review article

A review of recent progress in the design and integration of domestic heat pumps

Andreas V. Olympios[a,b,c], Paul Sapin[a], Matthias Mersch[a,d], Abdullah M. Maghrabi[a], Christos N. Markides[a,*]

[a] Clean Energy Processes (CEP) Laboratory and The Sargent Centre for Process Systems Engineering, Department of Chemical Engineering, Imperial College London, London, UK
[b] PV Technology Laboratory, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus
[c] PHAETHON Centre of Excellence for Intelligent, Efficient and Sustainable Energy Solutions, Nicosia, Cyprus
[d] Centre for Environmental Policy, Imperial College London, London, UK

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ABSTRACT

Electric (mechanical vapour-compression) heat pumps are acknowledged as a key technology for heat decarbonisation, their role being evidently more significant than thermally driven heat pumps and hydrogen boilers. The International Energy Agency estimates that, assuming governments meet their commitments, the global capacity of electric heat pumps will nearly triple by 2030. Heat pump systems come in a variety of designs, including system configurations, component (e.g., heat exchanger, compressor, working fluid) selection, and operation strategies that have a significant effect on performance and cost. In this article, we review current progress in technology development and in the methods used for techno-economic performance assessments of domestic (i.e., residential) heat pumps in the range of a few ~kWs. The principles upon which heat pump operation and performance depend are first stated. Then, drawing from widely used performance indicators and published data on hundreds of commercially available heat pump products and components over a wide range of operating conditions, a detailed methodology is presented for obtaining performance and cost estimates. A synopsis of potential synergies with other heating, cooling and storage technologies is presented, demonstrating that appropriate integration and operation are required to maximise cost-effectiveness and emission reduction capabilities. Furthermore, whole-energy system implications of widespread heat electrification and current policy measures supporting electric heat pumps in different countries are discussed. The models and analyses presented in this review are useful to a diverse set of stakeholders, including energy technology and system modellers, technology manufacturers, end-users, government, and policy makers.

1. Introduction

The transition to a low-carbon energy system is a challenge being tackled by engineers, scientists, economists, and policy makers all around the world. In this effort, the provision of hot water, space heating and space cooling in an efficient and low-cost way is necessary to meet sustainability goals. Heating and cooling account for more than half of the total energy consumption globally and almost 20% of global emissions are attributed to the residential sector [1]. Most major economies have yet to decarbonise heating in buildings, and as recently stated by the International Renewable Energy Agency (IRENA), progress worldwide is still inadequate [2]. For example, around 70% of domestic heating in the US and Germany still relies on natural gas and oil [3,4], while more than 80% of UK homes still utilise gas boilers for heating [5].

One of the main low-carbon alternatives to boilers that can be adopted by householders are electric (mechanical vapour-compression) heat pumps [6]. Electric heat pumps only need a fraction of the energy input of a traditional gas or oil boiler to provide the same heat output. The high thermodynamic performance of electric heat pumps compared to boilers, together with the increasing pressure for heat decarbonisation [7] and the growing integration of renewable energy sources in electricity grids [8], make electric heat pumps one of the most promising technologies to meet global sustainability goals. Towards the end of 2022, the International Energy Agency (IEA) stated that the pace of electric heat pump installations globally reached record levels, with growth in sales in the European Union reaching 35% in 2021 [9], while this growth later increased to 38% in 2022 [10]. In 2023, heat pump sales experienced their first decline in a decade, dropping by 5% [11]. This decline shows that there are still ongoing challenges in achieving

* Corresponding author.
E-mail address: c.markides@imperial.ac.uk (C.N. Markides).

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Nomenclature

Abbreviations

AHRI	Air-conditioning Heating & Refrigeration Institute
ASHP	Air-source heat pump
COP	Coefficient of performance
DSHP	Dual-source heat pumps
EER	Energy efficiency ratio
EHPA	European Heat Pump Association
EOS	Equation of state
GSHP	Ground-source heat pump
GWP	Global warming potential
HC	Hydrocarbons
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HFO	Hydrofluoroolefins
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LCC	Life-cycle cost
LCOH	Levelised cost of heating
LCOC	Levelised cost of cooling
LMTD	Logarithmic mean temperature difference
NTU	Number of transfer units
PBT	Payback time
PCM	Phase-change material
PV	Photovoltaic
PVT	Photovoltaic-thermal
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
SIC	Specific investment cost
TES	Thermal energy storage
SPF	Seasonal performance factor

Greek symbols

ε	Relative uncertainty (-)
η	Efficiency (-)

Symbols

A	Area (m^2)
C	Cost (£)
$\mathbb{C}$	Heat capacity (J/K)
c_p	Specific heat capacity (J/kg K)
h	Specific enthalpy (J/kg)
$\dot{m}$	Mass flowrate (kg/s)
P	Pressure (Pa)
Q	Heat (J)
$\dot{Q}$	Heat transfer rate (W)
T	Temperature (K)
ΔT	Temperature difference (K)
U	Overall heat transfer coefficient (W/m^{2}K)
u	Absolute uncertainty (-)
V	Volume (m^3)
$\dot{V}$	Volumetric flowrate (m$^{3/s}$)
W	Work (J)
$\dot{W}$	Power (W)

Subscripts/superscripts

c	Cold
cyl	Hot-water cylinder
comp	Compressor
cond	Condenser
el	Electricity
evap	Evaporator
h	Heat
in	Inlet
is	Isentropic
max	Maximum
min	Minimum
pp	Pinch point
sat	Saturated
sdt	Saturated discharge temperature
sh	Superheating
src	Source
sst	Saturated suction temperature
wf	Working fluid

widespread adoption [12]. A summary of heat pump sales per 1,000 households from 2021 to 2023 and heat pump stock per 1,000 households in 2023 as recorded by the European Heat Pump Association (EHPA) [10] is shown for several European countries in Fig. 1, showing the spectacular increase in heat pump capacity.

Achieving a high uptake of electric heat pumps requires addressing a wide range of challenges. One of the main challenges is the high upfront cost. Gas and oil boilers are still significantly cheaper, most often costing less than half of electric heat pumps [13]. Additionally, in many large economies electricity prices are high compared to natural gas prices [14,15], which reduces the potential for long-term energy savings. Government intervention through subsidies and grants can be of vital importance.

Electric heat pumps in domestic heating and cooling applications use electricity to transfer heat from a cold source to hot water or air. The performance and cost of heat pumps highly depend on various design variables, including the choice of heat source (air, ground, water), type and size of components (compressors, expansion valves, heat exchangers), and selection of working fluid [16]. Furthermore, performance and cost can be substantially affected by the choice of control strategy [17] and the integration of heat pumps into other systems [8].

The multiple ways in which electric heat pumps can be designed and operated at domestic level has led many authors to summarise related research. Some authors have provided an overview of the current status, performance, components and economic issues [18,19], while other reviews have focused on the integration with other technologies such as gas boilers [20], solar technologies [21,22] and thermal energy storage (TES) [23,24]. Furthermore, some recent studies have focused less on modelling and more on the practical issues arising from previous heat pump field trials [25] as well as on social and market acceptance issues [26]. In all review articles, it is made clear that the electrification of home heating through heat pumps will be vital to meet environmental sustainability goals, but economic, technical and awareness issues still exist. Although an effort was made in previous review articles to capture both technical and non-technical heat pump design aspects, electric heat pumps are rapidly evolving, and various advancements in novel working fluids, component designs and smart control methods have not yet been summarised. Furthermore, no effort was conducted to summarise modelling methods and predict cost and performance in different applications and scenarios.

In this article, we present a critical review of recent advancements in the design and integration of electric heat pumps for domestic applications. In many cases, insufficient documentation related to heat pump components means that evaluating the performance and cost of these systems in different conditions can be complicated. We have gathered a variety of useful recent resources, and focus is for the first time placed

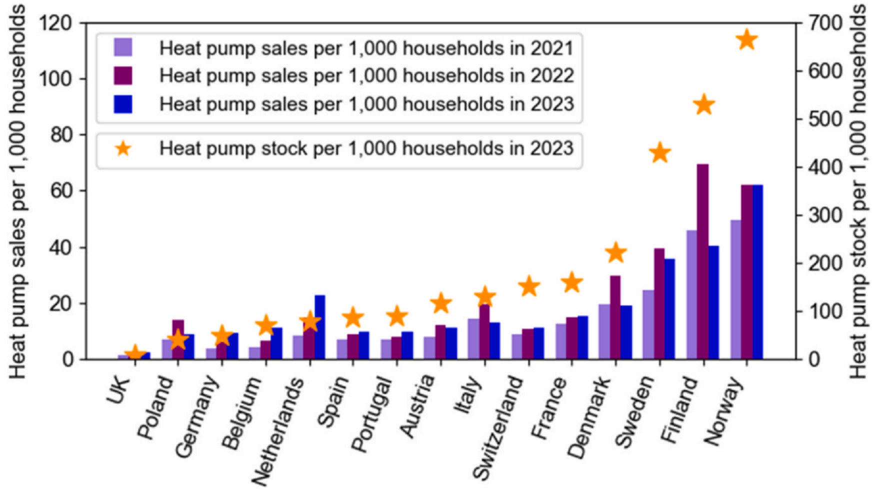

Fig. 1. Heat pump sales per 1,000 households from 2021 to 2023, and heat pump stock per 1,000 households in 2023 for various European countries, as reported by the EHPA [11].

on a detailed analysis of state-of-the-art modelling methodologies. The primary aim of this article is to guide techno-economic comparisons across various electric heat pump types. Specifically, the review sets the groundwork for modelling domestic electric heat pump technologies in a unified manner, by the:

- Provision of a synopsis of the current development of electric heat pump technologies.
- Identification of multi-fidelity heat-pump modelling approaches, ranging from technology-agnostic methods to comprehensive data-driven, thermodynamic and component-costing models.
- Evaluation of the potential integration of electric heat pumps with domestic solar technologies, energy storage solutions, and other heating systems.
- Examination of the broader implications of widespread electrification and current policy measures across different countries.

Engineers and policymakers can use the findings to identify relevant techno-economic indicators and methodologies for predicting electric heat pump performance under diverse conditions and scenarios.

In Section 2, an overview of the domestic electric heat pump working principles, technology characteristics and performance indicators is provided. Then, recent progress in components and modelling approaches for domestic heat pumps are discussed in Section 3. The role of smart integration with other systems is discussed in Section 4, while Section 5 involves an assessment of whole-energy system electrification implications and policies. Concluding remarks and future technology perspectives are provided in Section 6.

2. Working principles, components and definitions

In this section, the main operating principles of domestic electric heat pumps are defined. This is followed by a discussion of relevant performance indicators and key components.

2.1. Cycle description

The main components of an electric single-stage-compressor vapour-compression heat pump are shown in Fig. 2 and involve: (i) a compressor; (ii) an expansion valve; and (iii) two heat exchangers acting as condenser and evaporator units [27,28]. In a typical heat pump cycle, a working fluid, often referred to as the refrigerant, undergoes repeated phase transitions. The vapour working fluid is first compressed, which requires electrical energy (Process 1–2). Then, it enters the condenser, where it has a higher temperature than the heat-sink fluid, and heat is rejected (Process 2–3). In domestic applications, the heat-sink fluid can be hot water, which is used to satisfy the domestic hot water demand or is passed through radiators to provide space heating. The heat-sink fluid can also be the air of the internal environment, in which case space heating is provided directly (without the need for radiators) but no hot water is provided. During heat rejection, the working fluid is condensed, and then moves through an expansion valve that lowers the

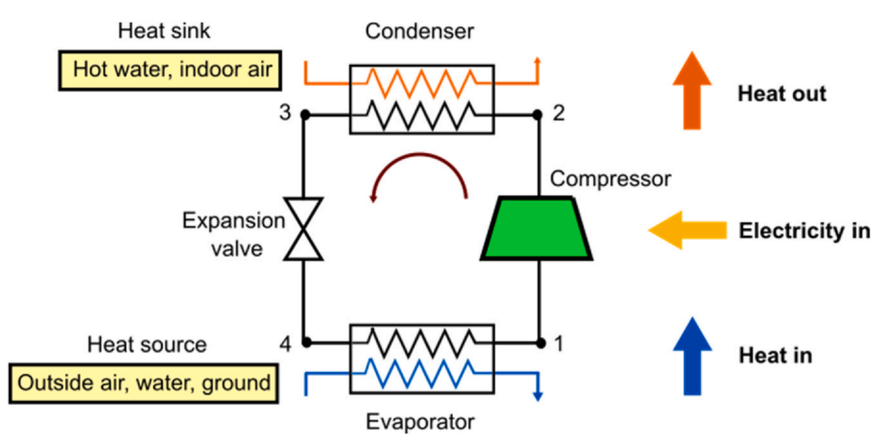

Fig. 2. Schematic showing the basic components of an electric single-stage-compressor vapour-compression heat pump (typical in domestic applications). Electricity is used to transfer heat from a heat-source fluid (e.g., outside air, flowing water, ground) to a hot-sink fluid (e.g., hot water, indoor air).

