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Heat4Future: A strategic planning tool for decarbonizing district heating systems ☆

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ABSTRACT

Strategic planning of future heat supply, particularly in the context of district heating systems, is essential for achieving a viable and cost-efficient energy transition. However, existing planning tools for district heating systems often require detailed data, which is frequently unavailable in the early stages of the planning process. In response to this challenge, this paper presents Heat4Future, a new planning tool designed to provide insights into potential decarbonized district heating systems for a given location using minimal input data.

The tool demonstrates the implementation of an innovative methodology for strategic planning of district heating systems. It uses a snapshot simulation model to configure the supply for a particular district heating system, taking into account the annual heat demand and user-specified heat sources. The tool comprises of four modules for calculating the cost-effective generation profile of the system. It is designed to generate detailed hourly profiles over an entire year for key parameters essential to the operation and planning of a DHS using a specified set of renewable energy sources, including heat load, generation, and storage profiles.

- Heat4Future provides an overview of the possibilities for a decarbonized district heating supply in a specific location.
- The simulation tool contains four modules for calculating the system's generation profile: Weather and Environmental Data Module, Thermal Load Module, Buffer Thermal Energy Storage Module, and Strategic Heat Planning Module.
- The tool is licensed under the MIT License and is available as an open-source repository on GitLab.

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Nomenclature

List of abbreviations

DHS	District heating system
TES	Thermal energy storage
TLP Generator	Thermal load profile generator
CHP	Combined heat and power
SOC	State of charge
KPI	Key performance indicator
COP	Coefficient of performance

Parameters and variables

T_{alloc}	Allocated ambient air temperature of the past three days
$\boldsymbol{t_{day\text{-}n}}$	Mean ambient air temperature of day-n
$\boldsymbol{h(\upsilon)}$	Normalized heat consumption profile
υ	Ambient air temperature
υ_0	Reference temperature (return flow temperature of the buildings)
A, B, C, D	Coefficients of the Sigmoid function
m_h, b_h, m_w, b_w	Additional coefficients for SigLinDe function
F_{hour}	Hourly heating profile factor for building
f_{hour}	Hour factor for determining the building heating profile factor
f_{day}	Weekday factor for determining the building heating profile factor
Q_{hour}	Hourly thermal load
Q_{annual}	Annual heat demand of building
$\boldsymbol{RHV}$	Relative hourly load variation
$\boldsymbol{RIV}$	Relative internal load variation
$\boldsymbol{IAHV}$	Interval accumulated heat volume
L_h	Average hourly heat load
L_i	Average heat load in individually chosen interval
L_a	Average annual heat load
Q_t	Hourly heat production profile
E_t	Hourly solar irradiance
Q_{rel}	Relative solar heat production
Q_{total}	Total heat production of solar thermal plant
$\boldsymbol{r}_{el/th}$	Ratio of electrical to thermal costs for heating plant operation
$\epsilon_{\mathbf{hp,t}}$	COP of heat pump
$\epsilon_{\mathbf{carnot},\mathrm{t}}$	Carnot COP
$\boldsymbol{\eta}_{\mathbf{hp}}$	Heat pump conversion efficiency
$\mathrm{T_{hot}}$	System supply temperature
$\mathrm{T_{source,t}}$	Temperature of heat source
$\mathrm{F_{biomass/el}}$	Conversion factor of biomass costs to electrical costs
$\boldsymbol{\eta}_{\mathbf{th}}$	Thermal efficiency
$\boldsymbol{\eta}_{\mathbf{el}}$	Electrical efficiency
$\mathrm{pr_{el,sell/el,con}}$	Price ratio between the selling price of electricity and the buying price of electricity

Background

In the current context of the energy transition, strategic heat planning is becoming more relevant due to climate protection plans in municipalities as well as national laws on CO_2 reduction. The introduction of strategic heat planning into the municipal planning process creates a need for supporting tools, especially in the context of district heating planning.

The majority of existing district heating system (DHS) planning tools require detailed input parameters, such as prices and asset information, to determine the most cost-effective generation mix. However, this approach is often impractical in the early stages of the planning process, when the goal is to outline the general long-term development of heat generation in a DHS. At this stage, decision-makers need support tools that allow for an initial estimation of the future heat generation mix, even without detailed information about future plants.

