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Simplified water-source heat pump models for predicting heat extraction and rejection

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ABSTRACT

Simplified heat pump models are needed for the design of ground heat exchangers used with ground-source heat pump systems. Design engineers commonly have only manufacturer's data with which to construct a heat pump model that can predict heat extraction and heat rejection given building heating and cooling loads and take account of the entering fluid temperatures to the heat pump. Earlier work has used simple polynomials to predict the ratio of heat extraction to heating and heat rejection to cooling. Unfortunately, manufacturers' catalog data do not always provide sufficient support to calculate the polynomial coefficients. Therefore, in the absence of experimental data, simplified and acceptably accurate models are needed to exploit a limited number of operating points.

This paper presents a review of available manufacturers' data in North American and European markets. The available data vary from country to country, depending on the standards in use in each country. In particular, data availability is poorer for the European heat pumps compared to North American heat pumps.

Then, a range of models is investigated, characterizing the results by the required inputs and the root mean square error and recommendations are provided. Models are validated against catalog and experimental data.

1. Introduction

Ground source heat pumps (GSHP) represent a good solution to abate energy usage and reduce greenhouse gas emissions. However, the design of ground heat exchanger fields is crucial to minimize installation costs and guarantee high efficiencies of the system for long-term operations.

The heat pump selection is important to the design of the ground heat exchangers because it affects heat rejection to the ground during cooling operation and heat extraction from the ground during heating operation. Conversely, the ground heat exchanger performance (specifically, fluid temperatures provided to the heat pumps) affects the heat pump performance. In the common situation where systems are designed to meet building-specific hourly heating and cooling loads, simulations are used to predict the combined performance of the GSHPs and the ground heat exchanger field to achieve a solution that provides the needed heating and cooling capacity while minimizing energy consumption and installation cost. Besides affecting the electrical consumption of the system and related operating costs, the choice of heat pumps directly impacts the size of the ground heat exchanger field. Therefore, GSHP models are needed to design the ground heat exchanger field.

Detailed models of heat pumps, e.g., those based on vapor compression cycle simulations [1], are widely described in the literature.

However, for most designers, only limited heat pump data from manufacturers' catalogs are available. The availability of data and temperature ranges for which data are provided vary from country to country, often depending on local standards. For example, North American manufacturers usually provide a wide range of operating points; fewer data points are presented in European catalogs, and in some cases, they are limited to a few specific rating conditions recommended by the standards.

Therefore, simpler heat pump models are needed to calculate the ground heat rejection and extraction. In contrast to detailed models, these models should depend on easy-to-obtain catalog data rather than specific measurement campaigns. For GLHEPRO [2,3] a simple polynomial model was developed on an expedient basis under the assumption that sufficient manufacturer's data would be available to fit 2nd order polynomials. These polynomials were used to calculate the ratio of heat extraction to heat pump heating capacity and heat rejection to heat pump cooling capacity as functions of heat pump entering fluid temperature. Visually, these models seem to give adequate performance,

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Nomenclature

C	Constant data
c_i	polynomial's coefficients
const	Constant
COP	Coefficient of Performance kW/kW
COP_{Carnot}	Carnot COP K/K
$COP_{Carnot,0}$	Carnot COP in rated conditions K/K
COP_c	COP in cooling kW/kW
COP_h	COP in heating kW/kW
D	Derivable data
GLS	Gleneralized least square
GRG	Generalized reduced gradient
GSHP	Ground source heat pump
HP	Heat pump
LAfr	Load air flow rate l/s
LEAT	Load entering air temperature °C
LExAT	Load exiting air temperature °C
LEFT	Load entering fluid temperature °C
LExFT	Load exiting fluid temperature °C
LFfr	Load fluid flow rate l/s
MPE	Mean percentage error %
NA	North America
NE	Northern Europe
P_{el}	Electrical power kW
Q_C	Cooling Capacity kW
Q_e	Heat extraction kW
Q_H	Heating capacity kW
Q_r	Heat rejection kW
RMSE	Root mean square relative error
SCOP	Seasonal coefficient of performance kWh/kWh
SQ_C	Sensible cooling capacity kW
SEAT	Source entering air temperature °C
SExAT	Source exiting air temperature °C
SEFT	Source entering fluid temperature °C
SE	Southern Europe
set	Set, fixed value
SExFT	Source exiting fluid temperature °C
SFfr	Source fluid flow rate l/s
T	Temperature °C
TQ_C	Total cooling capacity kW
T_{cond}	Condensation temperature °C
T_{evap}	Evaporation temperature °C
var	Variable
WB	Wet bulb
X	Omitted data
ΔT	Temperature lift between source and load side °C
$\eta_{Carnot,0}$	Carnot effectiveness [−]
η_{PL}	Correction factor for part load [−]
0	Rating condition

though in many cases, insufficient manufacturer's data is available to fit 2nd order polynomials. For this reason, a more comprehensive (North America and Europe) review of available manufacturers' data, as well as a review of available models, was undertaken.

This work provides an overview of catalog data availability for the North American and European markets, which has not been found in the recent literature. It reviews the literature on simplified and acceptably accurate models for predicting the ratios of heat extraction to heating and heat rejection to cooling. A range of existing and new models are tested for different data availability scenarios, and finally, recommendations are made for models that can be used within ground heat exchanger design tools. The basis for most of the work is manufacturers' catalog data. In addition, model results are compared to a field measurement described in Section 4. The present paper proposes a methodology to evaluate the heat pump performance and the heat extraction and rejection that can be easily applied to water-source and ground-source heat pumps. However, the methodology can be extended to a range of heat pumps, with different characteristics and sizes, independent of the type of refrigerant and the climatic conditions under which the heat pump operates.

1.1. Literature review

Models for ground source heat pumps have been proposed in the literature with varying degrees of complexity. Detailed models incorporating vapor compression cycle simulations are often used for research into heat pump design, control optimization, and other issues.

For example, Kinab et al. [4] presented a model simulating the steady-state characteristics of a reversible air-to-water heat pump. The model included detailed sub-models of each system component: heat exchangers, compressor, and expansion valve. Therefore, highly detailed inputs for the components are required by the user. Furthermore, the model handles partial load for a system equipped with a variable speed compressor or a multiple stage compressor. Li Y. et al. [5] proposed a model-based sizing approach for water-to-water trans-critical CO_2 heat pumps, developed using MATLAB and REFPROP. The quasi-dynamic model was developed by integration of dynamic and steady-state models. Dynamic models including the gas cooler, internal heat exchanger, and evaporator models were described using the governing partial differential equations. Steady-state models including the compressor and the expansion valve models were described using the equations identified by measured data. Cimmino and Wetter [6] implemented in Modelica a model for a water-to-water heat pump with a scroll compressor, based on a simplified vapor compression cycle with only five refrigerant states. Parameters to the model were evaluated minimizing the differences between the model predicted heating capacities and power input and those provided in the manufacturer technical data, using Python.

However, when it comes to the design of large GSHP systems, with a large number of boreholes and, sometimes, distributed heat pump units, detailed models will not be appropriate due to computational time and required input data that are not available to GSHP system design engineers. Computational time is important, considering that long-term simulations are used iteratively to design the ground heat exchanger.

International and national standards play a key role in defining the minimum energy efficiency requirements for new heat pumps and providing manufacturers with guidelines regarding the testing conditions and the documentation to be made available to users. Standards suggest performance calculation methods and define standard rating conditions for each country or area. In many cases, the standard rating conditions suggest a minimum data set to be presented in manufacturers' catalogs. Commonly, the performance of a heat pump is defined using the Coefficient of Performance (COP), which corresponds to the heating or cooling provided divided by the heat pump's electrical consumption. The performance test and rating conditions for water/brine source heat pumps are defined in ISO/ANSI/AHRI/ASHRAE 13256 (part 1 for water/brine-to-air heat pumps [7], part 2 for water/brine-to-water heat pumps [8]) for the North American market and EN14511 [9] for the European market.

ISO 13612-2 Appendix A [10] describes a method to calculate a heat pump performance matrix with a single test result. The model is based on the Carnot method for calculating the COP of the heat pump, knowing the performance at the rating conditions. The Carnot COP, for heating, is calculated as:

$$COP_{Carnot} = \frac{T_{cond}+273}{T_{cond} - T_{evap}} \tag{1}$$

Where T_{cond} and T_{evap} are the refrigerant condensation and evaporation temperatures in °C. The COP_{Carnot} corresponds to the COP for ideal inverse thermodynamic cycles at specific operating temperatures. In the same way, $COP_{Carnot,0}$ is the Carnot COP calculated at rating conditions ($T_{evap,0}$ and $T_{cond,0}$). Standard ISO 13612-2 [10] suggests some assumptions to estimate the condensation and evaporation temperatures of the refrigerant inside the heat exchangers. Depending on the secondary fluid type (air or water), the condensation and evaporation temperatures are calculated assuming a fixed temperature difference between the refrigerant fluid and the secondary fluid, starting from the outlet temperature of the user-side secondary fluid and the inlet temperature of the source/sink-side secondary fluid. If the value of the actual COP is known for the real heat pump working at the same operating temperatures, it is possible to define how much worse the real inverse thermodynamic cycle is compared to the ideal one, using the Carnot effectiveness $\eta_{Carnot,0}$, (also known as 2nd law efficiency):

$$\eta_{Carnot,0} = \frac{COP_{Carnot,0}}{COP_{Carnot}} \tag{2}$$

The higher the Carnot effectiveness, the closer the performance of the actual heat pump at the considered operating conditions compared with the ideal heat pump at the same operating conditions.

The Carnot effectiveness is then used to correct the COP_{Carnot}, and derive the actual COP at different operating conditions:

$$COP = \eta_{Carnot,0} \bullet COP_{Carnot} \tag{3}$$

As stated in ISO 13612-2 [10], this method has the main advantages of requiring few input data points and allowing good accuracy when the operating points are close to rating conditions. However, the accuracy of calculations drops when the operating conditions are far from the rating point. A higher level of accuracy can be obtained using a larger number of operating points. Some standard energy simulation software programs incorporate simplified heat pump models with various levels of detail.

EnergyPlus [11] models for water-to-water and water-to-air heat pumps are based on methods described in Refs. [12,13], and [14]. In particular, two types of models for water-to-air and water-to-water heat pumps are used: equation fit models and parameter estimation models. The parameter estimation models [12] incorporate a vapor compression cycle simulation, with parameters for internal components that require estimation. Given enough catalog data, it is possible to estimate the parameters, but it is computationally time-consuming to use the model and estimate the parameters. The parameter estimation procedure requires non-linear optimization, and there is the possibility that a local minimum will be found. The equation fit models [13,14] are based on non-dimensional curves to predict the heat pump performance in cooling and heating mode. The generalized least squares method is used to generate the equation's coefficients starting from the catalog data at determined reference conditions, giving the least differences between the model outputs and the catalog data. This procedure is robust and computationally efficient. The inputs to these equations are the load and source-side inlet temperatures and flow rates divided by the reference conditions. Concerning the water-to-air heat pump in cooling mode, the wet bulb and dry bulb entering air temperatures at the load side are used as the inputs. The model outputs are the cooling capacity (both sensible and total cooling capacity in the case of water-to-air heat pump) and heating capacity of the heat pump, the power consumption related to the rating conditions, and the heat rejection and extraction rates to the ground.

In TRNSYS [15], the standard components library contains a water-to-air heat pump model (Type 143). It is based on user-supplied data files containing catalog data for the capacity (total and sensible capacity in cooling mode) and electrical power, depending on the entering water temperature to the heat pump, the entering water flow rate, and the air flow rate. Other curve fits can be used to correct the capacities and power based on off-design indoor air temperatures. The model linearly interpolates between the performance data provided by the user, given the values of the air flow rate, fluid flow rate, and entering fluid temperature. Extrapolation is not permitted, and if values outside the data range are provided, the maximum or minimum cooling performance values are returned. Moreover, users who want to provide their own performance data must adhere closely to the syntax of the sample file [16]. In addition, one water-to-water and one water-to-air heat pump model are available in the TESS Library [17]. The structure of these models is similar to the one just described: it is based on catalog data, normalized by rating values. Linear interpolation is performed between provided operation points, depending on the current values (normalized by rating values) of the air or water flow rate, fluid flow rate, and entering fluid temperature.