Table 1
Technical performance indicators related to electric heat pumps and their definitions. Heating and cooling seasons represent the months of the year that require heating and cooling, respectively, according to the AHRI standards [31].

Technical performance indicator	Definition
Coefficient of performance (COP)	Ratio of heat output to electricity consumption at given conditions
Energy efficiency ratio (EER)	Ratio of cooling output to electricity consumption at given conditions
Seasonal coefficient of performance (SCOP)	Ratio of total annual heating provided to total annual electricity consumption for heating
Seasonal energy efficiency ratio (SEER)	Ratio of total annual cooling provided to total annual electricity consumption for cooling
Seasonal performance factor (SPF)	Ratio of total annual space heating provided to total annual electricity consumption for space heating

fluid pressure (Process 3–4). Lastly, the low-temperature and low-pressure working fluid flows through the evaporator, where it has a lower temperature than the heat-source fluid, and thus heat is injected (Process 4–1). The heat source can be the surrounding outside air [17], a nearby water flow [29], or the ground, from which heat is typically captured using boreholes or shallow slinky pipes (coiled plastic pipes, which are buried in the ground) [30].

2.2. Performance indicators

Various performance indicators exist to evaluate the efficiency and cost-effectiveness of electric heat pumps. These are summarised in Table 1 and Table 2. The technical performance indicators are aligned with the definitions provided by the American Air-Conditioning Heating & Refrigeration Institute (AHRI) [31], while techno-economic performance indicators are aligned with the definitions provided by the IEA [9] and the European Commission [32]. Heating and cooling seasons represent the months of the year that require heating and cooling, respectively. It is important to mention that methodologies for the calculation of these indicators slightly differ depending on the location and organisation, therefore careful consideration is required by manufacturers when reporting these values.

2.3. Heat sources

Heat pumps use electricity to move heat from a cold to a hot region. The appropriateness of heat sources may depend on a range of factors, including the availability of space, weather conditions, geographical location and regulatory requirements. A list of possible heat sources in domestic applications and a summary of previous studies focusing on reviewing or techno-economically analysing the performance of heat pumps based on those sources is provided in Table 3.

Apart from the various possible heat sources, electric heat pumps can be integrated with other technologies. The simultaneous decarbonisation of heating, cooling and electricity in buildings requires capturing synergistic benefits of multi-energy-vector technologies, therefore the coupling of electric heat pumps to energy storage, boiler (gas or hydrogen) systems and solar (photovoltaic, thermal, or both) systems is gaining increasing notice and is discussed in Section 4.

2.4. Components

In this section, the main components of electric heat pumps and their associated types are discussed.

2.4.1. Compressors

The compressor is a core component in the design and operation of electric heat pumps. The choice and sizing of compressors depend crucially on the operating conditions of the considered application, the type and mass flowrate of the working fluid, space limitations and noise considerations [54–56]. An in-depth examination of the domestic heat pump market has shown that three primary compressor types are commonly used in domestic applications: rotary-vane, scroll and reciprocating-piston compressors [13]. Based on this analysis, a summary of the working principles and main characteristics of these compressor types is shown in Table 4.

2.4.2. Heat exchangers

The two most common types of heat exchangers used in domestic heat-pumping applications are presented in Table 5. The condenser and evaporator could be made of plate or finned-tube heat exchangers based on whether the heat-source and -sink fluids are liquids or gases.

Table 2
Techno-economic performance indicators related to electric heat pumps and their definitions [9,32].

Techno-economic performance indicator	Definition
Specific investment cost (SIC)	Cost of purchasing a heat pump (capital cost) per unit of nominal heating or cooling output (£/kW)
Payback time (PBT)	Length of time required to recover the heat pump investment (yr)
Life-cycle cost (LCC)	Total cost over a heat pump's lifetime including capital, installation, operating, maintenance and end-of-life costs (£)
Levelised cost of heating (LCOH)	Average cost per unit of heat delivered over a heat pump's lifetime, including capital, installation, operating and maintenance costs (£/kWh)
Levelised cost of cooling (LCOC)	Average cost per unit of cooling delivered over a heat pump's lifetime, including capital, installation, operating and maintenance costs (£/kWh)

Table 3
Possible heat sources in domestic electric heat pump applications.

Heat source	Description	References
Air	Extract heat from outside (ambient) air. They involve low installation costs as no digging or piping is required on the side of heat source.	[6,17,25,33–39]
Ground	Extract heat from the ground. They have a higher and more consistent efficiency than air-source heat pumps. They require ground space and involve higher installation costs.	[40–44]
Water supply	Extract heat from nearby water flow (e.g., river, lake). They require an existing water flow and therefore they are location specific.	[45–47]
Waste heat	Extract heat from domestic sources (e.g., electric generators, wastewater, exhaust air from chimneys, cook stove)	[48–53]

Table 4
Compressor types in typical domestic heat pump applications and their characteristics.

Compressor type	Description	Characteristics
Rotary-vane	Most prevalent type in domestic applications. It consists of cylindrical cases and a rotor with eccentrically positioned vanes. As the rotor rotates, the vanes slide out, trapping and compressing the working fluid. Single-vane compressors are often known as rolling-piston compressors.	Compactness, low weight, low cost, efficient operation at low and moderate capacities [57,58]
Scroll	Employs two intermeshing scrolls, with one scroll fixed and the other orbiting eccentrically. As the orbiting scroll moves, the space between the two scrolls decreases, resulting in the compression of the working fluid.	Few moving parts, low vibration levels, long lifespan, enhanced efficiency at high capacities, quieter operation [59,60]
Reciprocating-piston	A piston is used to compress the working fluid within an enclosed cylindrical space. Can be categorised based on number of valves, cylinders, bodies, and compression stages.	High-pressure capabilities, robustness, high performance at part-load conditions, enhanced durability [61,62]

Table 5
Typical heat exchanger types in domestic heat pump applications and their characteristics.

Heat exchanger	Fluids	Description
Plate	Liquid-liquid	Comprise series of plates welded together. Each plate has a gasket arrangement, allowing for two separate channel systems and enabling the counter-current flow of the two liquids. Their main advantage when compared to other liquid-liquid types (e.g., shell and tube) are high effectiveness and compactness [13,63–65].
Finned-tube	Gas-liquid	Consist of tubes that pass through a packed array of fins supported by a frame. The liquid passes through the tubes, while fins on the outside of the tubes offer a greater contact with the surrounding gas and encourage heat transfer. Finned-tube heat exchangers, often referred to as plate fin-and-tube heat exchangers, are generally cheap and easy to maintain compared to other gas-liquid types (e.g., plate fin) [66,67].

Table 6
Typical expansion valve types in domestic heat pump applications and their characteristics [27].

Expansion valve	Description
Capillary tubes	Long, narrow tube that restricts the flow of refrigerant. It has a simple design and a fixed size, which makes it inexpensive, but only useful in small-scale applications with stable operating conditions [27,68].
Thermostatic expansion valves	An assembly of key components, including a diaphragm, a power element and a spring, enables the self-adjustment of the working fluid mass flowrate into the evaporator. This is determined by the temperature and pressure of the working fluid at the evaporator outlet, which in turn depend on the degree of superheat. These valves aim at maintaining a consistent degree of superheat, even when subjected to time-varying operating conditions [27,69].
Electronic expansion valves	The working fluid mass flowrate in the evaporator inlet is regulated by an electronic controller, which adjusts the valve opening area. This controller gets input from various sensors like thermistors (at the evaporator inlet, outlet, and the heat-source fluid outlet) and occasionally a pressure transducer. These sensors enable advanced dynamic control, optimising the heat pump's COP under time-varying operating conditions [27,70].

2.4.3. Expansion valves

The expansion valve of electric heat pumps serves two primary purposes: (i) control the degree of superheat at the outlet of the evaporator, which is necessary to avoid the injection of liquid in the compressor; and (ii) control the mass flowrate of the working fluid and the cycle pressure ratio (condenser pressure divided by evaporator pressure) for optimal heat pump performance [27]. Some of the main expansion valve options are listed in Table 6.

2.4.4. Working fluid classification

The performance of a heat pump can greatly vary depending on the choice of working fluid. It influences the heat exchange and compression processes within the heat pump cycle and determines the appropriate evaporator and condenser temperature levels. Factors such as the thermophysical properties including vapour pressure curves and heat transfer characteristics, the environmental impact, safety aspects, and relevant regulations influence the working fluid selection.

It is important to prevent leakage of working fluids to the atmosphere throughout the lifespan of heat pumps for two main reasons: (i) leaks contribute to the depletion of the ozone layer, which shields the Earth from harmful ultraviolet radiation; and (ii) the released working fluids contribute to global warming by absorbing infrared radiation [71,72]. A list of some of the main previously used, currently available and emerging working fluids in domestic heat-pumping applications along with their key characteristics is provided in Table 7. The global warming potential (GWP) is provided for a 100-year timeframe and is based on the 6th Assessment Report of the Intergovernmental Panel on Climate Change [73].

Environmental concerns have caused regulations to become more stringent [74,75], and a wide range of working fluid options have been phased out [76]. Synthetic hydrochlorofluorocarbons (HCFC) and hydrofluorocarbons (HFCs) have historically been widely used as working fluids in heat-pumping applications. R22 was a prominent choice due its high performance, but it was phased out due to its high ozone depletion potential [77], while R134a, which does not harm the ozone layer, is also being phased out due to environmental concerns and relatively lower performance than other alternatives [78].

R410a demonstrates high overall performance in many domestic heat-pumping applications, but its remarkably high GWP (2256) has caused a growing trend towards R32, which has an even better performance and lower GWP (771), and is thus dominant in domestic heating applications [79,80].

As regulations continue to become stricter, however, R32 will also be replaced by other fluids in the near future. Hydrofluoroolefins (HFOs), which are also synthetic, are gaining increasing attention (e.g., R1234yf) due to their lower GWP [81]. Hydrocarbons like propane (R290), butane (R600), isobutane (R600a), pentane (R601) and isopentane (R601a) have already received an AHREA refrigerant designation. In fact, propane (R290) is nowadays rapidly entering the domestic heat pump market, with global manufacturers either already introducing [82,83] or planning to release [84] domestic propane-based heat pumps. The challenge is that these fluids are highly

Table 7
List of some of the common working fluids in domestic heat-pumping applications and their current status and considerations [73].

Working fluid	Composition	Type	Status	GWP	Considerations
R22	Chlorodifluoro-methane	HCFC	Phased out	1960	High ozone depletion potential and GWP
R134a	1,1,1,2-Tetrafluoroethane	HFC	Being phased out	1530	High GWP
R410a	Mixture of difluoromethane and pentafluoroethane	HFC	Being phased out	2256	Very high GWP
R32	Difluoromethane	HFC	Currently used	771	Moderate GWP
R290	Propane	HC	Currently entering the market	0.02	Flammable
R1234yf	2,3,3,3-Tetrafluoropropene	HFO	Under consideration	0.5	Flammable
R600a	Isobutane	HC	Under consideration	0	Flammable
R717	Ammonia	natural	Under consideration	0	Toxic and flammable
R744	CO_2	natural	Under consideration	1	High operating pressures and complicated design

HC: = hydrocarbon; HCFC: hydrochlorofluorocarbon; HFC: hydrofluorocarbon; HFO: hydrofluoroolefin. Also, in the working fluid designations, R stands for refrigerant followed by a number indicating its specific chemical composition.

flammable, which means that they require careful handling, and they should be installed in spaces with adequate ventilation and in accordance with specified volume requirements.

Furthermore, organic working fluids, including hydrocarbons (HCs), carbon dioxide, and ammonia, are sustainable alternatives with zero or negligible ozone depletion potential and GWP [85,86]. Carbon dioxide (R744) is interesting due to low safety concerns, but it typically requires a supercritical process with high pressures, and therefore more complicated heat-pumping system designs. Ammonia (R717), on the other hand, has excellent thermophysical characteristics and is thus able to achieve outstanding performance, but it is corrosive and toxic in high concentrations.