Therefore, the objective of the proposed planning tool, Heat4Future, is to provide an overview of the possibilities for a decarbonized district heating supply in a specific location while requiring minimal data input from the user. The tool can be employed at an early stage in the planning process to explore potential options for renewable heat supply. It generates an hourly heat load and generation profile for a one-year period based on publicly available data for heat sources and/or input data from the user (if available). While

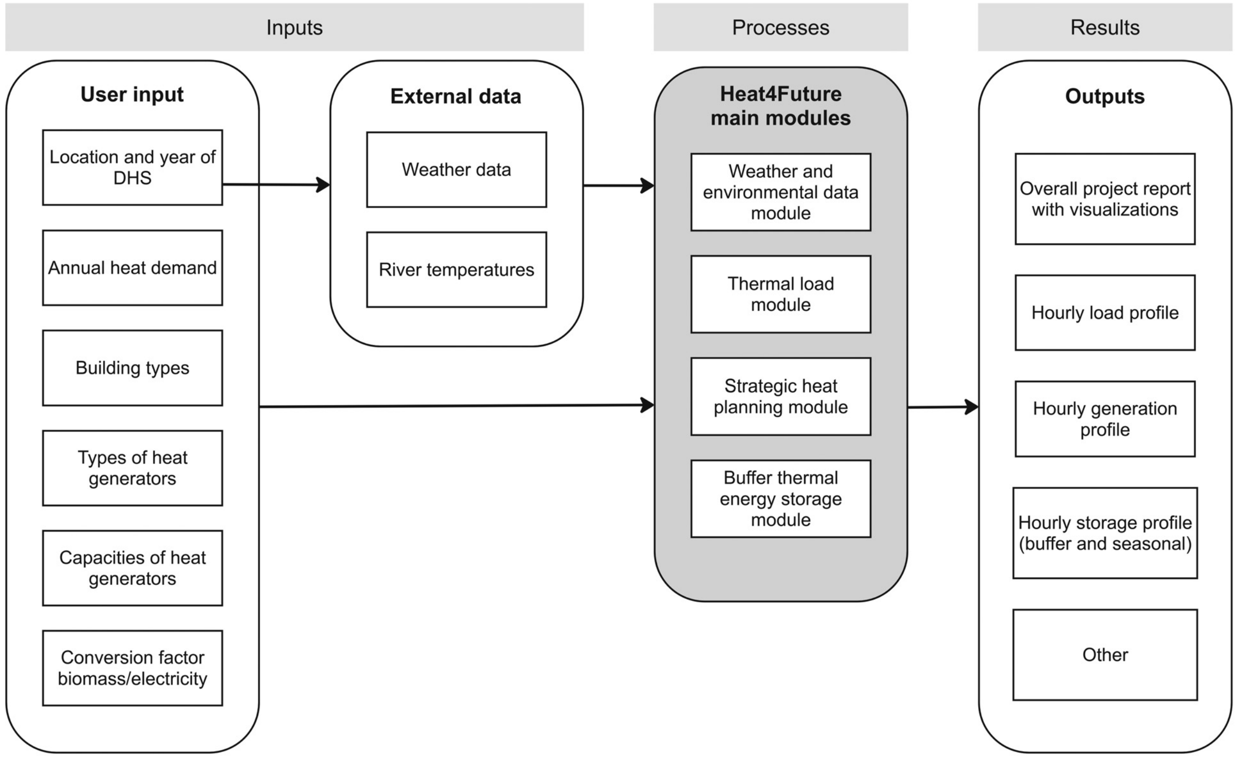

Fig. 1. General framework of the tool.

it does not perform a detailed optimization considering the network layout, it relies on a heat merit order based on a cost ratio. This ranking method evaluates heating plants according to their efficiency and other variable cost factors, allowing for an initial estimation of the future heat supply without needing specific input data, particularly concerning plant design and detailed cost parameters.

Method details

The Heat4future tool is designed to generate detailed hourly profiles over an entire year for key parameters essential to the operation and planning of a DHS using a specified set of renewable energy sources, including heat load, generation, and storage profiles. The tool uses a snapshot simulation approach that evaluates a specific energy system configuration over a given period of time. Unlike optimization models, which require extensive input data on highly uncertain parameters (e.g., future energy market developments), simulation models such as Heat4Future are straightforward and capable of producing robust results [1]. Moreover, simulation models are more suitable for non-specialists, and these models are user-friendly, which makes them particularly suitable for energy planners and policymakers, who are a primary audience for the Heat4Future tool [1].

In this tool, a planning horizon of one year with an hourly granularity is adopted, which is a common practice in energy system planning models [1,2,3]. The heat generation profile is calculated using a heuristic method that establishes the heat merit order according to their cost profiles, enabling the creation of a cost-efficient scheduling plan. The proposed tool is computationally efficient, allowing for rapid calculations without needing high-performance computing resources, making it suitable for the initial rough planning of a district heating system. Due to its fast computation time and the high-level representation of the results in the form of various diagrams and an automatically generated report, the user can quickly make iterative changes to the input parameters of the system components to achieve the preferred results and plan the desired DHS in a very short period. The necessary inputs from the user are kept to a minimum to allow for a broader application of the tool (see Fig. 1).