The performance data can be implemented as external files in the existing Types of the TRNSYS library or using the link to other external software, such as Microsoft Excel or Engineering Equation Solver (EES) [18]. For example, Safa et al. [19] monitored and numerically simulated a GSHP system in TRNSYS with Type 668 of TRNSYS 16, which reads the heat pump performance curves obtained from experimental data and evaluated at different load/source side temperatures. Starke et al. [20] performed the energy analysis of a solar-assisted heat pump by estimating the performance matrix and using TRNSYS Type 927. Instead of employing the datasheet of a commercial unit, the performance matrix was created using a thermodynamic model developed using EES. Cardemil et al. [21] simulated a water-to-water heat pump using an outdoor swimming pool as the heat source in Mediterranean climates. The same methodology as [20] was applied in this study to give more generality to the analysis, estimating the performance matrix through a thermodynamic model of a heat pump developed in EES. Emmi et al. [22] developed a TRNSYS model of a solar-assisted ground source heat pump using a ground loop and a solar loop as the thermal source/sink, in which the heat pump was modeled by simulating the operating conditions of a commercial heat pump in both heating and cooling modes and evaluated the performance of the system under different climatic conditions. In this work, two external Excel spreadsheets are called using TRNSYS Type 62. The numerical model interpolates two sets of energy performance maps: one is used when the heat pump is in heating mode and the other in cooling mode. In this way, the heat pump's power consumption and heating capacity are calculated as a function of the inlet water temperatures on the source and load sides. This approach allowed the authors to employ heat pump data sheets that declare the energy performance of the machine as a function of the inlet temperature of the heat carrier fluid at the source and load side, considering constant temperature drop at the heat exchangers and variable mass flow rates. Grossi et al. [23] developed a system with a double-source inverter heat pump (air and ground) in the TRNSYS environment. In this case, the experimental data of a prototype were interpolated to obtain the heating/cooling capacity and performance maps as a function of outdoor air temperature for air-source operation, the inlet brine temperature for the ground-source mode, the load side inlet water temperature and the inverter frequency for both modes. Ruiz-Calvo et al. [24] developed a TRNSYS model of a GSHP using the performance matrix obtained, as explained in Corberan et al. [25]. The maps were obtained using a quasi-state mathematical model developed using IMST-ART [26] integrated into EES, and validated against experimental data. The model was built and validated through a component-by-component approach, incorporating the key elements of the heat pump circuit (evaporator, condenser, compressor, expansion valve, and connecting piping).

TRNSYS allows users to create and add their own components (types) to the library. In a previous work [27], a novel TRNSYS type was developed modeling a heat pump with a vapor compression cycle simulation that incorporated the compressor's performance polynomials, and it is available with a link to REFPROP [28] for deriving the properties of the refrigerant. The type is also available without the internal link to REFPROP, allowing lower computational time. Although it is very flexible, the need for compressor polynomials might be a problem when they are unavailable from heat pump manufacturers or when the compressor's brand and model are not specified in catalogs.

The Modelica Buildings Library [29] contains several heat pump models. The simplest model is based on the Carnot efficiency method. As described in the standards, this approach is based on the idea that the heat pump's COP varies with temperatures in the same way as the Carnot efficiency. In this model, the Carnot effectiveness calculated using one operating point (usually at rating conditions) is used to compute the heat pump COP as:

$$COP = \eta_{Carnot,0} \bullet COP_{Carnot} \bullet \eta_{PL} \tag{4}$$

Where η_{PL} is a polynomial correction factor for part load heating conditions.

In addition, models based on the equation fit model [14] and the parameter estimation model [12] from EnergyPlus are implemented in the Modelica Buildings Library [29].

The GLHEPRO [2] heat pump model is based on a simple water-to-air heat pump model described in Ref. [2], in which the ratio of heat rejection to the ground in cooling mode is given by:

$$\frac{Q_r}{Q_C} = c_1 + c_2 \bullet SEFT + c_3 \bullet SEFT^2 \tag{5}$$

Where Q_r is the heat rejection rate, Q_C is the building cooling load met by the heat pump(s), c_1 are the coefficients determined by an equation fit of the manufacturer's catalog data, and *SEFT* is the entering fluid temperature to the heat pump (°C).

In the same way, in heating mode, the ratio of heat extraction from the ground to heating provided is given by:

$$\frac{Q_e}{Q_H} = c_1 + c_2 \bullet SEFT + c_3 \bullet SEFT^2 \tag{6}$$

Where Q_e is the heat extraction rate, Q_H is the building heating load met by the heat pump(s).

Users provide building cooling and heating loads previously determined by a building simulation program and are assumed to be met by the heat pump. Entering fluid temperatures are determined simultaneously with the heat extraction and rejection rates using GLHEPRO.

Similar equations used to quantify the performance of water-source heat pumps have been described in the literature. For example, in 2012, Staffel et al. [30] published an article to provide an overview of the state-of-the-art of heat pump technology in domestic applications. Their focus was on the real-world performance of air and ground-source heat pumps, indicating both commercial and environmental aspects of these systems. They provided a quadratic regression of experimental points obtained by industrial surveys and field test trials for deriving the COP of ground source heat pumps:

$$COP = 8.77 - 0.15 \bullet \Delta T + 0.000734 \bullet \Delta T^2 \tag{7}$$

Valid for a continuous range of ΔT between 20 °C and 60 °C, where ΔT is the temperature lift, meaning the temperature difference between the source and outlet.

Perers et al. [31] proposed a very simple water-to-water heat pump model to simplify the calculations and reduce the computational time in dynamic simulations. Their method consisted of modeling heating provided and electricity consumption through two equations depending on the source and load entering fluid temperatures and obtained through Multiple Linear Regression of test data:

$$P_{el} = c_1 + c_2 \bullet SEFT + c_3 \bullet LEFT + c_4 \bullet SEFT \bullet LEFT \tag{8}$$

$$Q_H = c_1 + c_2 \bullet SEFT + c_3 \bullet LEFT + c_4 \bullet SEFT \bullet LEFT \tag{9}$$

They found that, by combining these equations, COP could also be modeled very accurately.

Liu et al. [32] analyzed the COP of a water-to-water heat pump as a function of the water temperature on the source and load sides under variant working conditions. They derived a mathematical model and verified the results against the data. The equations for heating and cooling operations are:

$$COP_H = c_1 \bullet exp\,[c_2 \bullet SExFT + c_3 \bullet LEFT] + c_4 \bullet \frac{SExFT}{LEFT} + c_5 \tag{10}$$

$$COP_C = c_1 \bullet exp\,[c_2 \bullet LEFT + c_3 \bullet SExFT] + c_4 \bullet \frac{LEFT}{SExFT} + c_5 \tag{11}$$

2. Availability of manufacturers' data

The availability of manufacturers' data strongly affects the accuracy of models that do not rely on user-measured experimental data. As already mentioned, standards influence the documentation that manufacturers publish. However, many manufacturers voluntarily provide data that goes beyond the minimal requirements, e.g. several values measured at different inlet temperatures when only a single point is required. The available data often differ from country to country, even for the same heat pump, depending on the selected market. Characteristics and features of ground-source heat pumps can also vary in different areas: for example, in North America, water-to-air heat pumps are the most widespread, and they are used for both heating and cooling of buildings, while in Europe, ground-source heat pumps are generally water-to-water, and often, they are reversible heat pumps in Southern Europe and employed only for heating in Northern Europe. This section discusses several aspects of data availability, and particular attention is given to the differences between the North American and European catalog data.

a. *Data collection.* When available, heat pump catalogs can be found on manufacturers' websites. Sometimes users are required to subscribe to the website to access more complete datasheets and, in some cases, to have the possibility to use a tool (online or by downloading it) for the heat pump selection, where the desired boundary conditions and possible additional components can be set.
b. *Rating conditions and refrigerant.* Data on refrigerant fluid type, heating and cooling rating capacities, and COPs under rating conditions are generally available in North American and European catalogs. However, the rating conditions change in the European and North American markets, accordingly to the EN14511 Standard [9] and the ASHRAE/AHRI/ISO 13256-1 Standards [7], respectively. Usually, according to EN14511, European catalogs provide the heating and cooling capacities and performance for one or two load-side exiting water temperatures, considering that the heating/cooling will be distributed by fan coils or radiant systems. On the other hand, AHRI Standards set three operating conditions, corresponding to a heat pump coupled, at the source side, with a water loop, groundwater, and a ground loop. These performance data (for water-to-air heat pumps) will include fan power since the units have integrated fans.
c. *Rating flow rates.* The rating flow rate value is provided in most cases, but it is often missing in datasheets of products sold in Northern Europe.

d. *Seasonal Coefficient of Performance.* European manufacturers also provide information about the seasonal coefficient of performance (SCOP), according to product standard EN14825 [33], distinguished by low/medium/high-temperature applications in cold/mild/warm climate conditions. The SCOP is the overall coefficient of performance of the heat pump, representing the whole designated heating season (computed as the reference annual heating demand divided by the annual energy consumption for heating, expressed in kWh/kWh). In the same way, standards define the seasonal energy efficiency ratio (SEER) as the overall energy efficiency ratio of the unit for the whole cooling season, calculated as the reference annual cooling demand divided by the annual energy consumption for cooling and expressed in kWh/kWh. According to EN14825, reference cooling/heating demand is calculated as the product of the design load for cooling/heating and the equivalent active mode hours for cooling/heating. There are three reference heating demands: "A" average, "C" colder and "W" warmer, corresponding to the three reference heating seasons. The equivalent active mode hours for cooling/heating are the assumed annual number of hours, while the unit is assumed to operate at the design load for cooling/heating.
e. *Backup electric resistance.* The value of the backup electric resistance is usually specified in Northern European catalogs, where the resistance is often employed to meet the thermal load of the building during the coldest days or for domestic hot water production.
f. *Temperature limits.* In most datasheets, the operating temperature limits are provided either in graphs or tables.
g. *Compressor details.* The type of compressor installed in the heat pump is usually mentioned (i.e., scroll compressor), while the brand or model specifications are rarely published.
h. *Heat pump performance* – North America. In North America, data about the heat pump performance outside the rating conditions are often available and complete. The range of inlet water temperatures at the ground-coupled side of the heat pump is usually broad and covers temperatures that can go outside standard operating conditions. If the water-source heat pump has two-stage operation, the part-load conditions can be either reported in separate tables or obtained by applying correction factors that can be found in the same datasheets. Water-to-water heat pumps' performance and heating and cooling capacities are provided for different load-side fluid temperatures. On the contrary, this is not common for water-to-air heat pump datasheets, where values are usually given for the rating load entering air temperature. The capacity and power values can then be determined with correction factors based on different room air dry-bulb and wet-bulb temperatures. In the same way, performance values are provided for different flow rates at the source and load sides of water-to-water heat pumps, while correction factors can be applied to airflow rates different from the rating conditions in the case of water-to-air heat pumps.
i. *Heat pump performance* – Southern Europe. When available, manufacturers' data of operating points outside rating conditions are more limited in Europe than in North America. In southern Europe, full load operating conditions are reported as a function of the entering water temperature at the source and load sides and considering fixed temperature differences between water inlet and outlets (i.e., mass flow rates are constant). Therefore, information about the water flow rate is not generally available, as its value typically varies for each operating point. This aspect makes it very difficult to users to adapt European manufacturers' datasheets to heat pump performance models developed for North American catalog data. Correction factors to consider different water temperature differences are often provided.
j. *Heat pump performance* – Northern Europe. Scandinavian manufacturers' catalogs often contain only operating points of one or a few rating conditions.

3. Methodology

In general, water-source heat pump catalogs provide data on heat pump performance and heating or cooling capacities, depending on the source and load side temperature levels. Once the performance of a heat pump is known, it is possible to compute the heat extraction and rejection, given building heating and cooling loads, using Eq. (12) and Eq. (13).

$$Q_e = Q_H \bullet \left(1 - \frac{1}{COP_h}\right) \tag{12}$$

$$Q_r = Q_C \bullet \left(1 + \frac{1}{COP_c}\right) \tag{13}$$

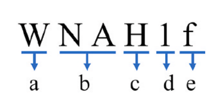
Therefore, once the building cooling and heating loads are determined using a building simulation software and are assumed to be met by the heat pump, simplified models for calculating the COP make the calculation of heat rejection and extraction extremely straightforward. This formulation neglects compressor shell losses, which are usually small (less than 5 % of the heating provided [34]).

After presenting the main characteristics of water-source heat pump datasheets, some selected catalogs are used in this work to evaluate several models for heat rejection and extraction calculation for GSHP design purposes. This section presents the characteristics of the utilized data and the proposed models, along with conventions for labeling the data and models.