3. Techno-economic assessment: Multi-fidelity approaches

Research and advancements in electric heat pump technology encompass a multitude of elements, such as material selection, component configuration, and design considerations. This results in a broad spectrum of available electric heat pump designs. The process of making design-related decisions often necessitates an examination of the trade-off between performance and cost. Several modelling approaches have been developed, ranging from analysing working fluids at the molecular level to optimising critical components like heat exchangers and compressors. Modelling efforts also extend to the integration of heat pumps into buildings, districts, and broader national whole-energy systems.

Energy system and planning models related to the integration of electric heat pumps to other technologies, whether at the building, energy-community, or national level, are extremely valuable in the efforts to capture how heat pumps can be best utilised in multi-energy-vector environments. However, it is important to note that many of these approaches often rely on simplified heat pump cost and performance assessment methods, which are based on fixed values or simplified, black-box relationships. This limitation arises from the trade-off between the level of detail in technology modelling and the computational resources required. Different applications require varying levels of detail in heat pump technology cost and performance. Nevertheless, across all heat pump modelling approaches, it is important to use reliable information for performance and cost to minimise simulation uncertainties and effectively support the integration of heat pumps within energy systems.

In this section, we present a broad spectrum of methodologies aimed at predicting the cost and performance of electric heat pumps. Our aim is to provide valuable information tailored to the needs of manufacturers, end-users, researchers, and policymakers, considering the specific models they may need and the objectives they seek to achieve in their respective applications.

Electric heat pumps are complex systems, and each component is subject to various energy losses and exergy destruction processes, with application limits that strongly depend on the choice of working fluid. The highly non-linear performance variations experienced, and limits faced by electric heat pumps can be captured and predicted using three main types of methods:

1. Technology-agnostic methods, which provide realistic estimates of a given technology performance solely from the external operating conditions, e.g., solely from the ambient air temperature and desired heating temperature for a domestic air-source heat pump (ASHP). These are explored in Section 3.1.
2. Data-driven methods, which are based on manufacturer data and are suitable for reliably estimating the techno-economic potential of existing, mature technologies. These are explored in Section 3.2.
3. Comprehensive physics-based and component-costing methods, which are particularly useful for the in-depth analysis of performance variations in real-world settings, for assessing and unlocking the full potential of innovative disruptive solutions, and thus for providing guidance to manufacturers. These are explored in Section 3.3.

3.1. Technology-agnostic approaches

Both data-driven and first-law based approaches face a similar, inherent limit: these methods require significant design-specific inputs. Technology-agnostic methods, on the other hand, do not require anything about the system inner workings to be specified to determine the potential of a given solution, which makes them highly attractive for the preliminary technical assessment of heat pumps for providing heating or cooling in specific conditions. On the downside, as these models do not capture the effects of the system size and design, they do not provide an informed link between performance and cost.

Unlike the theoretical Carnot coefficient of performance, which provides a theoretical upper bound to the efficiency that thermo-mechanical systems can achieve when operating between defined source and sink temperatures, design-agnostic indicators derived from finite-time thermodynamics account for the irreversibility of heat transfer across finite temperature differences [27]. As such, they provide simplified yet physics-based realistic estimates of the thermodynamic performance. Definitions and endo-reversible correlations found in the literature are summarised in Table 8.

3.2. Data-driven methods

The relationship between the size, cost and performance of ASHPs can be captured by collecting available manufacturer data and applying fitting techniques to create data-driven models. Given availability of data, the related uncertainty (i.e., variability) in technology characteristics from these models can be quantified. These data-driven models can serve as valuable tools in technology selection and energy system optimisation exercises, aiding in the reduction of uncertainties compared to the use of simplified black-box relationships.

Table 8
Technology-agnostic COP for both chiller and heat pump units.

	Heat pump COP	Chiller COP
Definition	$COP = Q_h/W_{el}$	$COP = Q_c/W_{el}$
Carnot COP	$COP = T_h/T_h - T_c$	$COP = T_c/T_h - T_c$
Endo-reversible correlation - Velasco [89]	$COP = \sqrt{T_h/T_h - T_c}$	$COP = \sqrt{T_h/T_h - T_c} - 1$
Semi-empirical correlation[a] - Blanchard [90]	$COP = T_h + \Delta T_k/T_h - T_c + \Delta T_k$	$COP = T_c/T_h - T_c + \Delta T_k$

[a] ΔT_k is an empirical temperature difference to be fine-tuned against test data. A value of 30 K is recommended for design-agnostic prediction of a heat pump performance.

Several authors have collected heat pump information and developed fits through the data. Staffell et al. [19] developed a relationship between the specific cost per unit of thermal output for 'all' types of heat pumps in the range between 5 and 100 kW_{th} based on data from the consulting company M.V.V. As the authors stated, the specific cost decreased sharply with capacity. The authors also provided figures for the average COP of ASHPs and ground-source heat pumps (GSHPs) as a function of temperature difference between heat-source and heat-sink fluids based on industrial surveys and field trials, showcasing that the average COP of ASHPs and GSHPs varies between about 2–5 and 2.5–6.5 depending on the temperature difference, respectively. Furthermore, Waite et al. [87] developed a correlation to predict the heat pump COP as a function of air temperature for electric heat pumps based on COP data gathered from more than 1,000 heat pumps found on the database of the Northeast Energy Efficiency Partnership. The authors used this to conclude that fossil fuels can be reduced to 43% of total heating energy in the U.S. using currently available heat pumps.

More recently, Gibb et al. [88] plotted the average COP of a mix of air-to-water and air-to-air heat pumps against external air temperature collected from seven field-testing studies in Canada, China, Germany, Switzerland, U.S. and UK (Fig. 3). The authors demonstrated that the average COP of heat pumps between −10 °C and 5 °C was 2.74, which is much higher than boiler-based heating and electric resistance heaters, therefore they concluded that heat pumps can provide efficient heating during cold winter in most of Europe.

In an effort to guide technology selection across various applications, the authors of this study have previously published data and associated fitting techniques related to commercially available small-scale ASHPs and GSHPs on the UK market [13,91]. The derived equations for assessing cost and specific cost relative to nominal heat output, along with the heat pump COP as a function of heat-source temperature have been reprinted and adopted here from Ref. [91] in Fig. 4 and Table 9, respectively. Furthermore, Table 9 presents additional data encompassing the cost and specific cost associated with hot water cylinders specially designed to be integrated to domestic heat pumps. It is useful to note that all cost data were collected in 2020 and therefore they should be corrected for inflation before use. The cost of heat pumps does not involve installation costs (e.g., labour) or costs related to the upgrading of domestic heating systems (e.g., replacement of radiators).

Data-driven methods not only capture variations in cost and performance but can also be used to quantify the uncertainty associated with the investigated techno-economic indicators. Uncertainty quantification can be useful for energy technology and system modellers when performing sensitivity analysis. The heat pump cost and COP correlations of Fig. 4 and Table 9 are provided alongside with uncertainty bounds based on 95% confidence intervals.

3.3. Comprehensive thermodynamic and component-costing modelling

In this section, heat pump components and modelling methods are discussed in detail.

3.3.1. Heat pump cycle modelling

The thermodynamic cycle undergone by the working fluid in a conventional electric single-stage vapour-compression heat pump is a closed-loop sequence of four processes detailed in Section 2.1, namely: (i) superheated vapour compression; (ii) near-isobaric heat removal in the condenser unit to the hot-temperature heat sink; (iii) isenthalpic expansion through the expansion valve; and (iv) near-isobaric evaporation, sucking heat from the low-temperature heat source. The equations and steps to predict the corresponding four thermodynamic states of the working fluid and thus the heat pump performance are presented below. SI units are consistently used in all equations throughout the manuscript. These units include K for temperature, Pa for pressure, J/K for heat capacity, W/m^2 K for overall heat transfer coefficient, J/kg K for specific heat capacity, and J/kg for specific enthalpy. Detailed unit descriptions are provided in the Nomenclature.

A zero-subcooling vapour-compression heat pump cycle can be fully defined by three thermodynamic parameters, namely:

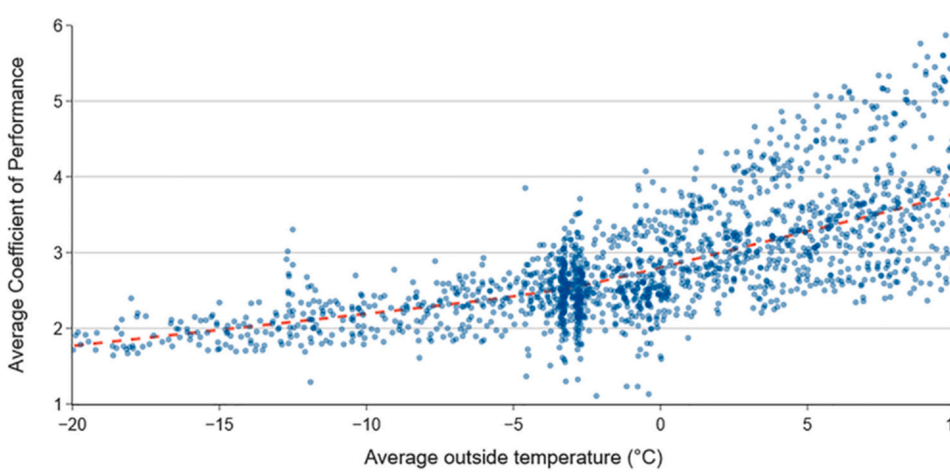

Fig. 3. Average COP of a mix of air-to-water and air-to-air heat pumps as a function of average outside temperature collected from seven field-testing studies in Canada, China, Germany, Switzerland, U.S. and UK. Reprinted from Ref. [88].

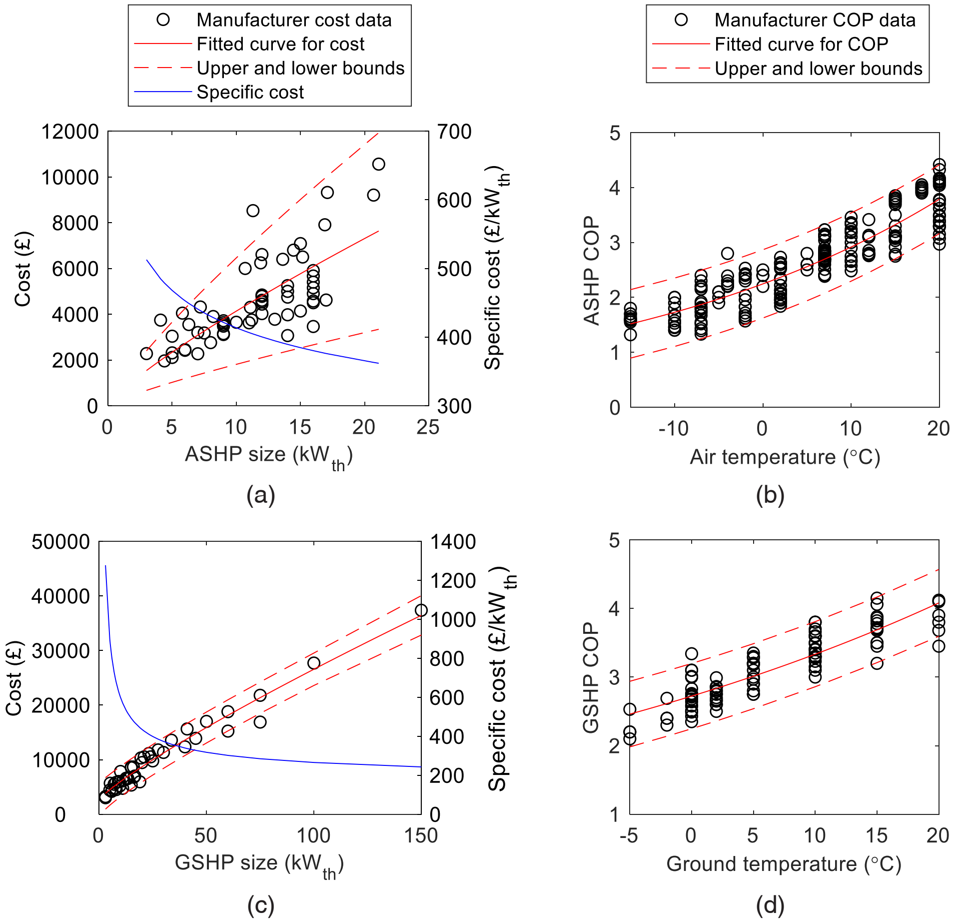

Fig. 4. Data-driven cost and performance predictions for commercially available heat pumps: (a) cost and specific cost of ASHPs as function of nominal heat output; (b) COP of ASHPs as function of ambient air temperature; (c) cost and specific cost of GSHPs as function of nominal heat output; and (d) COP of GSHPs as function of ground temperature. For COP-temperature relationships, the analysis considered small-scale heat pumps ($< 15\,kW_{th}$) and a heat-sink-fluid temperature of 55 °C. The specific cost appears in blue, while fitted curves and upper/lower prediction bounds appear in red. Adopted from Ref. [91].

- the saturated discharge temperature, T_{sdt}, which also provides the condensing pressure, P_{cond}, assuming an isobaric condensation process;
- the saturated suction temperature, T_{sst}, which also provides the evaporating pressure, P_{evap}, assuming an isobaric evaporation process; and
- the compressor suction superheat, ΔT_{sh}.

Starting at the evaporator outlet (i.e., compression suction), thermodynamic State 1 (see Fig. 2) can be determined thanks to the equation of state, f_{EOS} (discussed in Section 3.3.4):

$$T_1 = T_{sst} + \Delta T_{sh}; \text{ and} \tag{1}$$

$$h_1, s_1 = f_{EOS}(T_1, P_1), \tag{2}$$

with $P_1 = P_{evap}$. The compressor isentropic efficiency, η_{is}, can be determined from T_{sdt} and T_{sst}, either using manufacturer data or compressor efficiency maps as detailed in the Section 3.3.2. For an overall adiabatic compression process, the compressor discharge (State 2 in Fig. 2) occurs at $P_2 = P_{cond}$ and the working fluid enthalpy at the compressor outlet, h_2, is obtained as:

$$h_2 = h_1 + \frac{h_{2,is} - h_1}{\eta_{is}}, \tag{3}$$

where:

$$h_{2,is} = f_{EOS}(P_{2,is}, s_{2,is}) = f_{EOS}(P_2, s_1), \tag{4}$$

where $h_{2,is}$ is referred to as the isentropic discharge enthalpy, i.e., the enthalpy that the working fluid would reach in case of an isentropic compression ($s_{2,is} = s_1$) up to the actual discharge pressure ($P_{2,is} = P_2$).

The discharge temperature and specific entropy, T_2 and s_2, are then obtained as functions of h_2 and $P_2 = P_{cond}$. For a wet saturated (i.e., zero-subcooling) vapour-compression heat pump (typically achieved using a liquid receiver), the working fluid at the condenser outlet is a saturated liquid at the condensing pressure, P_{cond}, hence:

$$T_3 = T_{sdt}. \tag{5}$$

from which State 3 (see Fig. 2) is thus also fully defined. The throttling process through the expansion valve is an isenthalpic Joule-Thompson expansion, hence: $h_4 = h_3$. And, as the evaporation process is assumed isobaric, State 4 (see Fig. 2) is thus defined as:

$$T_4, s_4 = f_{EOS}(P_{evap}, h_4). \tag{6}$$

All four working fluid states defining the electric vapour-compression heat pump have been solely derived from the saturated suction & discharge temperatures and the suction superheat, controlled by the metering device (typically thermo- or electronic expansion valves). For given sink and source streams, it is also necessary to verify that the pinch-point constraints in the condenser and evaporator units are not violated:

- evaporator pinch-point temperature difference, $\Delta T_{pp,evap} > 0$; and,
- condenser pinch-point temperature difference, $\Delta T_{pp,cond} > 0$.

Provided that these constraints are respected, the components can be sized. Heat pump units are typically designed to supply a specific nominal heating capacity, $\dot{Q}_h$. The working fluid mass flowrate, $\dot{m}_{wf}$, can thus be determined from $\dot{Q}_h$, as:

$$\dot{Q}_h = \dot{m}_{wf}(h_2 - h_3), \tag{7}$$

Table 9
Data-driven correlations, applicability ranges and uncertainty measures for performance and cost data of ASHPs, GSHPs and hot-water cylinders. Data and analysis are taken from Ref. [91]. Price and performance data were collected in the UK in 2020.

Indicator	Model	Range	Absolute uncertainty[a]	Relative uncertainty[a]
Cost (£) of ASHPs as function of nominal heat output (kW_{th})	$C_{ASHP} = 620\dot{Q}_{ASHP}^{0.82}$	$\dot{Q}_{ASHP} < 25\ kW_{th}$	$u_{C_{ASHP}} = 2.5$k£ for $\bar{C}_{ASHP} = 4.8$k£	$\varepsilon_{C_{ASHP}} = 53\%$ for $\bar{C}_{ASHP} = 4.8$k£
Cost (£) of GSHPs as function of nominal heat output (kW_{th})	$C_{GSHP} = 470\dot{Q}_{GSHP}^{0.85} + 2600$	$\dot{Q}_{GSHP} < 150\ kW_{th}$	$u_{C_{GSHP}} = 2.9$k£ for $\bar{C}_{GSHP} = 22$k£	$\varepsilon_{C_{GSHP}} = 13\ \%$ for $\bar{C}_{GSHP} = 22$k£
COP of ASHPs as function of heat-source temperature (°C). The heat-sink temperature is 55 °C.	$COP = 2.3e^{0.026T_{src}}$	$\dot{Q}_{ASHP} < 25\ kW_{th}$ $-15 < T_{src} < 20$ °C	$u_{COP} = 0.6$ for $\bar{COP} = 2.4$	$\varepsilon_{COP} = 25\%$ for $\bar{COP} = 2.4$
COP of GSHPs as function of heat source temperature (°C). The heat-sink temperature is 55 °C.	$COP = 2.7e^{0.020T_{src}}$	$\dot{Q}_{GSHP} < 25\ kW_{th}$ $-5 < T_{src} < 20$ °C	$u_{COP} = 0.5$ for $\bar{COP} = 3.2$	$\varepsilon_{COP} = 16\%$ for $\bar{COP} = 3.2$
Cost (£) of heat-pump compatible hot-water cylinder as function of volume (m^3)	$C_{cyl} = 2100V_{cyl}^{0.35}$	$V_{cyl} < 0.6\ m^3$	$u_{C_{cyl}} = 0.5$k£ for $\bar{C}_{cyl} = 1.4$k£	$\varepsilon_{C_{cyl}} = 35\%$ for $\bar{C}_{cyl} = 1.4$k£

[a] Relative and absolute uncertainties are reported at mid-range values (denoted with an overbar $\bar{■}$).

while the heat input and power consumption rates are given as:

$$\dot{Q}_c = \dot{m}_{wf}(h_1 - h_4), \text{ and } \dot{W}_{el} = \dot{m}_{wf}(h_2 - h_1) \tag{8}$$

The coefficient of performance, COP, can then be derived from Eqs. (7) and (8), as equal to $\dot{Q}_h/\dot{W}_{el}$ for heating systems, or as $\dot{Q}_c/\dot{W}_{el}$ for chillers. The required heat exchangers area and design can finally be predicted using detailed heat exchanger models detailed in Section 3.3.3.

Along with dedicated heat exchanger models (detailed in Section 3.3.3) and component-specific costing methods detailed in the following sections, this first-law thermodynamic framework (Eqs. (1–8)) can be used to optimise the heat pump design, e.g., by identifying optimal suction and discharge saturation temperatures (i.e., optimal compressor and heat exchanger sizes for given source and sink streams), so as to minimise the specific investment cost. Furthermore, advanced compressor models (detailed in Section 3.3.2) can be implemented to predict the design and part-load performance of custom designed electric heat pumps. Since the throttling process through the expansion valve is adequately described by the heat pump model, no further physics-based methods are needed. Additionally, the literature on heat pump design does not include component-costing models for expansion valves, so no dedicated section for this component is provided.

3.3.2. *Compressor modelling*

Modelling the design and off-design operation of energy-conversion systems requires capturing the performance of different compression and expansion machines for a large range of operating conditions. In the case of heat-pump thermodynamic modelling, compressor performance can be estimated using comprehensive thermodynamic models [62,92] or performance maps that can predict efficiency for a set of given working conditions.

A wide range of first-law, or comprehensive, models have been developed to explore the inner workings, predict the capacity, identify the inherent limits of specific designs or enhance the thermodynamic performance of positive-displacement compressors, from fully-resolved 3-D transient models based on advanced computational fluid dynamics techniques [93–97] down to 0-D periodic models [98,99]. Wang et al. [61] used maps based on a comprehensive model of a reciprocating-piston expander by Sapin et al. [62] and Simpson et al. [92] and on experimental data for scroll expanders from Lemort et al. [100].

Although based on simplifying assumptions and often relying on a set of heuristic correlations, reduced-order models retain the capacity to explore novel or disruptive designs and provide an intelligible link between the compressor performance and its design, hence cost. For example, Astolfi [101] developed a data-driven screw compressor performance map based on manufacturer datasheets. In the recent work of Olympios et al. [102], the authors focused on the design and off-design operation of small-scale compressors and developed maps to represent the compressor isentropic efficiency as a function of volumetric flowrate at the compressor inlet and compressor pressure ratio for the three main types found in domestic applications. These were based on data collected from manufacturers who often report compressor performance using the ten-coefficient polynomial method suggested by AHRI [103]. The maps, which have been developed using information for 120 small-scale compressors, represent the average performance of commercially available compressors for each type. In this work, we have updated these maps to represent isentropic efficiency as a function of mass flowrate and compressor discharge-to-suction saturated temperature ratio (ratio between heat pump condensation temperature and evaporation temperature). Since compressor manufacturers often report compressor performance for these two conditions, this makes the below maps easy to use, analyse or compare with existing or novel compressors.

The compressor performance maps are second-order polynomial fits generated using the least-squares fit method. They take the following form:

$$\eta_{\text{comp,is}} = \alpha_1 + \alpha_2\left(\frac{T_{\text{sdt}}}{T_{\text{sst}}}\right) + \alpha_3 \ln(\dot{m}_{\text{wf}}) + \alpha_4\left(\frac{T_{\text{sdt}}}{T_{\text{sst}}}\right)^2 + \alpha_5\left(\frac{T_{\text{sdt}}}{T_{\text{sst}}}\right)\ln(\dot{m}_{\text{wf}}) + \alpha_6 \ln(\dot{m}_{\text{wf}})^2, \quad (9)$$

where $\dot{m}_{\text{wf}}$ is the mass flowrate of the working fluid, $\left(\frac{T_{\text{sdt}}}{T_{\text{sst}}}\right)$ the compressor discharge-to-suction saturated temperature ratio and α_1 to α_6 the obtained polynomial coefficients. The maps are shown in Fig. 5 and the corresponding polynomial coefficients are presented in Table 10.

Cost correlations were also developed to predict cost as a function of compressor inlet volumetric flowrate at the. These are reprinted here from Ref. [102] in Fig. 6 and take the following form:

$$C_{\text{comp}} = c_1 \dot{V}_{\text{comp,in}}{}^{c_2}, \quad (10)$$

where C_{comp} is the compressor cost, and c_1 and c_2 are the obtained regression coefficients.

Rotary-vane compressors were shown to exhibit isentropic efficiencies almost always exceeding 65% within the investigated temperature ratio range of 1.01–1.28. However, no commercially available units were found for flowrates exceeding $5 \cdot 10^{-3}$ m^3/s. Scroll compressors were shown to have isentropic efficiencies surpassing 70% for temperature ratios below 1.23, but the efficiency declines to as low as 50% for temperature ratios higher than 1.28. On the other hand, piston compressors were shown to perform best at high temperature ratios ranging from 1.15 to 1.35, achieving isentropic efficiencies exceeding 70%, but their performance falls short compared to rotary-vane and scroll compressors at lower temperature ratios.