Fig. 1 shows a schematic of the model's variables, for the water-to-water and water-to-air heat pumps operating in heating and cooling modes. In the figure, the thin arrows represent the flow rates of the fluid at the source side of the heat pump (source fluid flow rate - SFfr) or the fluid or air entering or leaving the load side heat pump unit (load fluid florw rate – LFfr or load air flow rate -LAfr). On the other hand, the thick arrows show the heat fluxes involving the borehole heat exchangers field, the heat pump and the user or heat pump heating/cooling load: at the heat pump souce side, the heat extracted (Q_e) from the ground field during heating operation and the heat rejected (Q_r) during cooling operation; at the user side, the heating capacity (Q_H) or cooling capacity (Q_C) provided to the user. In addition, the schematic shows the source entering and exiting fluid temperatures (SEFT and SExFT) and the load side entering and exiting temperatures for the water-to-water (LEFT and LExFT) and for the water-to-air heat pump models (LEAT and LExAT).

3.1. Data set labels

In order to characterize the data availability for the selected water-source heat pumps, the data sets are labeled using the following code composed of five letters and one number:



Where:

a. The first letter defines the type of heat carrier fluid at the heat pump load side, W-water and A-air;
b. The second and third letters represent the market's area, NA-North America, NE-Northern Europe, SE-Southern Europe;
c. The fourth letter defines if the heat pump mode is H-Heating or C-Cooling;
d. A sequential number is used to identify the different investigated units;
e. The last letter clarifies if the data refer to p-partial or f-full load operation.

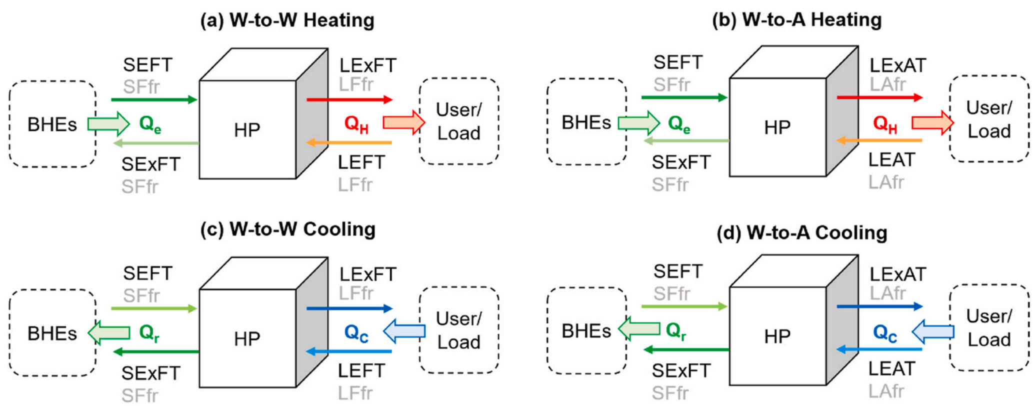


Fig. 1. A schematic reporting the variables used in the proposed simplified models.

3.2. Data categorization

The tables below are divided by load-side heat carrier fluid and mode (heating or cooling). The last rows of each table reports the rating heating or cooling capacity of the specific heat pump and the range of temperatures available in each catalog (minimum and maximum temperature of the fluid or air entering at the source and load sides of the heat pump).

The symbol reported under each variable in the table indicates if it can be found in the catalog, varying for the different operating conditions (*V*) or as a constant value (c), if it is omitted (x), or if it is derivable (D) using other information provided in the datasheet.

In general, data availability for North American heat pumps is higher. In Europe, it is particularly difficult to find data beyond the rating conditions for reversible water-to-water heat pumps in Northern Europe, as they are not widespread in the market. Likewise, the same happens for water-to-air heat pumps, which are not widely used in Europe.

In Table 1, data sets of water-to-water heat pumps in heating mode can be subdivided into three main categories. The first group (Group 1 - varΔT) includes data from North American manufacturers, characterized by the wide availability of operating points and variables, given for a range of entering temperatures and flow rates. In the second group (Group 2 - noLEFT), catalogs do not provide data about the source and load fluid flow rates and leaving fluid temperature (typical of Central/ Northern Europe). The third group (Group 3 - constΔT) collects catalogs typical of Southern European manufacturers. In this case, generally, data are provided for a range of source and load side temperatures, considering a fixed temperature difference between the inlet and the outlet of the heat exchangers. In the same way, the catalogs in Table 2 can be subdivided into two groups with the same characteristics as the ones mentioned for the water-to-water heat pumps in heating mode. However, as reversible water-to-water heat pumps are not common in Northern Europe, they are not considered in this analysis. Catalog WSEH4f is part of Group 3, as the machine is produced in South Europe. However, in this case the number of available operating points is limited to four rating points, provided for the heating model only. This particular catalog will be used for validating the investigated method against real data.

In Table 3, the catalogs of water-to-air heat pumps in heating mode can be subdivided into four types. The groups are differentiated by constant or variable value for the LEAT, for the different operating points, and the presence or absence of data concerning the LExAT. Catalogs of water-to-air heat pumps operating in cooling mode (Table 4) can be divided into two groups characterized by a variable or constant value of LEAT.

The use of such catalog data for the calibration of the models have some limitations:

- Different catalogs report different numbers of operating conditions, which can affect the accuracy of the models' calibration;
- The temperature range for which the operating conditions are reported might also be very different, depending on the heat pump usual application and the manufacturer's policy in publishing the performance data;
- The uncertainty of the catalog data is usually unknown;
- Heat pump performance depend on many factors, depends on many factors, including the quality of the installation, actual operating conditions encountered, and faults;
- Neither standby losses nor cycling losses are included in catalog data.

Table 1
Data availability for selected water-to-water heat pumps in heating mode.

Variable	Group 1 - varΔT							Group 2 –noLEFT		Group 3 - constΔT			
	WNAH1f	WNAH2f	WNAH3f	WNAH4f	WNAH5f	WNAH6p	WNAH6f	WNEH1f	WNEH2f	WSEH1f	WSEH2f	WSEH3f	WSEH4f
SEFT	V	V	V	V	V	V	V	V	V	D	D	D	V
SFfr	V	V	V	V	V	V	V	x	x	V	D	x	D
LEFT	V	V	V	V	V	V	V	x	x	D	D	D	V
Q_H	V	V	V	V	V	V	V	V	V	V	V	V	V
P_{el}	V	V	V	V	V	V	V	x	x	V	V	V	V
Q_e	V	V	V	V	V	V	V	D	D	V	V	V	D
LExFT	V	V	V	V	V	V	V	V	V	V	V	V	V
COP_H	V	V	V	V	V	V	V	V	V	V	D	D	V
LFfr	V	V	V	V	V	V	V	x	x	V	D	x	D
Q_H rating [kW]	50.6	14.7	14.2	16.4	24.5	10.8	13.3	7.57	3.51	8.3	13.1	8.2	18
min/max SEFT [°C]	−4/29	−4/32	−7/27	−1/27	−1/27	−1/21	−1/32	−5/15	−5/20	−6/15	13/17	−1/28	0/3
min/max LEFT [°C]	16/49	16/49	16/49	16/49	16/49	16/49	16/49	X	X	20/45	30/45	25/47	30/40

Table 2
Data availability for selected water-to-water heat pumps in cooling mode.

Variable	Group 1- varΔT							Group 2 - constΔT		
	WNAC1f	WNAC2f	WNAC3f	WNAC4f	WNAC5f	WNAC6p	WNAC7f	WSEC1f	WSEC2f	WSEC3f
SEFT	V	V	V	V	V	V	V	D	D	D
SFfr	V	V	V	V	V	V	V	V	D	D
LEFT	V	V	V	V	V	V	V	D	D	D
Q_C	V	V	V	V	V	V	V	V	V	V
P_{el}	V	V	V	V	V	V	V	V	V	V
Q_r	V	V	V	V	V	V	V	D	V	V
LExFT	V	V	V	V	V	V	V	V	V	V
COP_C	V	V	V	V	V	V	V	V	D	D
LFfr	V	V	V	V	V	V	V	V	D	D
Q_C rating [kW]	59.8	17	16.3	17.2	26.2	12.4	16	6.9	11.8	6.8
min/max SEFT [°C]	10/49	25/40	25/45	4/49	4/49	10/43	10/49	10/43	20/45	−1/43
min/max LEFT [°C]	10/29	10/18	9/23	10/32	10/32	10/27	10/32	10/32.2	−1/20	10/43

Table 3
Data availability for selected water-to-air heat pumps in heating mode.

Variable	Group 1 – constLEAT/varLExAT				Group 2 – varLEAT/noLExAT		Group 3 – varLEAT/varLExAT	Group 4 – constLEAT/noLExAT	
	ANAH1f	ANAH2f	ANAH3f	ANAH3p	ANAH4f	ANAH5f	ANAH6f	ANAH7f	ANAH8f
SEFT	V	V	V	V	V	V	V	V	V
SFfr	V	V	V	V	V	V	V	V	V
LEAT	c	c	c	c	V	V	V	c	c
Q_H	V	V	V	V	V	V	V	V	V
P_{el}	V	V	V	V	V	V	V	V	V
Q_e	V	V	V	V	V	V	V	V	V
LExAT	V	V	V	V	x	x	V	x	x
COP_H	V	V	V	V	V	V	V	V	V
LAfr	c	c	c	c	c	c	c	c	c
Q_H rating [kW]	7.5	2.9	12.8	4.8	6	8.4	13.6	5.5	11.4
min/max SEFT [°C]	−7/32	−7/32	−7/32	−7/32	−1/27	−1/28	−7/32	−4/30	−4/30
min/max LEAT [°C]	21	21	21	21	16/27	16/27	18/27	20	20

Table 4
Data availability for selected water-to-air heat pumps in cooling mode.

Variable	Group 1 - constLEAT						Group 2 - varLEAT		
	ANAC1f	ANAC2f	ANAC3f	ANAC4f	ANAC5f	ANAC5p	ANAC6f	ANAC7f	ANAC8f
SEFT	V	V	V	V	V	V	V	V	V
SFfr	V	V	V	V	V	V	V	V	V
LEAT DB	c	c	c	c	c	c	V	V	V
TQ_C	V	V	V	V	V	V	V	V	V
P_{el}	V	V	V	V	V	V	V	V	V
Q_r	V	V	V	V	V	V	V	V	V
COP_C	V	V	V	V	V	V	V	V	V
LAfr	c	c	c	c	c	c	c	c	c
LEAT WB	c	c	c	c	c	c	V	V	V
SQ_C	V	V	V	V	V	V	V	V	V
Q_C rating [kW]	10.2	3.5	8	15.2	13.2	5.3	10.9	11.8	19.4
min/max SEFT [°C]	−1/49	−1/49	7/46	7/46	−1/49	−1/49	10/43	10/43	−1/43
min/max LEAT [°C]	27	27	27	27	27	27	24/29	24/29	18/29

3.3. Proposed models

Depending on the data availability discussed in the previous section, several models to calculate the performance of ground source heat pumps have been assessed based on the methods from the literature and presented in Section 1.1. First, these models have been applied to catalog data of the selected heat pump models. Afterward, based on the data availability, some models have been modified to reduce the RMSE in the COP calculation. Each model can or cannot be applied to a specific group of catalog data, depending on the data availability, as discussed in the previous section 2.

Once the COP is computed, the heat rejection and extraction can also be calculated using the cooling and heating capacity reported in the datasheets using Eqs. (12) and (13). The proposed models are labeled using two lowercase letters and one serial number (two digits). The first letter defines the type of heat carrier fluid at the heat pump load side, w-water and a-air; the second letter defines if the heat pump mode is h-heating or c-cooling.

3.3.1. Water to water heat pump - heating

Table 5 summarizes the models applied to the catalogs of water-to-water heat pumps operating in heating mode. Some points can be made regarding the models:

- Models applicable to catalog data of the heat pumps produced in Northern Europe are different from those suggested for North American and Southern Europe catalogs. The differences are because information about the source fluid flow rate and load fluid entering temperature are generally unavailable in the Northern European cases.

Table 5
Selected simplified models for water-to-water heat pumps in heating mode.