3.3.3. Heat exchanger modelling

As the other heat pump components, heat exchangers can be modelled with different fidelity depending on the accuracy required and computational time available. Simple heat exchanger models use the logarithmic mean temperature difference (LMTD) to estimate heat flux. Assuming constant fluid properties and flow conditions as well as a constant overall heat transfer coefficient, U, the heat flux, $\dot{Q}$, can be calculated as:

$$\dot{Q} = \text{UA}\bullet\text{LMTD} = \text{UA}\frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1) - \ln(\Delta T_2)}, \quad (11)$$

with A being the heat exchanger area and $\Delta T_{1,2}$ the temperature differences at both ends of the heat exchanger. The heat transfer

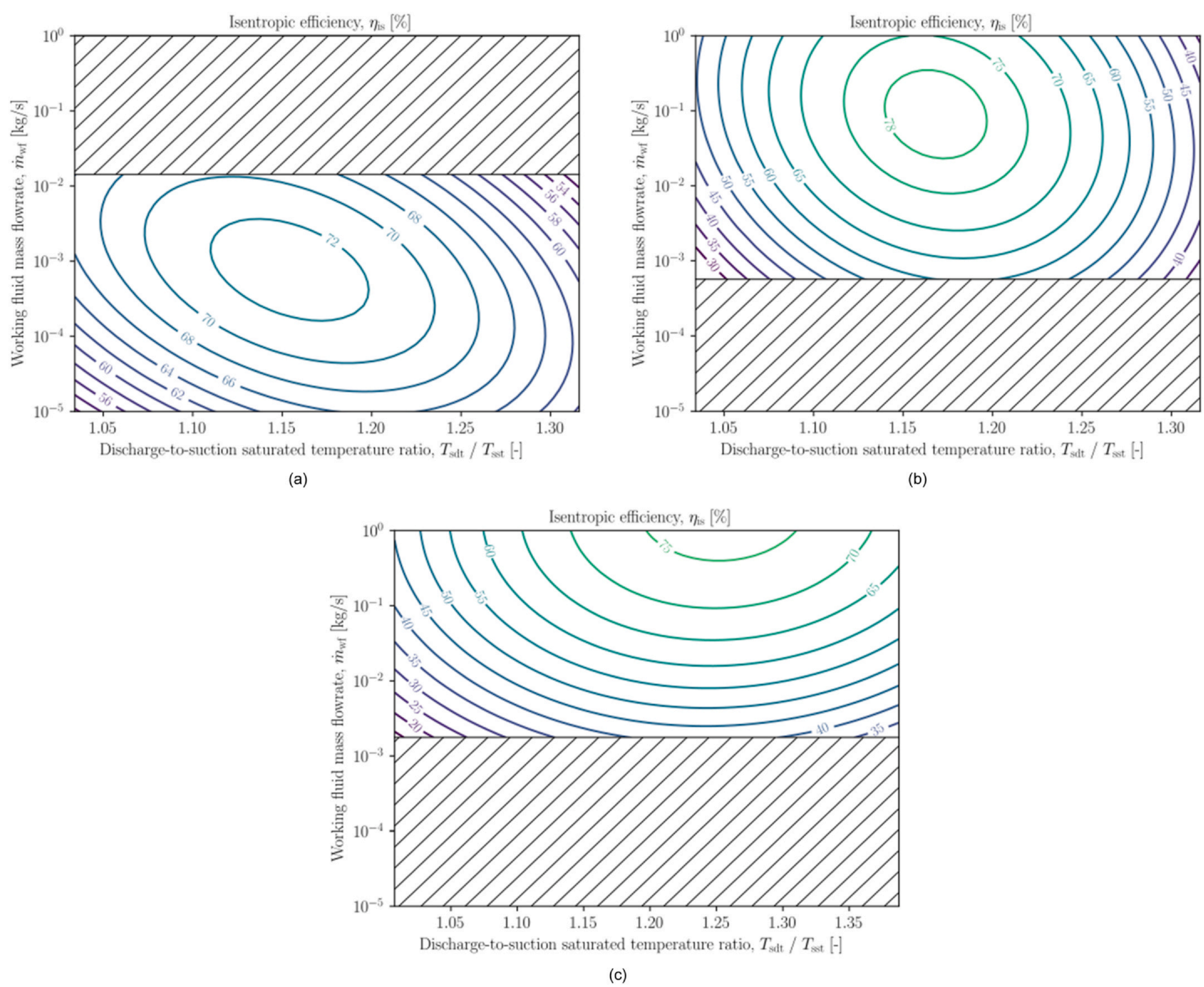

Fig. 5. Design-agnostic and fluid-independent compressor performance maps for three different compressor types: (a) rotary-vane, (b) scroll, and (c) reciprocating-piston. The maps show the isentropic efficiency as a function of the discharge-to-suction saturated temperature ratio and the working fluid mass flowrate. They are obtained based on the performance curves of 120 compressors found on the UK market. The dashed area denotes regions of the design space for which no data was found. Data obtained from Ref. [102].

Table 10
Polynomial coefficients for the calculation of isentropic efficiency (in %) for each compressor type and associated RMSE. The coefficients correspond to those of Eq. (9).

Compressor type	α_1	α_2	α_3	α_4	α_5	α_6
rotary-vane	-538	1110	17.2	-515	-26.8	-2.20
scroll	-2200	3930	22.8	-1690	-26.7	-4.00
reciprocating-piston	-739	1300	-3.23	-519	4.71	-3.66

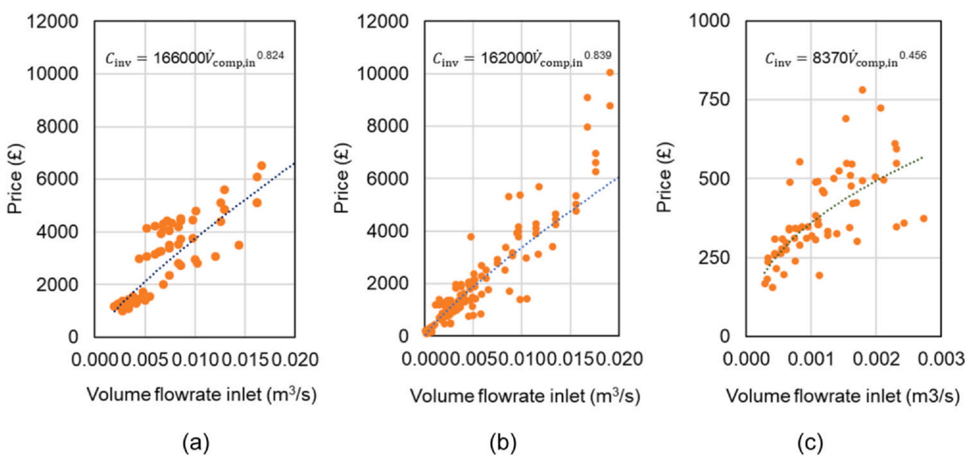

Fig. 6. Compressor price as a function of volumetric flowrate at compressor inlet for three types of compressors: (a) rotary-vane; (b) scroll; and (c) piston. Adopted from Ref. [102].

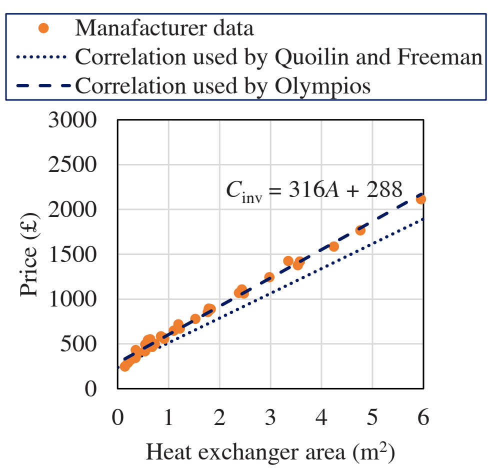

Fig. 7. Plate heat exchanger manufacturer cost data and cost correlation developed by Quoilin [107] and validated by Freeman [106] and correlation developed by Olympios [108]. Adopted from Ref. [108].

coefficient can hereby be taken from manufacturer data, estimated from experience, or calculated approximately using thermal resistance models.

Other heat exchanger models use the effectiveness-number of transfer units (ε-NTU) method. Here, the heat flux is calculated from the heat exchanger effectiveness ε, defined as the ratio of actual to theoretical maximum heat transfer rate:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{\dot{Q}}{C_{min}(T_{1,in} - T_{2,in})}, \quad (12)$$

with C_{min} being the minimum heat capacity rate $\min(\dot{m}_1 c_{p,1},\ \dot{m}_2 c_{p,2})$. Analytical expressions for the heat exchanger effectiveness based on the number of transfer units NTU are available for typical heat exchanger configurations. The NTU is hereby defined as:

$$\mathrm{NTU} = \frac{\mathrm{UA}}{C_{min}}. \quad (13)$$

It is again necessary to estimate the overall heat transfer coefficient U. Both the LMTD and the ε-NTU methods only work for constant fluid properties and single-phase flow. More sophisticated heat exchanger models avoid these issues by using a discretisation approach. The heat exchanger is divided into many small elements, and heat transfer equations are solved for each discrete element. Therefore, fluid properties and heat transfer coefficient are only assumed to be constant over small sections of the heat exchanger, yielding a higher accuracy in calculations. However, the computational complexity of the model increases with increasingly finer discretisation.

A key challenge for heat exchanger models is the calculation of heat transfer coefficients. Many different approaches and correlations have been proposed in literature, from large handbooks [104,105] to countless academic publications developing analytical and empirical methods. Additionally, heat exchanger manufacturers typically provide proprietary software to estimate the performance of their products.

In terms of heat exchanger costing, Freeman [106] compiled data on small-scale plate heat exchangers from various manufacturers and verified the applicability of the linear correlation suggested by Quoilin [107]. Olympios [108] then updated the correlation based on more recent online catalogue lists to capture recent changes in industrial economic conditions and inflation. The correlations are presented in Fig. 7.

For finned-tube heat exchangers, Olympios [108] split the cost in a fixed part equal to the fixed part of the plate heat exchanger cost (attributed to design, machining, insulation and screw fittings) and a variable part based on material cost and geometry (as developed by Lecompte et al. [109] and Stewart [110]). A correlation for the cost of the air fans was developed by Lecompte et al. [109].

3.3.4. Working fluid properties and selection

Working fluids can have a significant impact on heat pump performance. A multitude of working fluid candidates are available, as introduced in Section 2.4.4. Given the variety of available working fluids, the question of selecting the most appropriate one for a given application remains.

Optimal working fluid selection and process design is a highly researched topic. Traditional approaches involve a heuristic screening of potential working fluids followed by a process optimisation for each pre-selected working fluid [111,112]. The best-performing working fluid/process combination is then picked a solution. More sophisticated approaches combine working fluid selection and process design in one simultaneous optimisation, using a computer-aided molecular and process design (CAMPD) approach [113]. This approach is more established for other processes such as organic Rankine cycles [114,115] but can be easily adapted to heat pumps. The benefit of this approach is that no promising working fluids/mixtures are inadvertently excluded in the screening process, and no heuristic screening criteria are required.

Any heat pump process optimisation requires the calculation of thermophysical working fluid properties. This is typically done using equations of state (EOSs) that can calculate all required properties from known state variables. A variety of EOSs have been developed and are used in heat pump working fluid selection, such as the Peng-Robinson (PR) EOS [116], Suave-Redlich-Kwong (SRK) EOS [117], or different statistical associating fluid theory (SAFT) approaches [118].

The most commonly used EOS packages are NIST REFPROP [119], the industry standard for fluid property calculations, and the open-source alternative CoolProp [120]. Both REFPROP and CoolProp are primarily based on Helmholtz energy models that have been fitted to experimental data. The accuracy of both depends on the data available for fitting. For many common fluids with many experimental data points, REFPROP and CoolProp achieve excellent fits. However, for less common fluids errors may be higher, or no data is available at all, and the packages cannot be used. Other EOSs face the same issue, as they always depend on fitting to experimental data.

Group-contribution approaches aim to overcome this issue by identifying EOS parameters for functional groups rather than entire molecules. The group-contribution parameters can then be used to predict properties of fluids for which no EOS parameters are available. Another advantage of group-contribution approaches is that is allows the integration of working fluid and process design optimisation in a single optimisation step, as the functional groups of the working fluid can be translated to optimisation variables. Group-contribution approaches are available for many common EOSs, such as PR [121], SRK [122], and SAFT [123].

4. Integration of domestic electric heat pumps with other technologies

The integration of electric heat pumps with other technologies is crucial for fully harnessing their cost-effectiveness, efficiency, flexibility, and emissions-reduction potential. In this section, recent advancements made in leveraging key integration opportunities are explored.

Focus is first placed on potential synergies between heat pumps and solar technologies, such as photovoltaic (PV), photovoltaic-thermal (PVT) and solar thermal technologies in Section 4.1. The benefits, challenges and progress related to integrating heat pumps with these technologies are highlighted. Second, the progress in the integration of heat pumps with TES (hot water and phase-changing materials) are explored in Section 4.2. TES is vital to enhance the overall heating system performance, flexibility, and reliability. Then, the interactions between domestic heat pumps and backup technologies (such as electric, gas and hydrogen boilers) are examined in Section 4.3.

The examination of various integration possibilities and configurations shows that substantial benefits can be unlocked through a multi-faceted approach when selecting and integrating domestic heat pumps to other domestic technologies. The most common technologies with which heat pumps are integrated in domestic applications are shown in Fig. 8.

4.1. Integration with solar technologies

Integrating domestic heat pumps with solar systems can involve various configurations and has led to extensive research and development. Table 11 provides a summary of the main configurations and highlights a few recent relevant studies in the literature. Three types of solar systems are investigated: (i) PV; (ii) PVT; and (iii) solar thermal.

Solar PV systems have steadily gained momentum over the past decade due to their enhanced efficiency and reliability. Their integration to domestic heat pumps is becoming an opportunity to potentially achieve economic and environmental benefits for both the end-users and the energy system. A recent report published by SolarPower Europe [124], which represents over 300 organisations in the solar sector, revealed that a shift from the use of local gas boilers to PV-driven heat pumps can lead to a reduction in energy bills equal to 62%, 83% and 84% in Germany, Italy and Spain, respectively. This operational cost reduction potential was shown to be significantly higher compared to

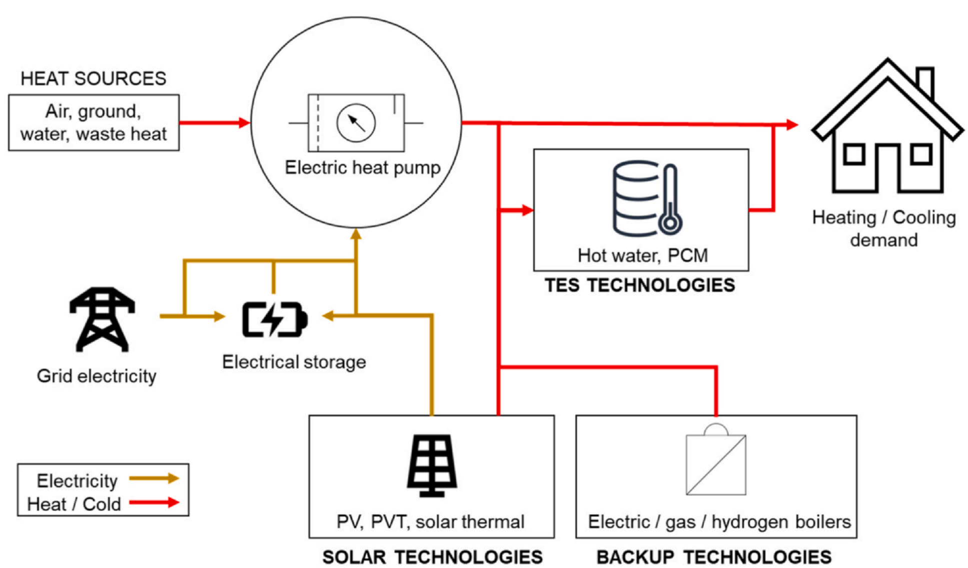

Fig. 8. Possible integration of electric heat pumps with solar, backup heating and TES technologies.

Table 11
Potential configurations and relevant studies for integrated solar-electric heat pump systems.

Solar technology	Solar – heat pump integrated system description	Refs.
PV	• PV system used to drive an electric heat pump • Heat pump used to cover the heating/cooling demand	[124–128]
PVT	• PVT system used to drive an electric heat pump and to provide heating • Heat pump used to cover the rest of the heating/cooling demand	[130–134]
Solar thermal	• Solar thermal system used to provide heating or pre-heat the electric heat pump heat-source fluid • Heat pump used to cover the rest of the heating/cooling demand	[135–138]

installing a heat pump alone (32%, 11% and 28% in Germany, Italy and Spain, respectively). Furthermore, the recent review article of Nazari et al. [125] summarised various research works on integrated PV-heat-pump systems, highlighting that, depending on the location, building and weather characteristics, these integrated systems have shown potential for exceeding 50% in energy savings and 70% reduction in CO_2 emissions compared to natural gas boilers. Facci et al. [126], investigated the effectiveness of substituting natural gas boilers with PV-driven ASHPs for three locations with different weather characteristics and demonstrated a CO_2 emission reduction and an energy cost saving of up to 73% and 41%, respectively.

Although PV-driven heat pumps have operational cost saving potential, the capital cost is significantly higher than boiler alternatives. Sommerfeldt and Pearce [127] recently conducted a techno-economic study involving life-cycle analysis for the integration of heat pumps with solar PV systems to replace gas heating for a representative house in the U.S. The authors showed the significant effect of domestic electricity prices on the competitiveness of PV-driven ASHPs. At current U.S. electricity and gas prices, the life-cycle costs between a natural gas-based heating system and a PV-driven ASHPs were found to be nearly identical, but there is a critical tipping point at a specific electricity price (currently 0.13 USD/kWh), beyond which the integration of PVs becomes cost-effective. Furthermore, it is important to emphasise that the economic and environmental characteristics of PV-driven heat pumps of proper rely on intelligent control. Clift et al. [128] recently tested the optimised operation of a PV-integrated variable-speed ASHP for four ambient temperature conditions (in the range 7–35 ˚C) and demonstrated that a real-time controller can be used to reduce electricity consumption by 88% even in the absence of energy storage systems.

Apart from PVs, heat pump integration to photovoltaic-thermal (PVT) systems has also been widely investigated. The latter systems combine PV and solar thermal collectors into single hybrid systems, enabling the simultaneous production of electrical and thermal energy [129]. In a PVT-electric heat pump system, the electricity and heat produced by the PVT system can be used to power the electric heat pump and meet a proportion of the heating requirements, respectively. Simultaneously, the remaining heating demands can be addressed by the heat pump itself. Chae et al. [130] conducted an economic and environmental analysis of ASHP-PVT systems using theoretical model-based analysis and real observations. The prediction model was developed using a simulation model validated on a real building. The optimal ASHP-PVT system design was found to result in a payback period of 9 years for a real building in South Korea compared to an ASHP-only system. Moreover, PVT design characteristics when integrated to heat pumps were investigated by Herrando et al. [131], who later conducted an analysis of PVT systems concerning their integration potential with either vapour-compression ASHPs or absorption refrigeration units [132]. Their findings suggested that absorption refrigeration might serve as a viable alternative to electric heat pumps in locations with substantial cooling needs, such as Seville. Conversely, PVT-integrated electric heat pumps are more advantageous in areas like Rome and Paris.

PVT systems were also analysed in terms of the potential for integration to GSHPs by Wang et al. [133], who suggested that such an integrated system could be used to provide heating and cooling with reduced heat transfer losses and increased system flexibility compared to GSHP-only systems. They proposed five operation modes depending on the air and ground temperature (the latter was varied between 5 ˚C and 15 ˚C) and showed that the COP of the system would vary between 4 and 6 while preventing any significant ground temperature decrease. In addition, Besagni et al. [134] experimentally tested the integration of a PVT system to an electric heat pump with both an air-source and a water-source evaporator, showing that the integrated system was able to maintain a better overall performance throughout different seasons (COP increase of 15.4%) compared to an air-source-only heat pump. This was mainly due to the water-source evaporator playing a significant role to minimise the need for defrost cycles.

The integration of electric heat pumps with solar thermal systems offers another approach for meeting heating demands. Solar thermal collectors can cover a significant portion of the required heating, with electric heat pumps complementing to fulfil the remaining needs. Neves and Silva [135] demonstrated that implementing a mix of solar thermal collectors and heat pumps in the island of Corvo in Azores is cost-effective assuming that this is accompanied with a suitable TES capacity. The use of a combined solar thermal-heat pump system was also investigated in the work of Panaras et al. [136] for Athens in Greece, with the findings indicating substantial energy savings of 70% compared to conventional electric-resistance and direct-fired-heater heating systems. The role of proper control mechanisms was quantified in the case of solar thermal integrated heat pumps in the work of Hosseinirad et al. [137]. A different method for integrating solar thermal technologies to electric heat pumps was investigated by Treichel and Cruickshank [138], who modelled the use of air-based solar collectors to preheat the inlet air of an electric heat pump. This innovation led to a higher overall system efficiency by more than 10% compared to using a simplified heat pump system, and the study concluded that the competitiveness of their configuration varies significantly based on the climate zone and household specific heating and cooling needs.

Another interesting way to integrate electric heat pumps with solar thermal systems is through direct expansion solar heat pumps. In these systems, the heat pump working fluid passes directly through the solar collector, eliminating the need for separate solar thermal and heat pump systems, thus reducing components and minimising energy losses. Tagliafico et al. [139] found that a typical direct expansion solar assisted heat pump can save approximately half of the primary energy compared to a standard gas boiler, and Rabelo et al. [140] demonstrated a payback period of 1.7–3.3 years for such systems in three cities in Brazil. Shi et al. [141] reviewed how direct expansion solar assisted heat pumps can integrate with other technologies. They suggested that additional testing, optimisation of control strategies, and practical project experience could enhance system competitiveness. Furthermore, Sezen et al. [142], in their review, concluded that direct expansion solar heat pumps are cost-effective in various scenarios due to their simplified design, provided they are appropriately sized and installed in locations with suitable solar irradiation characteristics.

4.2. Integration with thermal energy storage (hot water and phase-change materials)

Integrating domestic heat pumps with TES systems enables the decoupling of demand and supply, and thus presents the potential for multiple benefits, including enhancing system efficiency, greater flexibility and reduced operational expenses. However, implementing TES in houses poses challenges. Two main challenges are cost-effectiveness and space limitations. Furthermore, ensuring compatibility of TES systems with existing and new heat pump technologies requires careful planning and system design. Finding the right balance between the TES system size, cost, and efficiency remains a key challenge. Common TES systems encompass hot-water cylinders and phase-change materials (PCM), while potential solutions can also involve a blend of these systems. A summary of a few relevant studies related to the main TES technologies for domestic heat pump integration are provided in Table 12.

Various researchers have studied how hot-water cylinders can be used most efficiently to minimise operational costs for end-users. For example, Renaldi et al. [143] showcased that, when coupled with appropriate governmental incentives, heat pumps emerge as a cost-effective option compared to natural gas boilers, despite gas being notably cheaper than electricity. For this to happen, though, they highlighted the importance of coupling the heat pump to a hot-water cylinder with volume in the range 210–300 L. Furthermore, Arteconi et al. [38] conducted a study for a detached house in Northern Ireland to showcase the influence of time-of-use electricity tariffs on encouraging users to use their ASHP during periods of low electricity demand by employing a 500-L hot-water cylinder. The cylinder was necessary to ensure that the ASHP could be switched off during peak-demand periods while meeting all space heating needs at the required time. Furthermore, Fischer et al. [36] compared various strategies to control a PV-driven ASHP within a multi-family house in Potsdam, Germany, concluding to the use of a hot-water cylinder of 3000 L.

Latent-heat TES systems based on PCMs are gained increasing research and commercial interest as an alternative method to store thermal energy in domestic applications. This interest is attributed to two main potential advantages: (i) PCM-based stores have a higher energy density than hot-water cylinders; and (ii) heat can be stored in small temperature bands, which can lead to a higher heat pump COP during operation if operated smartly. The review article of Gu et al. [144] summarises the latest advancements in PCM and heat pump integration, highlighting the need for: (i) improving PCM technologies at material level; (ii) optimising the operation of integrated PCM-heat-pump systems; and (iii) comparing different packaging technologies for PCMs.

In terms of techno-economic studies, Olympios et al. [17] recently compared a standard configuration of an ASHP system coupled to a hot-water cylinder to an advanced configuration of an ASHP system coupled to two PCM thermal stores. The authors reported that optimising the integrated heat pump-TES system operation can enable the avoidance of high-electricity-price periods and thus result in a reduction in average annual cost savings of up to 22% and 20% for the standard configuration, and up to 39% and 29% for the advanced configuration, in the UK and Germany, respectively. Furthermore, In the work of Kelly et al. [39], a building simulation model was developed to study the economic and environmental performance of a heat pump-integrated system when using a hot-water cylinder or a PCM store for a typical UK house. The results indicated that, to completely avoid periods of peak electricity price, a 1000-L hot water cylinder or 500-L PCM store was required. The study showed an increase rather than a decrease in electricity use when performing load shifting, concluding that cautious planning is necessary to avoid negative performance impacts. In addition, Yao et al. [145] studied the effectiveness of combining PVT-driven heat pumps with a heat storage module, involving a hot-water cylinder and PCMs within walls and floors. The research highlighted that incorporating PCMs in building surfaces can save space and improve the system COP by up to 70% compared to systems without TES. However, implementing such a system would incur substantial capital expenses, costing roughly five times more than a standard heat-pump unit.