	Model (wh01)	Group 1							Group 2		Group 3			
		WNAH1f	WNAH2f	WNAH3f	WNAH4f	WNAH5f	WNAH6p	WNAH6f	WNEH1f	WNEH2f	WSEH1f	WSEH2f	WSEH3f	WSEH4f
wh01	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet SFfr + c_3 \bullet (LExFT - SEFT) + c_4 \bullet (LExFT - SEFT)^2$	V	V	V	V	V	V	V			V	V	V	
wh02	$COP_H = c_0 + c_1 \bullet (LExFT - SEFT) + c_2 \bullet (LExFT - SEFT)^2$	V	V	V	V	V	V	V	V	V	V	V	V	V
wh03	$COP_H = 8.77 - 0.15 \bullet (LExFT - SEFT) + 0.000734 \bullet (LExFT - SEFT)^2$	V	V	V	V	V	V	V	V	V	V	V	V	V
wh04	$COP_H = c_0 \bullet \exp(c_1 \bullet SExFT + c_2 \bullet LEFT) + c_3 \bullet \frac{SExFT}{LEFT} + c_4$	V	V	V	V	V	V	V			V	V	V	V
wh05	$COP_H = c_0 \bullet \exp(c_1 \bullet SEFT + c_2 \bullet LExFT) + c_3 \bullet \frac{SEFT}{LExFT} + c_4$	V	V	V	V	V	V	V	V	V	V	V	V	V
wh06	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet LEFT + c_3(SEFT \bullet LEFT)$	V	V	V	V	V	V	V			V	V	V	V
wh07	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet LExFT + c_3(SEFT \bullet LExFT)$	V	V	V	V	V	V	V	V	V	V	V	V	V
wh08	$COP_H = COP_{Carnot} \bullet \eta_{carnot,0}$	V	V	V	V	V	V	V	V	V	V	V	V	V
wh09	$COP_H = c_0 + c_1 \bullet LExFT + c_2 \bullet (LExFT - SEFT) + c_3 \bullet (LExFT - SEFT)^2$	V	V	V	V	V	V	V	V	V	V	V	V	V
wh10[a]	$COP_H = c_0 + c_1 \bullet (LExFT - SEFT) + c_2 \bullet (LExFT - SEFT)^2$								V	V				
wh11[a]	$COP_H = c_0 + c_1 \bullet (LEFT - SEFT) + c_2 \bullet (LEFT - SEFT)^2$	V	V	V	V	V	V	V						

[a] Can be used with rating conditions data.

- Wh01 is the most complex model, as it is a function of the source fluid flow rate (SFfr), the SEFT, and the temperature difference between the load-side outlet and the source-side inlet and its square. The equation's coefficients can be generated using the generalized least squares (GLS) method from the catalog's data. This model can be used when data for more than four operating conditions are available due to the high number of required coefficients.
- Model wh03 uses generic coefficients given in Ref. [30]. Model wh02 uses the same equation form as wh03 but fits the coefficients using the GLS method.
- Model wh04 is the same as proposed in Ref. [32], and coefficients can be computed using the GRG (Generalized Reduced Gradient) non-linear solver implemented in Microsoft Excel [35]. (The GLS method fits coefficients for linear combinations of functions but cannot handle, for example, the multiple terms used to form an exponent in wh04.)
- Equation wh05 is supposed to improve method wh04 using SEFT and LExFT as inputs instead of SExFT and LEFT, as these data are generally available in all catalogs.
- Model wh06 is based on the work presented in Ref. [31], with a difference: the method consists in computing the COP starting from catalog data, while in Ref. [31], it was derived only after calculating the electrical power and heating capacity using Eqs. (8) and (9). This variation reduces the computational effort and allows the calculation in case data about the electrical consumption are unavailable.
- Model wh07 improves the wh06 by considering the whole temperature lift between the heat pump source and load sides, using the LExFT instead of the LEFT.
- Model wh08 is based on the Carnot method, but the COP is calculated differently from the standards.
- For the sake of simplicity and for minimizing the assumptions, it directly depends on the entering source and load side temperatures (the same is done for the Carnot COP at rating conditions), as in Eq. (14).

$$COP_{Carnot} = \frac{LEFT + 273}{LEFT - SEFT} \tag{14}$$

The COP_{Carnot} is then corrected using the $\eta_{carnot,0}$, as reported in Section 1.1, Eqs (2) and (3). Moreover, a control is used to limit the COP value and reduce the error in the calculation of the COP and heat extraction from the ground outside the rating conditions. When the temperature difference between the entering fluids at the source and load sides of the heat pump is low, then the COP computed as in Eq. (3) might result as unrealistically high. For this reason, if the temperature difference between LEFT and SEFT is lower than a set value (for example, $\Delta T_{set} = 15\ ^\circ C$), the LEFT is divided by that set value, and Eq. (14) becomes Eq. (15).

$$COP_{Carnot} = \frac{LEFT + 273}{\Delta T_{set}} \tag{15}$$

The set temperature difference can be adjusted so that the COP does not reach remarkably high values (for example, higher than 8) for low temperature differences. In this work, the computation of the *COP* is calibrated using the available data sets. The heat pump performance and related errors between catalog data and models' results depend on the operating conditions reported in the catalog and on the rating conditions used for the calculation of the $\eta_{carnot,0}$ Therefore, the ΔT_{set} value might be different for different data sets.

On the other hand, if only one rating condition is available, the ΔT_{set} can be set equal to 15 °C and the user can reduce or increase this value if the considered operating conditions lead to high values of *COP*.

For the Northern European catalogs, the LExFT replaces the LEFT in the equation, and the control on the Carnot COP is done on the SEFT: if the SEFT is higher than 13 °C, it is considered equal to 13 °C.

- Model wh09 is an alternative to model wh01 when data on the SEFT and the SFfr are unavailable, like in Northern European datasheets.
- When at least three operating points at rating conditions are available, they can be used to compute the coefficients for a model dependent on the temperature differences between the LEFT and the SEFT in North America (wh11) and the LExFT and the SEFT in Northern Europe (wh10).

3.3.2. Water to water heat pump - cooling

The models applied to the data of water-to-water heat pumps operating in cooling mode are presented in Table 6. Most models for calculating the COP in cooling are similar to those used for deriving the COP in heating. In particular, the structure of models wc01, wc02, wc06, and wc07 is the same as models wh01, wh02, wh06, and wh07, respectively. However, the coefficients are different and calculated using the GLS or the GRG non-linear methods from the catalogs containing the cooling performance of the investigated heat pumps. Model wc03 is the same as proposed in Ref. [30], while wc04 and wc05 investigate some possible modifications to the original equation, which might reduce the RMSE and whose effectiveness will be discussed in the Results section 5.

Model wc08 is based on the Carnot method and directly depends on the entering source and load sides temperatures (the same is done for the Carnot COP at rating conditions), as in Eq. (16).

$$COP_{Carnot} = \frac{LEFT+273}{SEFT - LEFT} \tag{16}$$

If the difference between the SEFT and the LEFT is lower than a set value (usually $\Delta T_{set} = 10\,^{\circ}C$), the Carnot COP is obtained by dividing the LEFT by that assessed value. The set temperature difference can be adjusted to prevent the COP from reaching very high values (for example, higher than 8) in case of low temperature differences.

When the catalog contains more than three points defined by the standards, they can be used to derive the coefficients of equation wc09, where the COP for cooling given as a second order polynomial of SEFT.

3.3.3. Water to air heat pump – heating and cooling

Table 7 contains the equations for calculating the COP in heating for water-to-air heat pumps. The model proposed by Staffel et al. [30] cannot be applied to water-to-air heat pumps, as the error would be very high. Models ah01, ah02 and ah04 have the same shape as models wh01, wh02, and wh05, respectively, where the LEAT is used instead of the LExFT. Likewise, equations ah03 and ah05 correspond to models wh04 and wh06, where the input LEFT is substituted with the input LEAT, while models ah06, ah08, ah09, and ah10 correspond, respectively, to models wh07, wh01, wh02, and wh05, where the input LExAT substitutes the input LExFT.

Model ah07 is based on the Carnot method and directly depends on the entering source and load sides temperatures (the same is done for the Carnot COP at rating conditions), as in Eq. (17).

$$COP_{Carnot} = \frac{LEAT+273}{LEAT - SEFT} \tag{17}$$

In calculating the Carnot COP, the same considerations as for the water-to-water heat pump in heating about the minimum temperature difference between the LEAT and the SEFT can be done.

Moreover, models ah11 and ah12 can be applied either to a broader matrix of operation points or to the heat pump data operating in rating conditions (if more than three points are available), depending on the SFfr and SEFT and its square.

The usability of each model is related to the availability of data. Concerning water-to-air heat pumps operating in heating or cooling, the fact that the operating conditions are often given considering constant LEAT values limits the number of models that can be employed. Models ac01, ac02, ac03, ac04, and ac05, shown in Table 8, have the exact shape of equations ah01, ah02, ah05, ah06, and ah12, respectively. The Carnot COP for cooling is calculated using Eq. (18) in ac05. In this case, it is suggested to use the assumptions described in Appendix A of ISO 13612-2 [10] to obtain the refrigerant's condensation and evaporation temperatures, starting from the temperatures of the heat source and the room air.

$$COP_{Carnot} = \frac{T_{evap}+273}{T_{cond} - T_{evap}} \tag{18}$$

Once the LExAT and the SEFT are known, according to ISO 13612-2, the Carnot COP in cooling becomes:

$$COP_{Carnot} = \frac{(LExAT-10)+273}{(SEAT+10) - (LExAT-10)} \tag{19}$$

Where a minimum temperature lift between the source and the load side, meaning the denominator in Eq. (19) should be kept constant to a set value ($\Delta T_{set} = 10\ ^{\circ}C$).

If more than three rating conditions are available, they can be used to compute the coefficients of model ac07 using the GLS method and

Table 6
Selected simplified models for water-to-water heat pumps in cooling mode.

	Model (wc01)	Group 1							Group 2		
		WNAC1f	WNAC2f	WNAC3f	WNAC4f	WNAC5f	WNAC6p	WNAC6f	WSEC1f	WSEC2f	WSEC3f
wc01	$COP_C = c_0+c_1 \bullet SEFT + c_2 \bullet SFfr + c_3 \bullet (LExFT - SEFT) + c_4 \bullet (LExFT - SEFT)^2$	V	V	V	V	V	V	V	V	V	V
wc02	$COP_C = c_0 + c_1 \bullet (LExFT - SEFT) + c_2 \bullet (LExFT - SEFT)^2$	V	V	V	V	V	V	V	V	V	V
wc03	$COP_C = c_0 \bullet \exp(c_1 \bullet SExFT + c_2 \bullet LEFT) + c_3 \bullet \frac{LEFT}{SExFT} + c_4$	V	V	V	V	V	V	V	V	V	V
wc04	$COP_C = c_0 \bullet \exp(c_1 \bullet SEFT + c_2 \bullet LExFT) + c_3 \bullet \frac{LExFT}{SEFT} + c_4$	V	V	V	V	V	V	V	V	V	V
wc05	$COP_C = c_0 \bullet \exp(c_1 \bullet SExFT + c_2 \bullet LExFT) + c_3 \bullet \frac{LExFT}{SExFT} + c_4$	V	V	V	V	V	V	V	V	V	V
wc06	$COP_C = c_0 + c_1 \bullet SEFT + c_2 \bullet LEFT + c_3(SEFT \bullet LEFT)$	V	V	V	V	V	V	V	V	V	V
wc07	$COP_C = c_0 + c_1 \bullet SEFT + c_2 \bullet LExFT + c_3(SEFT \bullet LExFT)$	V	V	V	V	V	V	V	V	V	V
wc08	$COP_C = COP_{Carnot} \bullet \eta_{carnot,0}$	V	V	V	V	V	V	V	V	V	V
wc09[a]	$COP_C = c_0 + c_1 \bullet (SEFT) + c_2 \bullet (SEFT)^2$	V	V	V	V	V	V	V			

[a] Can be used with rating conditions data.

Table 7
Selected simplified models for water-to-air heat pumps in heating mode.

	Group	Group 1				Group 2		Group 3	Group 4	
	Model (ah01)	ANAH1f	ANAH2f	ANAH3f	ANAH3p	ANAH4f	ANAH5f	ANAH6f	ANAH7f	ANAH8f
ah01	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet SFfr + c_3 \bullet (LEAT - SEFT) + c_4 \bullet (LEAT - SEFT)^2$					V	V			
ah02	$COP_H = c_0 + c_1 \bullet (LEAT - SEFT) + c_2 \bullet (LEAT - SEFT)^2$					V	V		V	V
ah03	$COP_H = c_0 \bullet \exp(c_1 \bullet SExFT + c_2 \bullet LEAT) + c_3 \bullet \frac{SExFT}{LEAT} + c_4$	V	V	V	V	V	V	V	V	V
ah04	$COP_H = c_0 \bullet \exp(c_1 \bullet SEFT + c_2 \bullet LEAT) + c_3 \bullet \frac{SEFT}{LEAT} + c_4$					V	V		V	V
ah05	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet LEAT + c_3 (SEFT \bullet LEAT)$					V	V	V		
ah06	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet LExAT + c_3 (SEFT \bullet LExAT)$	V	V	V	V			V		
ah07	$COP_H = COP_{Carnot} \bullet \eta_{carnot,0}$	V	V	V	V	V	V	V	V	V
ah08	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet SFfr + c_3 \bullet (LExAT - SEFT) + c_4 \bullet (LExAT - SEFT)^2$	V	V	V	V			V		
ah09	$COP_H = c_0 + c_1 \bullet (LExAT - SEFT) + c_2 \bullet (LExAT - SEFT)^2$	V	V	V	V			V		
ah10	$COP_H = c_0 \bullet \exp(c_1 \bullet SEFT + c_2 \bullet LExAT) + c_3 \bullet \frac{SEFT}{LExAT} + c_4$	V	V	V	V			V		
ah11	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet Sfr + c_3 \bullet SEFT^2$	V	V	V	V	V	V		V	V
ah12[a]	$COP_H = c_0 + c_1 \bullet SEFT + c_2 \bullet Sfr + c_3 \bullet SEFT^2$	V	V	V	V					

[a] Can be used with rating conditions data (for example, AHRI Standards).

Table 8
Selected simplified models for water-to-air heat pumps in cooling mode.

	Group	Group 1						Group 2		
	Model (ac01)	ANAC1f	ANAC2f	ANAC3f	ANAC4f	ANAC5f	ANAC5p	ANAC6f	ANAC7f	ANAC8f
ac01	$COP_C = c_0 + c_1 \bullet SEFT + c_2 \bullet SFfr + c_3 \bullet (LEAT - SEFT) + c_4 \bullet (LEAT - SEFT)^2$							V	V	V
ac02	$COP_C = c_0 + c_1 \bullet (LEAT - SEFT) + c_2 \bullet (LEAT - SEFT)^2$	V	V	V	V	V	V	V	V	V
ac03	$COP_C = c_0 \bullet \exp(c_1 \bullet SEFT + c_2 \bullet LEAT) + c_3 \bullet \frac{LEAT}{SEFT} + c_4$	V	V	V	V	V	V	V	V	V
ac04	$COP_C = c_0 + c_1 \bullet SEFT + c_2 \bullet LEAT + c_3 (SEFT \bullet LEAT)$							V	V	V
ac05	$COP_C = COP_{Carnot} \bullet \eta_{carnot,0}$	V	V	V	V	V	V	V	V	V
ac06	$COP_C = c_0 + c_1 \bullet SEFT + c_2 \bullet SFfr + c_3 \bullet SEFT^2$	V	V	V	V	V	V	V	V	V
ac07[a]	$COP_C = c_0 + c_1 \bullet SEFT + c_2 \bullet SEFT^2$	V	V	V	V	V	V			

[a] Can be used with rating conditions data (for example, AHRI Standards).

extrapolate the results for operating points different from the rating ones.

The models presented in this section are evaluated using the RMSE (Eq. (20)) and the Mean Percentage Error MPE (Eq. (21)), calculated for the COP_H and heat extraction from the ground in heating operation and the COP_C and heat extraction and rejection to the ground in cooling operation. In Eq. (20) and Eq. (21), y_c is the catalog value, y_m is the modeled value, and N is the number data.

$$RMSE = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_{c,i}-y_{m,i}}{y_{c,i}}\right)^2} \tag{20}$$

$$MPE = \frac{100}{N}\sum_{i=1}^{N}\frac{y_{m,i}-y_{c,i}}{y_{c,i}} \tag{21}$$

3.3.4. Data matrix reduction and data extrapolation

Regarding the range of data used to derive the equations' coefficients, it is tempting to think the more data available, the better. However, in this research, for some cases with extensive ranges of operating conditions, we observed that it was better (more accurate) to utilize only data from the range over which the heat pump would be applied. Therefore, it is suggested to use reduced matrixes of data to calculate the coefficients based on the predicted operating domain: this will lead to lower RMSE if the area of interest is limited and reduces the amount of data the user is required to employ. On the contrary, if larger intervals are needed, the suggestion is to use all the available data to reduce the error at the extremes of the boundary conditions. The minimum and maximum temperature limits for the reduced matrix of data used in this work are reported in Table 9.

Table 9
Minimum and maximum temperature limits for the reduced matrix of data.

Type and Mode	min/max SEFT	min/max LEFT	min/max LEAT
WtoW Heating	−6/23 °C	15/48 °C	–
WtoA Heating	−6/32 °C	–	15/27 °C
WtoW Cooling	10/43 °C	4/26 °C	–
WtoA Cooling	10/43 °C	–	18/29 °C

In addition, the extrapolation of results has been evaluated for these models, and data showed a continuity outside the matrix limits. However, extrapolation could be problematic for the models derived from the Carnot efficiency method, which show significant errors when the difference between the source and sink temperature levels is large. In these cases, if values outside the data range must be evaluated, the maximum or minimum performance values obtained over the range of catalog data should be used.

4. Field measurement

The models introduced in Section 3.3.1 are validated against field measurements. This section describes the system and measurements. The ground-source heat pump system uses a water-to-water heat pump operating in heating mode, corresponding to WSEH4f in Table 1.

4.1. Method

Experimental data from an energy plant [36,37], including a water-to-water heat pump operating in heating mode, are employed to validate the study. The available catalog data are used to build the models presented in Table 5, as proposed in Section 3.3. Once the coefficients of the equations are computed, the models are used to predict COP_H given the field measured entering and exiting fluid temperatures and fluid flow rates. Subsequently, the building heating load is used to derive the heat extraction from the ground through Eq. (12) for a comparison with the field measured heat extraction rate. The RMSE is calculated as in Eq. (20) to verify the applicability of the proposed models.

4.2. Case study

The investigated energy plant is located in Como (Italy), and the measurement campaign was carried out from November 2013 to January 2015 [36,37]. A water-to-water ground source heat pump with a rated heating capacity of 18 kW is used to provide space heating, cooling, and domestic hot water to a two-story building with a total heated area of 270 m^2. The space heating and cooling distribution system includes radiant floor panels. Table 10 shows the operating points provided by the manufacturer and used to calculate the models' coefficients.

Fig. 2 shows a schematic of the plant, which includes the heat pump connected to two thermal storages, one used for domestic hot water production (300 L) and provided with electrical resistance, and the other is used for heating and cooling (200 L). Three vertical ground heat exchangers are employed. The polyethylene borehole heat exchangers are double-U shaped, 110 m long, and the pipes have a diameter of 40 mm, with a mutual distance of 10 m. The source-side and the load side circulation pumps are located inside the heat pump. The electrical power absorbed by the source-side circulation pump ranges from 335 W to 390 W, while the load-side's ranges from 110 W to 170 W.

In Fig. 2, the data monitored and considered for this analysis are as follows:

- Energy flow meters are used to monitor the energy flow at the load side of the heat pump. In particular, an ultrasonic flow meter (accuracy Class 2 EN 1434) and Pt500 temperature sensors are employed to measure the load entering flow rate (LEfr) and load entering and exiting temperatures (LEFT and LExFT), respectively;
- Two temperature sensors (Pt100) are employed to measure the source entering and exiting fluid flow rates (SEFT and SExFT) ($\pm$0.05 °C);
- An electrical power and energy meter monitors the heat pump's electrical consumption ($\pm$0.2 %).

The energy flow due to domestic hot water production is also monitored, but it is not considered in this work. The monitored data are provided with a 1-min timestep.

Table 10
Manufacturer's data for the heat pump's operating conditions.

SEFT [°C]	SExFT [°C]	LEFT [°C]	LExFT [°C]	Q_H [kW]	P_{el} [kW]	COP [kW/kW]
0	−3	30	35	18.5	4.75	3.80
3	0	30	35	20.0	4.90	4.08
0	−3	40	45	17.0	5.55	3.06
3	0	40	45	18.8	5.70	3.30

5. Results

5.1. Performance of the models

The present section analyzes the performance of the models characterized by RMSE. Figs. 3–5 show the RMSE values calculated as in Eq. (20) for each set of catalog data of water-to-water or water-to-air heat pumps. The RMSE is relative to the COP_H and COP_C (Figs. 3–6 (a)), computed by applying the models discussed in section 3.3, and to the heat exchanged with the ground (Figs. 3 to 6(b)). This last value is calculated using Eqs. (12) and (13), starting from the thermal load demanded by the building and met by the heat pump at different operating conditions, according to the catalog data. If the error is higher than 15 %, in the graphs, a control bar is shown in the pink area (RMSE>15 %) in place of the actual value for the specific model's RMSE. In the case of non-applicable models, the RMSE value is not shown.

The graphs in Fig. 3 are for water-to-water heat pumps operating in heating mode. In general, the deviation between catalog and simulated data is higher for COP_H values than for the heat extraction values. For example, applying models wh03 and wh08 to all selected data sets leads to an average $RMSE_{COPh}$ of 21 % and 17 %, respectively, but only to an $RMSE_{Qe}$ of 6 % and 4 %. Moreover, models wh03 and wh08 are likely to overestimate the COP_H and the Q_e, compared to catalog data. Indeed, the mean percentage error MPE_{Qe} for models wh03 and wh08 is equal to 5 % and 2 %, while MPE_{COP} is equal to 17 % and 11 %. On the other hand, as expected, the MPE is equal to zero for the models where the GRG non-linear solver and the GLS method are used to fit the equation's coefficients. The application of model wh11 leads to very good results when a wide range of data is available. However, model wh11 leads to high $RMSE_{COPh}$ and $RMSE_{Qe}$ when the number of operating conditions provided in the manufacturer's catalog is limited, like in the case of the WSEH4f data set.

The application of model wh11 leads to an $RMSE_{COPh}$ up to 20 % (WNAH1f) but results in an $RMSE_{Qe}$ of only 6 %. The application of the other models to the catalog data leads to an average maximum $RMSE_{COPh}$ of 5 % and an average maximum $RMSE_{Qe}$ equal to 3 %.

The matrix reduction applied to some of the catalogs, according to Table 9, does not strongly affect the results of the models, in terms of RMSE. Indeed, the RMSE is very close to the RMSE calculated considering the extended data matrix for the calibration of the equations. The highest difference can be found when applying model wh01 to catalogs WNAH1f and WNAH2f, where the $RMSE_{COPh}$ is 6 % with the extended matrix and 4 % with the reduced one. Some differences, as expected, can be found also in the use of equations wh03 and wh08: being an experimentally derived curve, model wh03 might or might not better fit catalog data if they are describing a larger number of operating conditions; model wh08, being calibrated on a single data point, is likely to lead to higher RMSE if operating conditions far from the rated one are included in the calculations.

Fig. 4 illustrates the values of $RMSE_{COPc}$ and $RMSE_{Qr}$ for the models applied to catalog data of the selected water-to-water heat pump in cooling mode. The error in the heat rejection rate calculation is considerably lower than the error in the computation of the COP_C. For example, $RMSE_{COPc}$ of models wc08 and wc09 exceeds 15 % for all the catalogs of Group 1- varΔT, but $RMSE_{Qr}$ is always lower than 5 % and 7 %, respectively. The use of the other models leads to $RMSE_{COPc}$ lower than 10 % and $RMSE_{Qr}$ lower than 2 %. In this case no tendency in overestimating or underestimating the COP_C and Q_r is observed when using the models. In general, when the availability of catalog data is low, the risk of overestimating and underestimating the heat pump performance increases because there is a higher probability of calibrating the

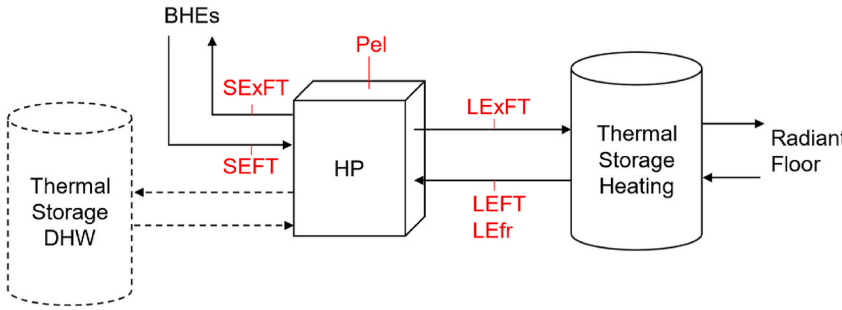


Fig. 2. Schematic of the real energy plant.