4.3. Integration with backup heating technologies

Domestic heat pumps can be supplemented with backup/additional heating systems, mainly to cover heat demand peaks. Typically, gas boilers (or hydrogen boilers in the near future) or electric resistive heaters can be used as backup. Depending on the system design, this can reduce the required capacity of the heat pump and thus overall capital costs, avoid operating heat pumps at low efficiencies (e.g., on very cold days, or at high temperature to provide hot water), and reduce the investment required in electricity generation capacity and the electricity grid [146].

Vering et al. [147] presented a two-stage multi-level optimisation framework for heat pump systems including design of heat pump, backup heater and thermal stores, showing that the backup heater is especially valuable for defrosting and thermal disinfection of the hot water tank. In related work, Wüllhorst et al. [148] investigated the optimal design and control of backup heater in retrofitted heat pump systems, showing that for optimal performance electric backup heaters should be placed at the outlet of the thermal store rather than within it. Dongellini et al. [149] showed that condensing gas boilers used as backup heater can increase the seasonal efficiency by 6–22% compared to standalone heat pump systems, if controlled correctly. However, if the backup heating system has to work in parallel with the heat pump, the only advantage is that the heat pump can be slightly undersized. Bagarella et al. [150] studied heat pump and backup systems with different control strategies in domestic buildings in cold-humid and mild-dry climates. The authors found that a system with gas backup boiler can save up to 10.5% in capital costs in addition to fuel cost savings due to a higher overall efficiency, compared to heat pumps without backup heater.

Protopapadaki and Saelens [151] studied the impact of electric backup heaters that run in parallel to heat pumps on the coldest days. The authors found that such electric backup systems can significantly strain the grid on the coldest days and advocate for smarter heat pump controls and larger thermal stores to reduce backup heat demand. Electric backup heaters were found to account for a large portion of peak loads, resulting in challenges for the grid. It is argued that gas-fired backup systems may be a better solution. This is supported by the findings of Aunedi et al. [152], who identified hybrid systems consisting of electric heat pumps and hydrogen boilers as the most attractive heat decarbonisation option in the UK. On the other hand, Fischer et al. [153] showed that electric backup heaters can significantly increase the flexibility of heat pump heating systems. The system was

Table 12
Potential TES technologies and relevant studies for integration with electric heat pumps.

TES technology	TES – heat pump integrated system description	Refs.
Hot-water cylinder	• Hot-water cylinder can be charged at periods of low electricity price or favourable temperature conditions, and discharged whenever there is demand	[17,36,38,143]
PCM system	• PCM thermal store can be used in place of a hot-water cylinder • PCMs can also be integrated within materials of the building (e.g., in the walls or floors)	[17,39,144,145]

able to shift more energy consumption to off-peak hours and could therefore aid the balancing of the electricity grid.

5. Whole-energy system significance and policy implications

Widespread deployment of heat pumps represents a seismic shift in many energy systems, away from conventional heating systems based on the decentralised combustion of fossil fuels, such as coal, oil, natural gas, and biomass towards locally emission-free heating systems. As heat pumps use electricity, which is generated many different ways and used ubiquitously, rather than dedicated fuels, energy systems become more integrated and the fuel mix changes. The implications of heat electrification on whole-energy systems and the current policy landscape are discussed in this section.

5.1. Whole-energy system implications of heat electrification

Widespread rollout of heat pumps will change both the total annual electricity demand as well as the shape of the demand profile. Different studies on the impact of heat electrification on the electricity demand in various energy systems are summarised in Table 13. High heat pump penetration will increase annual and peak electricity demand significantly in most regions, with absolute values depending on penetration rates, heat pump efficiency and climate conditions. In rare cases in warm climates however, (reversible) heat pumps can reduce electricity demands if cooling demand is significant and they are more efficient than incumbent cooling technologies.

The change in electricity demand profiles has a range of implications for the power sector. Firstly, a higher overall power generation capacity is required to meet to additional electricity demand. Secondly, it is likely that a higher dispatchable generation capacity and/or more energy storage is required. Heat demand is the highest on cold winter mornings and evenings and thus coincides with traditional peaks in electricity demand in moderate and cold climate regions [160]. It is also high specifically at times of low solar irradiation. Consequently, solar power plants are not well suited to match the added electricity demand from heat pumps if no storage is present in the system.

The electricity demand from heat pumps will also require higher electricity transmission grid capacities as well as local grid reinforcements [161]. Especially in rural areas, low-voltage grid reinforcement costs per dwelling may be significant, while also in urban grids reinforcements are necessary, mainly transformer replacements [162].

The impact of widespread heat pump rollout on required power generation and transmission capacities can be partially mitigated by 'smart' heat pump operation and TES, also called load-shifting or demand-side management [8]. The idea is to operate heat pumps during times of low electricity demand and/or high renewables availability to charge thermal stores, which are then discharged during times of high demand. Thermal stores can be hot water tanks or phase-change material (PCM) systems [17], as well as the thermal mass of the building [163]. If operated correctly, heat pumps can then even provide a positive service to the energy system by providing significant flexibility. Demand side management can flatten the electricity demand curve [38] and reduce required generation capacity [164], reduce network reinforcement cost [165], increase utilisation of renewable energy sources [166] and reduce grid-scale energy storage demand [167]. It has been observed that cost-optimal TES capacities increase significantly when considering grid constraint compared to the optimal solution for individual buildings [168].

Despite the challenges to the energy system, it is widely accepted that heat pumps can help significantly reduce emissions associated with space heating and hot water provision. Recent data from real-world ASHP installations in the UK show a median SPF_{H4}, that is seasonal performance factor including all auxiliary heaters and pumps, of 2.8 [169], an improvement of 0.36 compared to a similar report from 2017 [170]. Heat pump installations in Germany were already measured to

Table 13
Studies on the impacts of heat pump rollout on annual and peak electricity demand in different energy systems.

Study	Energy system	Scenarios	Annual electricity demand impact	Peak electricity demand change
Quiggin & Buswell (2016) [154]	UK	6 policy scenarios with varying degrees of heat electrification	10–120 TWh/yr heat pump demand (4–40% of traditional elec. demand)	10–50 GW increase
White et al. (2021) [155]	Texas	100% reversible ASHPs installed; standard, high and ultra-high efficiency	1.2–4.2 TWh/yr increase for heating 4.3–15.2 TWh/yr reduction for cooling	Up to 12 GW (36%)[a] increase
Thomaßen et al. (2021) [156]	EU + UK	20–100% electrification with heat pumps	Up to 750 TWh/yr (25% increase)	100–500 GW (20–90%) increase
Deetjen et al. (2021) [157]	US	Economical (32%), subsidy potential (37%) and 100% heat pump adoption	-	Depending strongly on local climate. At 100% adoption, more than 100% increase in 24 of 55 cities.
Hoseinpoori et al. (2022) [158]	UK	6 scenarios, some forcing 100% ASHPs, other limiting building emissions	Up to 237 TWh/yr (80%) increase[b]	84 GW (170%) increase[b]
Peacock et al. (2023) [159]	UK	41% or 100% of heating from ASHPs	Up to 92 TWh/yr (31%) increase	Up to 40 GW (75%) increase

[a] Winter peak increases, but summer peak decreases due to the reversible ASHPs.
[b] Includes demand from the electrification of other sectors.

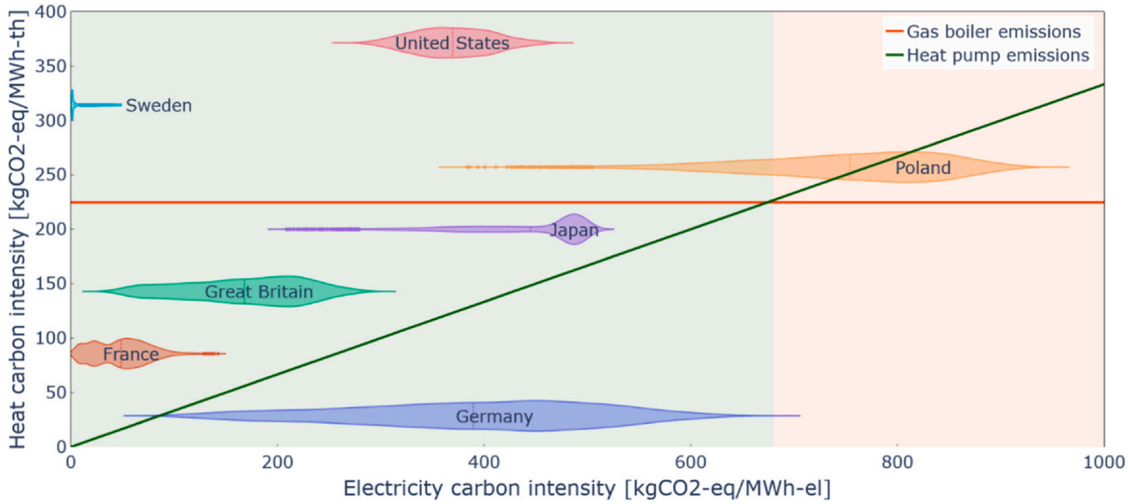

Fig. 9. Emission intensity of ASHP and gas boiler heating depending on electricity carbon intensity. The plot also shows grid carbon intensities in 2021 & 2022 in selected countries as reference. The green-shaded area indicates the range for which heat pumps provide heating at a lower carbon intensity, while in the orange-shaded area gas boilers have lower emissions.

have an average SPF of 3.1 in 2012/2013 [171]. This value was confirmed in 2020 for heat pump retrofits [172]. Monitored average boiler efficiencies on the other hand were 85% for regular boilers and 83% for combi-boilers in the UK [172], while a new standard considers raising the minimum required efficiency to 92% [173]. Assuming an ASHP SPF of 3, a gas boiler efficiency of 90% [174] and a natural gas emission factor of 0.20 $kgCO_2$-eq/kWh [175], the emission intensity of ASHP vs. gas boiler heating depending on the energy intensity of consumed electricity is shown in Fig. 9. For a wide range of electricity carbon intensity factors, ASHPs result in significantly lower heating emissions compared to gas boilers. This is only expected to improve in future, as countries progress with the decarbonisation of their electricity systems. It should be noted however, that any emissions associated with the construction of ASHPs and boilers are not considered here.

Fig. 9 also shows the importance of running heat pumps at times of low grid carbon intensity. Calculating emission savings based on average grid carbon intensity would be an oversimplification. The marginal electricity carbon intensity during times of heat pump operation is more relevant to determine the emission impact of ASHP heating [176].

Unfortunately, the efficiency of heat pumps decreases with lower ambient temperatures and thus higher heat demand. Moreover, the grid carbon intensity tends to increase with decreasing temperatures, as shown for the example of Germany in Fig. 10. Here again energy storage can help by shifting heat pump operation to times with higher ambient temperature and thus higher efficiency and potentially lower grid carbon intensity.

5.2. Current policy landscape

Recognising the emission saving potential of heat pumps, they play a key role in the decarbonisation strategy of many countries. The UK heat and buildings strategy pledges to deploy at least 600,000 heat pumps per year by 2028 [177], while the European Commission's REPowerEU Plan aims to double the current heat pump deployment rate, with a target of 10 million units installed between 2022 and 2027 [178]. In the US, four states target a total heat pump deployment of over 12 million units by 2030 [179]. Overall, an analysis by the IEA shows that current pledges will result in an increase in the share of heat pumps in the global heating demand from 9% in 2021 to 19% in 2030 [9].

Several countries have put in place dedicated policies to support heat pump rollout. These include financial subsidies to reduce upfront costs, removing taxes on electricity or increasing taxes on fossil alternatives, and regulatory measures, as well as education and information campaigns [118].