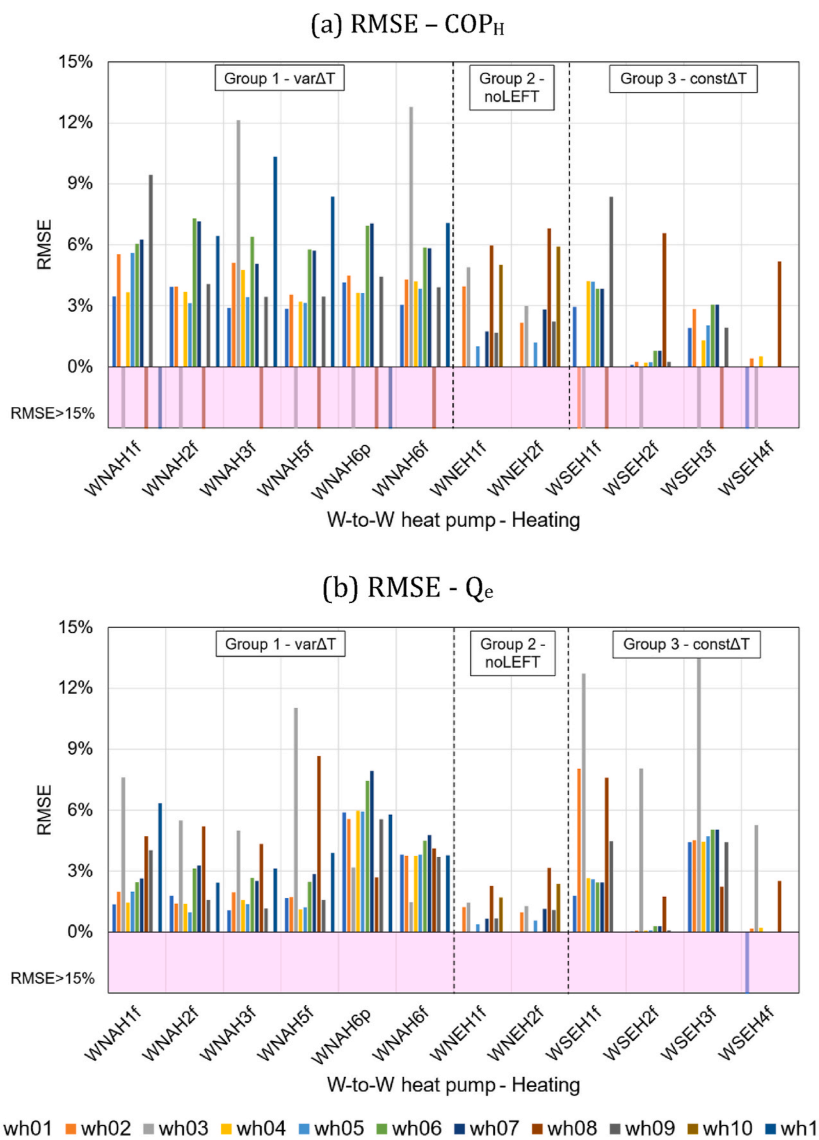


Fig. 3. Water-to-water heat pump, heating mode. RMSE for COP_H and Q_e for the different catalogs and models.

models using declared operating points far from the real (or considered) operating conditions. Compared to the reduced data matrix (as reported in Table 9), models applied to the entire range of available data could lead to higher $RMSE_{COPc}$ and $RMSE_{Qr}$. For example, models wc06 and wc07, which lead to higher error compared to the others, perform better with a reduced matrix. For catalogs WNAC1f and WNAC5f they show $RMSE_{COPc}$ around 12–14 % when the extended matrix is considered, to 10-8% with the reduced matrix, and $RMSE_{Qr}$ from 3 to 4% with the extended matrix, to 2 % with the reduced matrix.

The graphs in Fig. 5 show the $RMSE_{COPh}$ and $RMSE_{Qe}$ for the water-to-air heat pumps operating in heating mode. The application of models ah07 and ah12, which can be employed when only one to four rating data points are available, leads to the highest values of $RMSE_{COPh}$ and $RMSE_{Qe}$. On average, model ah07 leads to an $RMSE_{COPh}$ of 13 % and $RMSE_{Qe}$ equal to 4 %, while by applying ah12, the average $RMSE_{COPh}$ increases to 17 % and the $RMSE_{Qe}$ to 5 %. Considering the other models,

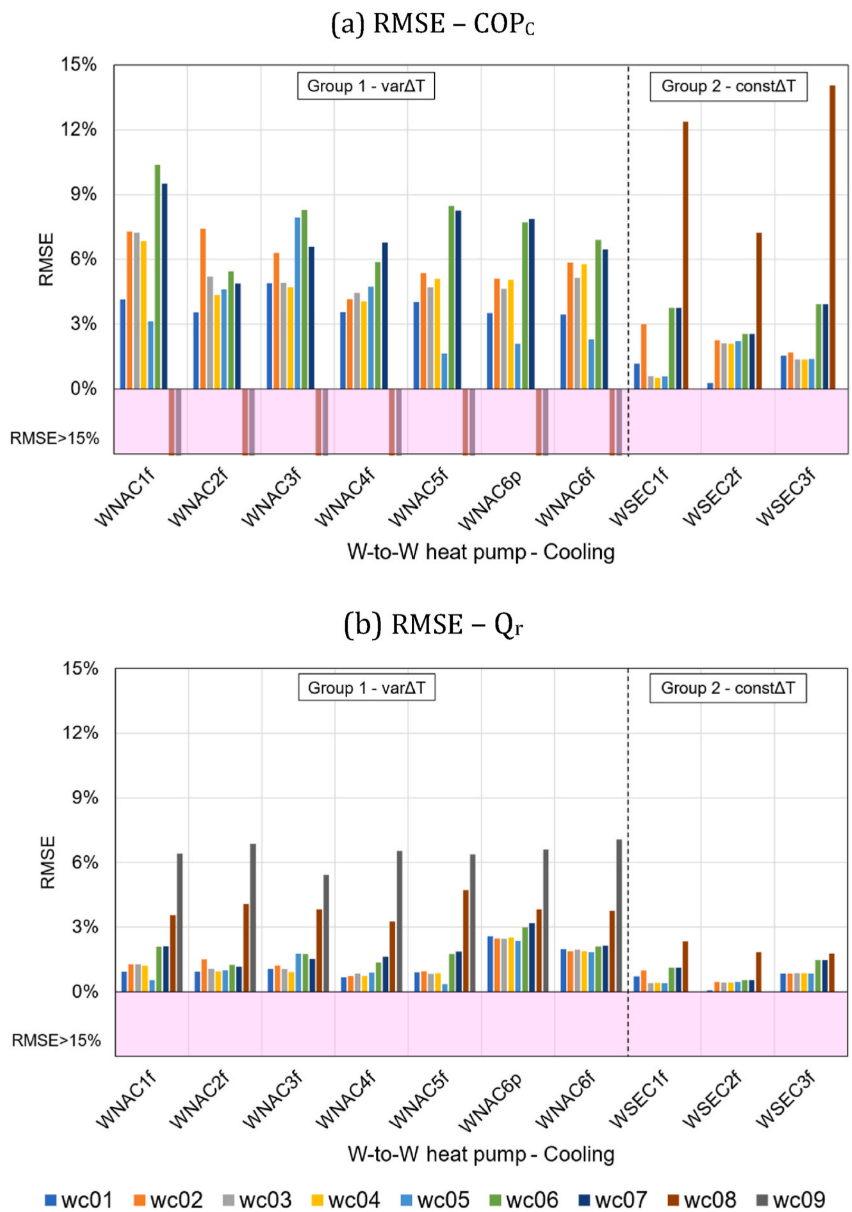


Fig. 4. Water-to-water heat pump, cooling mode. RMSE for COP_C and Q_r for the different catalogs and models.

they provide a maximum average $RMSE_{COPh}$ equal to 5 % and a maximum average $RMSE_{Qe}$ equal to 3 %. In the case of the water-to-air heat pump in heating mode, a general overestimation in the COP_H is observed for model ah07, with an average MPE_{COPh} equal to 3 %, while the overestimation trend is not significant in the computation of the Q_e. In this case, no matrix reduction was considered, compared to the temperature ranges reported in the catalogs.

The results in terms of $RMSE_{COPc}$ and $RMSE_{Qr}$ for the data sets of water-to-air heat pumps in cooling operation are shown in Fig. 6. Acceptable results can be obtained using models ac01, ac02, ac03, ac04, and ac06, with a maximum value of $RMSE_{COPc}$ equal to 8 % and a maximum $RMSE_{Qr}$ of 2 %. The errors are higher when model coefficients are determined from a small number of operating points, typically rating conditions, using models ac05 and ac07. The $RMSE_{COPc}$ is generally higher than 15 % in these cases, while $RMSE_{Qr}$ is lower than 8 %. In this case, the average MPE_{Qe} for model ah5 is equal to −3%, while MPE_{COPc} is equal to +25 %, showing a tendency to underestimate the Q_r and overestimate the COP_C.

Also in this case, data matrix from catalogs presenting a wide range of operating conditions can be reduced when calibrating the models, without decreasing their accuracy. The focus on the reduced operating temperatures can lead to lower RMSE for the models applied to the area of interest. For example, catalog ANAC8f presents $RMSE_{COPc}$ around 6 % for models ac01, ac02, ac03 and ac04, which decreases to 2–3% when considering the reduced matrix.

5.2. Validation against experimental data

Data collected during the field measurement campaign described in Section 4 were used to further validate the models after verifying the results against catalog data. The model coefficients used to compute the COP_H were determined using the manufacturer's catalog data, as described in Section 3. Subsequently, the calculated COP_H values were employed to compute the heat extraction from the ground, which in turn was compared to field-measured data.

Table 11 shows the monthly $RMSE_{Qe}$ and the monthly MPE_{Qe} for the models and calculated considering the experimental measurements as the reference for January 2014, March 2014, and January 2015. The lowest error is obtained using models wh02, wh04 and wh07. On the contrary, the use of models wh03 and wh08 generates the highest error.

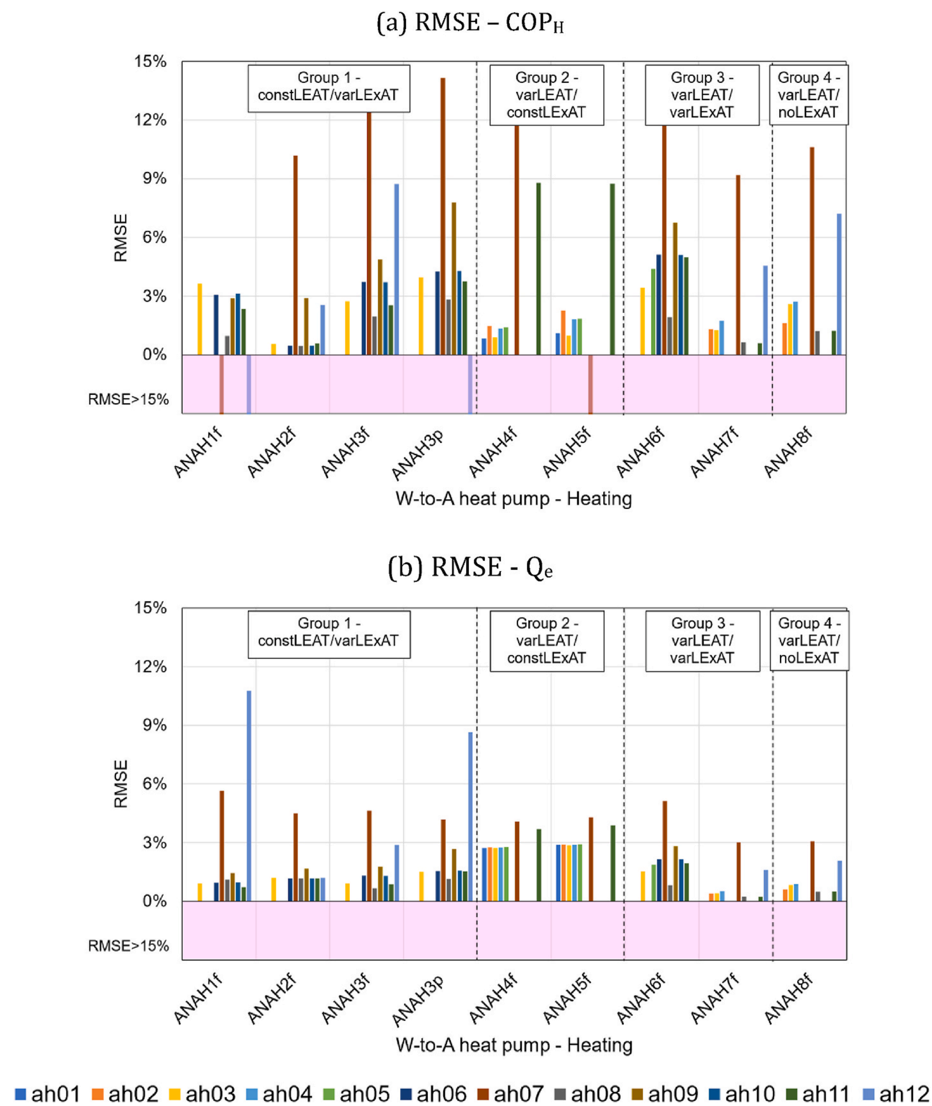


Fig. 5. Water-to-air heat pump, heating mode. RMSE for COP_H and Q_e for the different catalogs and models.

This result was predictable because the coefficients of equation wh03 were calibrated using the data set reported in Ref. [30], and model wh08 is based on one operating condition. In addition, Table 11 shows, for each month, the number of hours the heat pump operates in heating mode. As demonstrated through the MPE_{Qe} values, the models overestimate the field measurements.

Fig. 7 shows the monthly heat extraction measured and modeled, for January and March 2014, and January 2015. The bar chart with error bars shows uncertainties in the measured heat extraction, as well as the uncertainty in the model's results, due to the heating load input (the propagated uncertainties due to errors in the SEFT and LEFT are here ignored, as the heating load error has the strongest influence). In this case study, although the models overestimate the measured heat extraction, within the uncertainties, the best models (wh02, wh05) overlap the field measurements. Fig. 7 shows that models wh03 and wh08 present a higher deviation compared to the others, as already observed. This evaluation does not consider the uncertainty related to catalogs' data, used for the models' calibration, which is generally not available.

Figs. 8–10 show the results for three representative days in January 2014, March 2014 and January 2015, when the heat pump operates in heating mode. Figs. 8–10 show the measured heat extraction from the ground (red indicators), with the measurement uncertainty represented with error bars, and the heat extraction calculated using two representative models wh02 (which generally produces a low error compared to measured data) and wh08 (which generally leads to higher errors), for January 2014 and March 2014. The measured source and load side entering and exiting fluid temperatures and heat load (purple indicators) are also plotted.

A general observation regards the frequency of heat pump on-off cycles. The heat pump seems oversized based on the short (a few minutes) on-off cycles. Every point indicated in the graph corresponds to 1 min of operation.

Fig. 8 reports the results for a typical day in January 2014. During this day, the $RMSE_{Qe}$ between the simulated and measured heat extraction values is around 9 % for model wh02 and 13 % for model wh08. The temperature difference between the exiting and entering fluid temperatures at the load side of the heat pump is around 9 °C, higher than the temperature difference considered for the rating conditions declared in the catalog (5 °C). Fig. 8 also reports the experimental error (vertical bars starting from the red indicators), which, in January 2014, was around 8.5 %.

Fig. 9 compares the measured and simulated heat extraction rates for March 27th, 2014. Source and load side fluid temperatures are also shown. Due to the higher mean outdoor air temperature on March 27th, 2014 (9.3 °C), compared to January 30th, 2014, the daily mean SEFT is

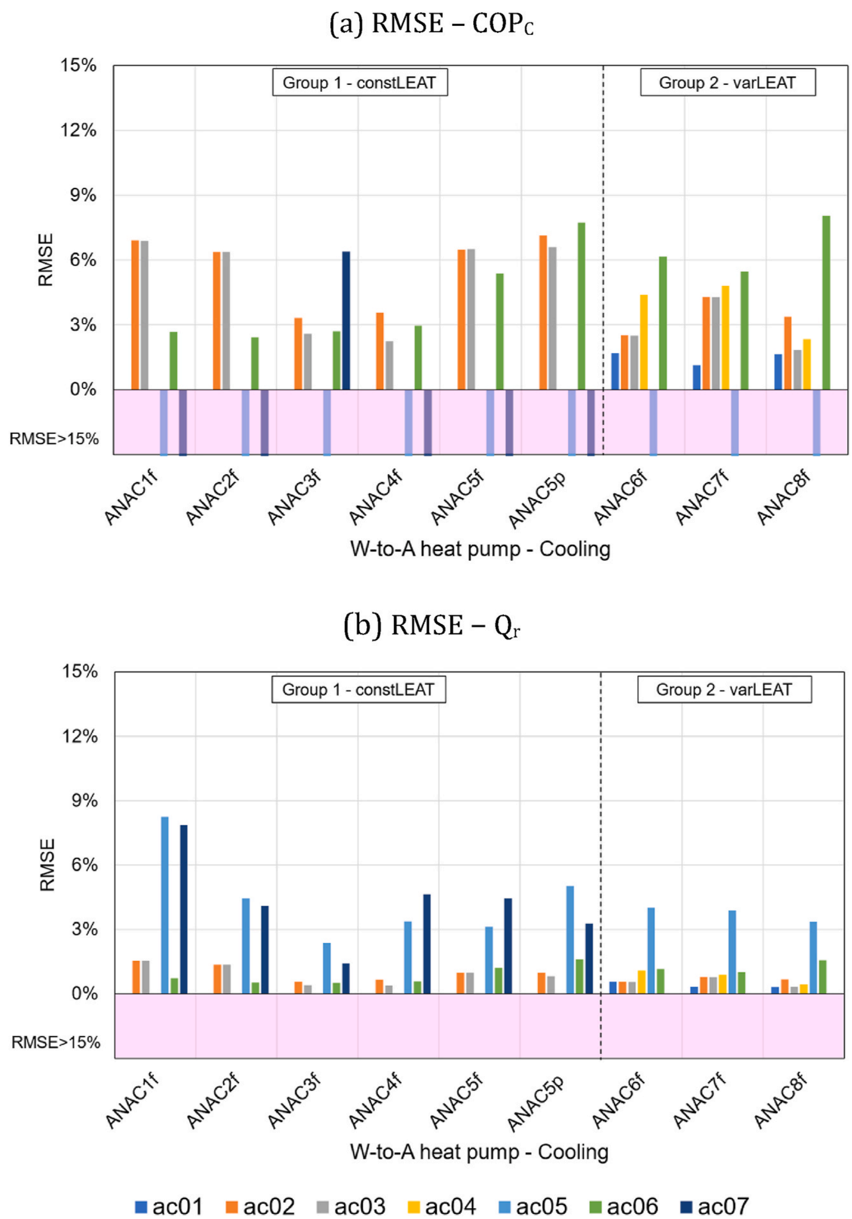


Fig. 6. Water-to-air heat pump, cooling mode. RMSE for COP_C and Q_r for the different catalogs and models.

Table 11
Monthly $RMSE_{Qe}$ calculated between the experimental data and the models' results.

		wh02	wh03	wh04	wh05	wh06	wh07	wh08	wh09	Hours
Jan 2014	$RMSE_{Qe}$	10 %	15 %	12 %	11 %	12 %	11 %	15 %	11 %	62
	MPE_{Qe}	+9 %	+14 %	+11 %	+9 %	+12 %	+9 %	+14 %	+10 %	
Mar 2014	$RMSE_{Qe}$	12 %	16 %	14 %	12 %	14 %	12 %	19 %	13 %	20
	MPE_{Qe}	+11 %	+16 %	+13 %	+11 %	+13 %	+11 %	+18 %	+12 %	
Jan 2015	$RMSE_{Qe}$	13 %	17 %	12 %	13 %	12 %	13 %	14 %	13 %	61
	MPE_{Qe}	+12 %	+17 %	+11 %	+12 %	+12 %	+12 %	+14 %	+13 %	

slightly higher (9.8 °C compared to 7.2 °C). At the same time, the daily mean LExFT is slightly lower (37.4 °C compared to 39.6 °C) because of the heat pump's heat load modulation. The lower temperature lift measured on March 27th, 2014, has a negligible influence on the measured COP and Q_e, but leads to an increase of nearly 11 % and 24 % in the average COP and of 2 % and 4 % in the average Q_e, when models wh02 and wh08 are used. These results show that the simplified models strongly depend on the temperature lift and do not consider the effect of the heating capacity modulation of the heat pump. On March 27th, 2014, the $RMSE_{Qe}$ was around 12 % using model wh02 and 19 % using model wh08. Lastly, Fig. 10 shows the data for a day in January 2015. After the summer, the fluid flow rate at the load side of the heat pump was considerably increased by the technicians, going from around 2200 L/h measured on January 18th, 2014, to nearly 5000 L/h on January 25th, 2015. This increase in the fluid flow rate reduces the difference between the exiting and entering fluid temperatures at the load side of

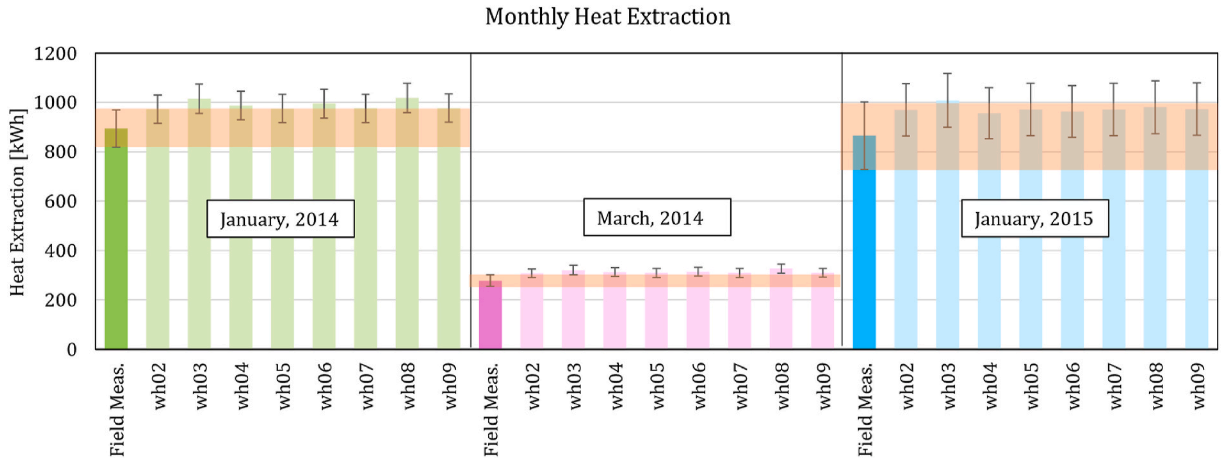


Fig. 7. Experimental data and model results in terms of monthly heat extraction for January and March 2014 and January 2014, considering the uncertainty of the sensors in the measured value and in the model's inputs.

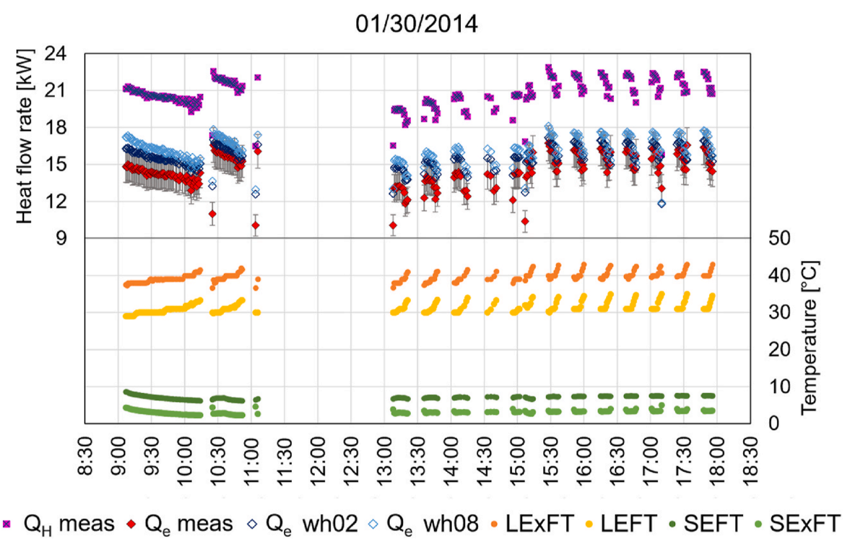


Fig. 8. Experimental data and model results for a representative day in January 2014. Measured heat extraction from the ground and relative error, modeled heat extraction using wh02 and wh08, measured heating capacity, and measured load and source-side entering and exiting fluid temperatures.

the heat pump, now closer to 5 °C.

Figs. 8–10 show the strong dependency of the heat extraction calculation (and relative error) on the heat load met by the heat pump and the temperature lift.

Concerning the COP, the monthly MPE_{COP} using model wh02 is equal to +26 % in January 2014, +34 % in March 2014, and +38 % in January 2015.

In conclusion, the discrepancy in actual temperature lift and catalog temperature lift has an adverse impact on the models' ability to predict the field-measured heat extraction. Concerning the investigated case study, the catalog only describes four operating conditions, which do not allow for an optimal calibration of the models, as the temperature lift is quite different from the real operating conditions of the unit (as reported in Figs. 8–10). Neglecting the intrinsic error between declared and experimental data, the proposed models could lead to more accurate results if the manufacturer's catalog provided a more extended range of operating temperatures for their calibration.