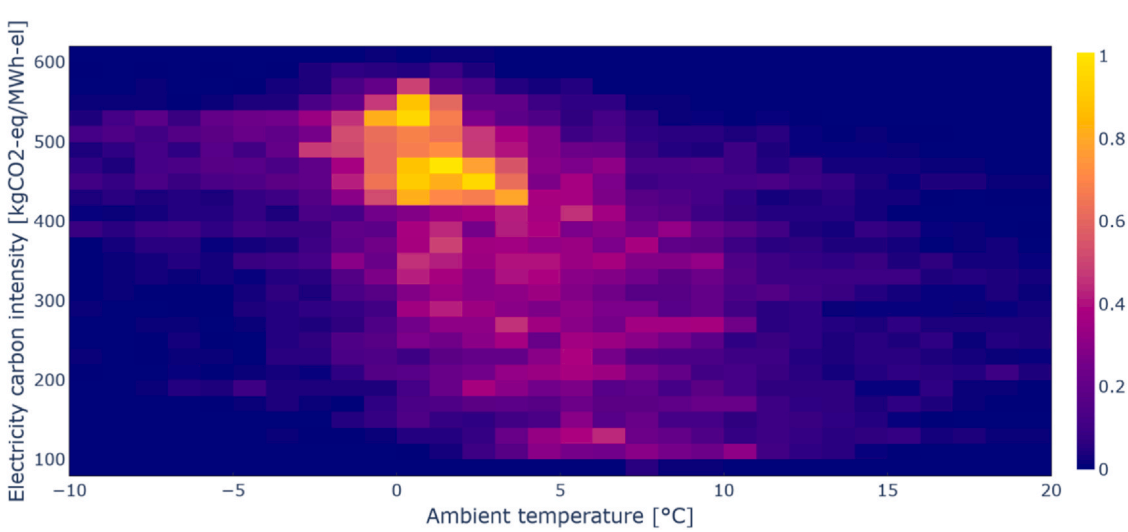

Fig. 10. Grid carbon intensity and ambient temperature in 2021 & 2022 in the six largest German cities (Berlin, Hamburg, Munich, Cologne, Frankfurt, Stuttgart).

Heat pump penetration is the highest in the Nordic countries Norway, Sweden, Finland, and Estonia [180]. Norway achieved significant uptake of ASHPs in the early 2000's with a subsidy programme that paid households up to 20% of initial investment costs [181]. Since 2016, the installation of new fossil fuel-based heating systems has been banned [182]. Sweden followed a similar trajectory with a wave of subsidy schemes that covered up to 30% of investment costs [183]. Currently, retrofit installations are supported with a 30% tax rebate on labour costs [184]. Finland also provides significant financial subsidies for heat pump installations, with a grant of up to 3,420 £ using an exchange rate of 1.17 €/£ (4,000 €) and tax deductions [184], while Tallinn, the capital of Estonia, provides a subsidy of up to 30% of installation costs [185].

Other European countries are aiming to catch up to the Nordic countries by providing significant support for heat pumps. Austria provides a subsidy of 20% for new buildings and 35% for retrofits, Belgium grants 850–5,130 £ (1,000–6,000 €) for retrofits, Croatia 3,630 to 7,260 £ (4,250–8,500 €) or 40–80%, Czech Republic 2,780 to 4,870 £ (3,250–5,700 €), Denmark up to 3,930 £ (4,600 €), France up to 7,690 £ (9,000 €) for ASHPs and 12,800 £ (15,000 €) for GSHPs, Germany 12,800 £ (15,000 €), Ireland up to 5,560 £ (6,500 €), Lithuania up to 12,400 £ (14,500 €), the Netherlands up to 4,360 £ (5,100 €), Poland up to 6,410 £ (7,500 €), Portugal up to 2,140 £ (2,500 €), Slovakia up to 9,740 £ (11,400 €), Spain up to 11,500 £ (13,500 €), Switzerland potentially over 17,100 £ (20,000 €) depending on region and counterfactual technology, and the UK 7,500 £ [184,186]. In Italy 50–110% of costs are covered by tax breaks [184]. Additionally, France, Germany, Hungary, Norway, and Switzerland have a ban on new fossil heating systems either already in effect or planned, while many other European countries have carbon prices, energy efficiency schemes, and/or building standards in place that support heat pump deployment [184].

In the United States, households can claim a 30% federal tax credit for heat pump installations, up to 1,590 £ using an exchange rate of 1.26 $/£ (2,000 $ [187]). Additionally, 198 M£ (250 M$) of funding was pledged to accelerate heat pump manufacturing [188], while many state and local government targets and support schemes are also in place [179]. Canada supports the switch from oil heating to heat pumps with grants of up to 5,880 £ using an exchange rate of 1.70 C$/£ (10,000 C$ [189]).

China has the largest number of heat pump installations [190], which are promoted under China's clean heating plan [191] and subsidised with a discount of 20–25% on electricity tariffs [192]. Japan is home to many heat pump manufacturers and has clearly defined efficiency and deployment targets, as well as subsidies for high-efficiency heat pumps [193], while South Korea offers low-interest rate loans [194].

Overall, a large number of countries representing a significant share of the global heating demand recognise heat pumps as a valuable emission reduction technology and have dedicated policies in place to support their deployment. These include subsidies on investment costs, but also subsidies on operating costs, penalties for competing fossil-based technologies and regulatory measures.

5.3. Discussion and significance of domestic heat pumps

Even though heat pumps are typically more thermodynamical efficient than most alternative heating technologies, their widespread adoption will have complex and widespread implications for the electricity sector. Both the total annual electricity demand and demand peaks are expected to increase substantially, requiring an increase in low-carbon electricity generation (and storage) capacity as well as upgrades to electricity grids. Smart domestic heat pumps can help mitigate these impacts. Achieving high efficiencies should be a target to minimise the added electricity demand, although the impact of such efficiencies on costs should be carefully considered [16]. Perhaps more importantly, however, the increased flexibility of domestic heat pumps, enabled by thermal energy storage and smart controllers, can play a key role in integrating millions of heat pumps into the energy system. Ideally, domestic heat pumps can provide a service to the energy system by offering demand-response capacity that can adjust to changing wind and solar availability, rather than simply being a burden to the wider system by increasing peak loads.

Already with today's power generation mix, heat pumps significantly reduce emissions compared to fossil-based heating systems in many countries. As the electricity sector becomes more decarbonised, the emission savings from heat pumps will increase further. Recognising this potential, many countries have implemented supportive policies for domestic heat pumps, aiming to make them more cost-competitive than fossil-based heating systems.

6. Conclusions

Energy system electrification and the use of electric heat pumps have emerged as one of the most promising pathways in the context of heating and cooling decarbonisation. The aim of this article was to review recent advancements in component and system development, along with predictive methods for assessing the techno-economic performance of heat pumps, while noting that the performance and cost of heat pumps are to some extent correlated [16], and that both vary significantly based on their design, operation, and integration with other technologies. The focus of this review was on small-scale domestic heat pumps with capacities of a few kWs.

The review included a presentation of the fundamental underlying principles upon which electric heat pumps rely and an overview of commonly used performance indicators, heat sources, components and working fluids. This was followed by an outline of a broad range of methodologies aimed at predicting the cost and performance of electric heat pumps from: (i) technology-agnostic methods, which provide realistic estimates solely based on external operating conditions; to (ii) data-driven methods, which are based on manufacturer data and are suitable for reliably estimating the techno-economic potential of existing, mature technologies; and (iii) physics-based and component-costing methods, which are necessary for detailed analyses of cost and performance variations and thus for assessing the full potential of both existing and innovative solutions. This was followed by a synopsis of how electric heat pumps can be coupled to solar technologies (photovoltaic, photovoltaic thermal, solar thermal), thermal energy storage technologies (hot-water cylinders, phase-change materials) and other backup heating technologies (electric, gas and hydrogen boilers). Lastly, whole-energy system implications arising from wide electrification and current policy measures in different countries were presented and discussed. It is recognised that, given the wide scope of this review, not all developments in heat pump component and system design options are captured in detail, but the review provides a benchmark for the understanding of the current technology landscape and modelling methodologies for domestic electric heat pump technologies.

Based on this review, the following conclusions can be drawn:

- Electric heat pumps are an efficient low-carbon alternative to traditional boilers, with record-breaking global installations and a growth of over 50% in many European countries from 2021 to 2023 driven by an increased pressure for heat decarbonisation and supportive policies.
- Although the electrification of heating and cooling is vital for environmental sustainability, economic (especially the high upfront costs), technical (part-load performance, need for green refrigerants, smart-grid integration), and awareness challenges still persist.
- Electric heat pumps are evaluated using technical and techno-economic performance indicators aligned with methodologies that vary based on location and organisation, requiring manufacturers and researchers to report and compare values carefully.
- The performance and cost of electric heat pumps depend highly on the selection of the heat source, component types and sizes, and the control strategy.

- The working fluid significantly impacts heat pump performance. While ozone-depleting working fluids have been phased out, many currently used fluids have a high global warming potential and thus a significant environmental impact when leaked into the atmosphere. New lower-warming-potential fluids have been introduced, but they are often flammable, which means that research and development is still necessary to reach high performance and safety standards.
- Modelling approaches range from detailed molecular-level analyses of working fluids and optimisation of critical components to the optimisation of entire heat pumps, to simulations of the effects of heat pump integration into broader multi-energy-vector systems at household, neighbourhood, national and international scales.
- Different applications require varying levels of detail and accuracy in heat pump technology cost and performance modelling, which can be performed using technology-agnostic, data-driven, and comprehensive physics-based methods.
- The effective integration of heat pumps with other domestic technologies is crucial for maximising the economic and environmental benefits to end-users and to the broader energy system. Integration with thermal energy storage offers significant benefits, enabling heat pumps to operate flexibly, providing operational benefits such as lower electricity requirements and lower running costs, as well as benefits to the wider energy system.
- Integration of domestic heat pumps with photovoltaic and/or solar-thermal systems can increase the efficiency of systems and reduce reliance on electricity imports from the grid. Backup heating technologies can reduce the required heat pump capacity and thus the cost of the system.
- The large-scale deployment of electric heat pumps can result in an increase in peak national electricity demands by 10 s of GWs, necessitating an increased low-carbon electricity generation capacity. Thermal energy storage capacity and smart operation of heat pumps are valuable to reduce the impacts of heat electrification on the electricity system. Flexible domestic heat pumps have the potential to provide valuable demand response services.
- Heat pumps offer significant emission reductions compared to gas boilers even at today's electricity generation mix in many countries, and these benefits will increase as the electricity supply is further decarbonised.
- Many countries worldwide consider heat pumps to be a key technology in the energy system transition and offer significant support and incentives for heat pump deployment.

Finally, substantial potential exists in several key areas for further research and the development of domestic electric heat pumps:

- Enhancing the efficiency and durability of heat pumps can be achieved through research aimed at optimising core components, particularly the compressor and heat exchangers. The losses and noise from compressors can be reduced further with new materials, optimised geometries and proper lubrication, while heat exchanger design can be advanced to make them more compact, durable, and capable of high heat transfer.
- Conducting further research into environmentally friendly working fluid alternatives such as hydrocarbons, carbon dioxide, and ammonia is necessary to overcome challenges with current alternatives such as flammability and toxicity.
- Identifying cost-effective configurations can lead to innovative heat pump designs and integration methods (e.g., solar-assisted heat pumps, hybrid heating systems) that are both high-performing and affordable.
- Developing advanced multi-fidelity modelling techniques is vital for the accurate prediction of the performance and cost of heat pumps across various operating conditions and applications.
- Designing intelligent control strategies for the operation of electric heat pumps can result in improved performance, comfort, and integration with the grid, enhancing their cost-effectiveness. This involves advancements in sensors, controls, and smart home integration platforms for real-time communication and remote heat pump management.
- Acquiring reliable information on performance and cost through experiments, field trials, pilot projects, and practical applications is essential for reducing uncertainties and supporting effective integration within energy systems. This will allow accurate evaluations of heat pump investment and operation costs, maintenance requirements, and potential energy savings.
- Investigating strategies for integrating electric heat pumps into complex energy systems alongside renewable energy sources, multi-vector energy storage systems, and grid infrastructure is vital for achieving sustainable energy systems.
- Mitigating the increase in electricity demand that results from widespread heat pump deployment requires the use of thermal energy storage with smart controls that can shift significant demand to times with high renewable energy availability or low electricity demand.
- Advocating for supportive policies, such as subsidies, tax incentives, and regulations mandating the use of electric heat pumps in new constructions, can promote their adoption.

The insights and tools presented in this article are valuable to manufacturers, end-users, researchers, technology operators and policymakers. These stakeholders can use specific models, data, or analyses outlined here based on their specific objectives, contributing to informed decision-making.

Declaration of Competing Interest

The authors 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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