5.3. Discussion and recommendations

This section provides recommendations for applying the proposed models based on the available quantity of manufacturers' catalog data and on field measurements. In Section 3.2, the type of data available was used to divide the heat pumps into three groups for water-to-water heat pumps in heating, four for water-to-air heat pumps in heating and two for cooling (both water-to-water and water-to-air heat pumps).

Tables 12–15 show the average $RMSE_{COP}$ and $RMSE_{Qe/Qr}$ for each group of water-to-water and water-to-air heat pumps operating in heating and cooling. In the tables, when a model is applicable to the catalogs, the average RMSE is highlighted with a color: green if the RMSE is lower than 5 % (the results of the model are good), light orange if its value is between 5 % and 10 % (the results of the model are acceptable), orange when the RMSE is higher than 10 % (the model is not recommended for that set of data). When the model is not applicable to a specific group of catalogs, it is indicated with "N/A".

Therefore, a decision making process for choosing the most suitable model can be outlined as follows, depending on what types of catalog data are provided for the heat pump:

a. If only one data point is available, the only applicable models are the ones derived from the Carnot efficiency calculation (wh08, wc8, ah07 and ac05) or from an experimentally derived curve (wh03). These models, in general, lead to higher $RMSE_{COP}$ but more than acceptable $RMSE_{Qe/Qr}$.

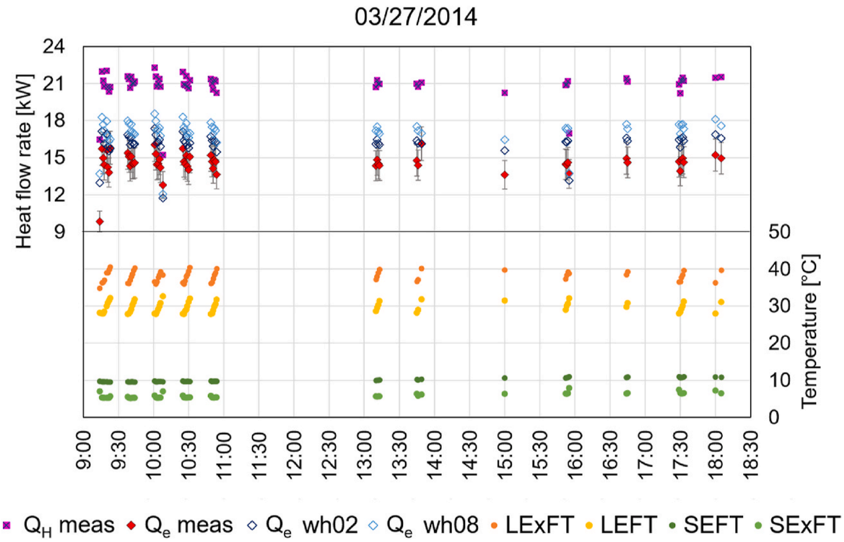


Fig. 9. Experimental data and model results for a representative day in March 2014. Measured heat extraction from the ground and relative error, modeled heat extraction using wh02 and wh08, measured heating capacity, and measured load and source-side entering and exiting fluid temperatures.

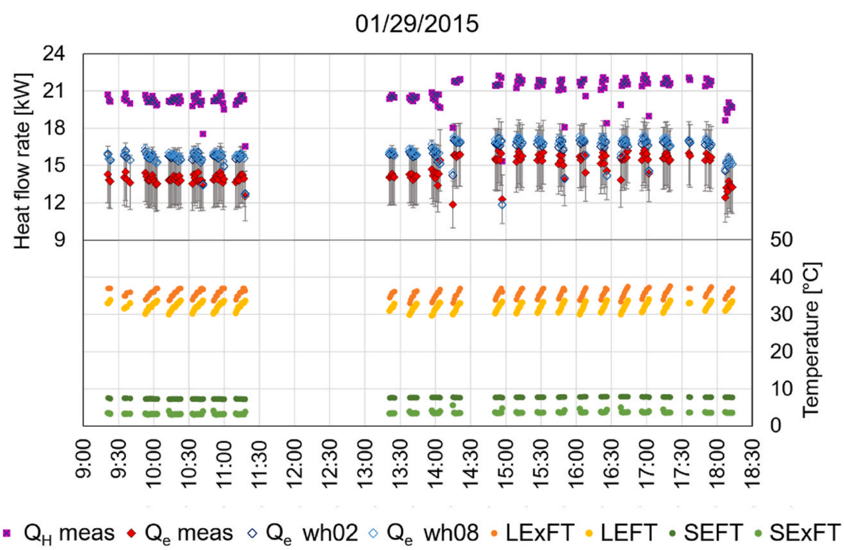


Fig. 10. Experimental data and model results for a representative day in January 2015. Measured heat extraction from the ground and relative error, modeled heat extraction using wh02 and wh08, measured heating capacity, and measured load and source-side entering and exiting fluid temperatures.

b. If only rating conditions (three or four operating points) are available, models wh10, wh11, wc09, ah12, and ac07 can be used. However, models wh08, wc8, ah07 and ac05 can also be a good option.
c. If more than four operating points are available in the catalog data, the corresponding group from Tables 1–4 can be identified by comparing the data available for the type of heat pump and operation mode to the data available for each group in Tables 1–4 With the group identified, Tables 12–15 can be used to identify the best choices – that is, the model or models with the lowest $RMSE_{Qe/Qr}$. A secondary consideration may be the model performance in predicting COP, also summarized in Tables 12–15 Taking first the model performance in predicting Q_e/Q_r, and, secondarily, the model performance in predicting COP, a final recommendation is made for each group in Tables 12–15 An “x” is used to identify the recommended model or models.

The proposed methodology has been applied to the field measurements, and the results showed a good agreement between the real and simulated results concerning the heat extraction from the ground due to the use of a water-to-water heat pump operating in heating mode. All the proposed models have been tested using the experimental data, considering the manufacturer’s data availability. As demonstrated through the validation using catalog data, models wh04, wh05, wh06, and wh07 give an acceptable $RMSE_{Qe}$. In addition, it was found that models wh02 and wh09 can be employed with reasonable confidence, while models wh03 and wh08 are not suggested if more than four operating points are defined in the catalog. The heat pump heating load and the temperature lift between the source and load fluids are the most significant variables in calculating the heat extraction from the ground. The discrepancy in actual temperature lift vs. catalog temperature lift had an adverse impact on the models’ ability to predict the field-measured heat extraction. This aspect might lead to significant errors in the heat extraction calculation if catalogs for the models’ calibration contain only a limited operating conditions range.

The results of the models are strongly affected by the accuracy and the level of detail of the manufacturer’s catalog data: if the accuracy is high, the agreement between the models’ results and field

Table 12
Water-to-water heat pump in heating mode. Average RMSE by group of data and model and final recommendations.

	WtoW_H	wh01	wh02	wh03	wh04	wh05	wh06	wh07	wh08	wh09	wh10	wh11
$RMSE_{COPh}$	Group 1	3%	4%	19%	4%	4%	6%	6%	24%	5%	N/A	12%
	Group 2	N/A	3%	4%	N/A	1%	N/A	2%	6%	2%	5%	N/A
	Group 3	2%*	5%	32%	2%	2%	2%	2%	12%	3%	N/A	N/A
$RMSE_{Qe}$	Group 1	3%	3%	6%	3%	3%	4%	4%	5%	3%	N/A	4%
	Group 2	N/A	1%	1%	N/A	0%	N/A	1%	3%	1%	2%	N/A
	Group 3	2%	3%	10%	2%	2%	2%	2%	4%	2%	N/A	N/A
Recomm.	Group 1	x										
	Group 2					x		x		x		
	Group 3	x			x	x	x	x				

* model wh01 is considered not applicable to catalog WSEH4f, where only four operating points are provided.

Table 13
Water-to-water heat pump in cooling mode. Average RMSE by group of data and model and final recommendations.

	WtoW_C	wc01	wc02	wc03	wc04	wc05	wc06	wc07	wc08	wc09
$RMSE_{COPc}$	Group 1	4%	6%	5%	5%	4%	8%	7%	20%	30%
	Group 2	1%	2%	1%	1%	1%	3%	3%	11%	N/A
$RMSE_{Qr}$	Group 1	1%	1%	1%	1%	1%	2%	2%	4%	6%
	Group 2	1%	1%	1%	1%	1%	1%	1%	2%	N/A
Recomm.	Group 1	x				x				
	Group 2	x		x	x	x				

Table 14
Water-to-air heat pump in heating mode. Average RMSE by group of data and model and final recommendations.

	WtoA_H	ah01	ah02	ah03	ah04	ah05	ah06	ah07	ah08	ah09	ah10	ah11	ah12
$RMSE_{COPh}$	Group 1	N/A	N/A	3%	N/A	N/A	3%	14%	2%	5%	3%	2%	22%
	Group 2	1%	2%	1%	2%	2%	N/A	14%	N/A	N/A	N/A	9%	N/A
	Group 3	N/A	N/A	3%	N/A	4%	5%	13%	2%	7%	5%	5%	N/A
	Group 4	N/A	1%	2%	2%	N/A	N/A	10%	1%	N/A	N/A	1%	6%
$RMSE_{Qe}$	Group 1	N/A	N/A	1%	N/A	N/A	1%	5%	1%	2%	1%	1%	6%
	Group 2	3%	3%	3%	3%	3%	N/A	4%	N/A	N/A	N/A	4%	N/A
	Group 3	N/A	N/A	2%	N/A	2%	2%	5%	1%	3%	2%	2%	N/A
	Group 4	N/A	0%	1%	1%	N/A	N/A	3%	0%	N/A	N/A	0%	2%
Recomm.	Group 1								x			x	
	Group 2	x		x									
	Group 3			x					x				
	Group 4		x						x			x	

measurements will also be increased. Moreover, the accuracy of the models improves if the catalog contains detailed information about the operation of the heat pump, for example, correction factors for different temperature differences at the load and source sides or for the use of a mixture of water and glycol, or, in general, if it includes a relevant number of operating points.

Although the primary objective of these models is to derive the heat extraction or, in the case of cooling operation, the heat rejection to the

Table 15
Water-to-water heat pump in heating mode. Average RMSE by group of data and model and final recommendations.

	WtoA_C	ac01	ac02	ac03	ac04	ac05	ac06	ac07
$RMSE_{COPc}$	Group 1	N/A	6%	5%	N/A	48%	4%	29%
	Group 2	2%	3%	3%	4%	26%	7%	N/A
$RMSE_{Qr}$	Group 1	N/A	1%	1%	N/A	4%	1%	4%
	Group 2	0%	1%	1%	1%	4%	1%	N/A
Recomm.	Group 1						x	
	Group 2	x	x	x				

ground, they might also be used to compute the COP of the heat pump. As already pointed out, the COP results are more accurate when the catalog data are numerous and precise.

6. Conclusions

This paper addresses a problem encountered when designing ground heat exchangers that are used with ground-source heat pump systems. Engineers designing the system typically only have catalog data for the heat pumps, and the data provided vary with manufacturer and location. This research focuses on simple models that can be used to determine the GSHP heat rejection or heat extraction required to meet building loads.

A review of available manufacturers' catalog data for water-to-water and water-to-air heat pumps in North American and European markets is presented, and catalog data are categorized by type of heat pump, mode of operation, and data availability. After reviewing the existing simplified models of heat pumps from the literature, a range of models are investigated; their accuracy is evaluated by their ability to reproduce the catalog data, as well as comparisons made against field measurements. Models are recommended based on the type of heat pump, mode of operation, and data availability. For all cases, the recommended models give acceptable accuracy in the calculation of the heat extraction, with no more than 3 % RMSE when compared to catalog data. Nevertheless, the model accuracy depends on the range and quantity of catalog data. As shown in the field measurements, the accuracy decreased when the temperature lift deviated from the catalog data, giving monthly RMSE on the order of 10%–13 % for predicted heat extraction. Although the proposed models overestimate the measured heat extraction in the investigated case study, within the uncertainties, the best models (for this case study, models wh02 and wh07) overlap the field measurements.

The recommended models presented in this work are suitable for single-speed heat pumps in quasi-steady operation. Future work will focus on increasing the flexibility of the simplified models to simulate multi-speed and variable-speed heat pumps, heat pump cycling, and heat pumps with integrated back-up heating.

CRediT authorship contribution statement

Sara Bordignon: Conceptualization, Methodology, Software, Data curation, Formal analysis, Investigation, Writing – original draft. **Jeffrey D. Spitler:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Angelo Zarrella:** Methodology, Supervision, Writing – review & editing, Resources.

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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