The tool requires the location of the respective DHS as well as the year to be considered. On the demand side, the tool needs values for the annual heat demand and the types of buildings in the DHS. On the generation side, the user must specify which types of generators should be considered and provide a maximum available capacity for each generator type.

In order to prioritize the generators whose variable costs are mainly based on their primary energy source (either electricity or biomass fuel), a cost ratio is introduced. This cost ratio enables a simple economic ranking of the generators without the need for detailed and often highly uncertain forecasts for electricity and fuel prices. With this cost ratio, the user can also run multiple scenarios to evaluate the effect of different price ratios between electricity and biomass fuel. A more detailed description of the ranking process for the generators is provided in Section Strategic heat planning module.

The tool contains four modules for calculating the system's generation profile, as presented in Fig. 1. A detailed description of each module can be found in the following sections:

- **Weather and environmental data module:** This module collects and preprocesses external data from various sources to provide the users with the minimum set of data required for determining heat demand and generation potential. If available, users can also employ their own customized time series instead of running this module.
- **Thermal load module:** Generates an hourly load profile based on the user's input parameters, such as annual heat demand and building type structure of the respective DHS or area.
- **Buffer thermal energy storage module:** Estimates the recommended buffer thermal energy storage (TES) capacity based on the DHS load profile.
- **Strategic heat planning module:** This is the core of the Heat4Future tool. It calculates an hourly generation profile by considering the outputs from other modules or customized time series, different technical and economic constraints, as well as user specifications regarding available generator alternatives. It also provides a sizing estimation for the required seasonal thermal energy storage.

To run the tool, the user is prompted to select the preferred technologies from the existing models and assign them the desired capacity. The tool categorizes heating plants into two distinct types: Must-run heating plants (e.g., geothermal plants) and variable heating plants (e.g., heat pumps). Must-run heating plants have the lowest marginal costs and are assumed to operate continuously to supply the base load. Variable heating plants consume either fuel or electricity to produce the heat, covering medium and peak loads, and can be turned off by the grid operator. For the variable plants, the tool determines a cost-effective scheduling plan based on the cost ratio of biomass to electricity costs (for details, see Section Strategic heat planning module).

In addition to heat production technologies, the tool also includes models for buffer and seasonal thermal energy storage units. The buffer TES is integrated into the heating system to ensure a smoother operation of variable plants on a daily basis. On the other hand, the seasonal TES compensates for the seasonal mismatch between heat production and consumption. The operation of both storage technologies is fully integrated into the cost-effective scheduling of the heating plants.

It is important to note that the Heat4Future tool provides an initial estimation of the future heat generation mix. To achieve this, certain simplifications are adopted:

- Must-run heating plants are assumed to operate continuously at their maximum capacity. Their hourly heat energy production profiles consist of constant values equal to the maximum capacity defined by the user.
- The models for variable heating plants are based on a black-box principle, considering only input and output parameters without a detailed representation of the internal operation processes. It is assumed that efficiency remains constant during both full and partial-load plant operation.
- There is a global minimum run time for all types of variable heating plants.
- The tool provides a heat supply hierarchy for different heating plants and predefined operation rules for buffer TES, as described in Section of Strategic heat planning module.
- Heat losses of storage and buildings are roughly estimated as fixed annual shares.

Technical details of the tool

The tool is licensed under the MIT License and is available as an open-source repository on Gitlab [4]. It can be installed by cloning the repository to any development environment, such as *PyCharm* [5]. The tool has been developed and tested for compatibility with *Python 3.10* and above, so *Python* must be preinstalled on the user's machine. All dependencies are listed in *Pipfile* [6] and can be automatically installed using the Python virtual environment management tool called *pipenv* [7]. Currently, the tool does not offer a user interface. Instead, specially programmed *Python Scripts* serve as the input mask and the program's "run button". A more detailed description of how to use the tool, along with a step-by-step instruction for getting started, can be found in the README file.

The aforementioned modules can be considered as stand-alone tools and can be run independently. However, the output data of one module is sometimes used as input for another module. Therefore, it is important to ensure the proper integration between modules, especially when using custom data. To facilitate this, naming conventions for the output files of the modules can also be found in the README file.

The required input parameters for each module are defined within the *Parameters* dataclass inside the main script of each module directory. The tool provides a high-level representation of results through various graphs and charts and automatically generates a KPI report. The captions of the graphs and charts support multiple languages. To accommodate different physical units, the package called *qnit,* developed by HAW Hamburg [8] is integrated.

Weather and environmental data module

The weather and environmental data module includes an API that connects to two external data sources [9] and [10], facilitating an automatic data acquisition to provide the necessary minimal data set for the calculation of the heat plan.

Hourly data on ambient air temperature, direct irradiance, and diffuse irradiance are retrieved from [9]. This source employs NASA's MERRA-2 reanalysis and CM-SAF's SARAH datasets to provide simulated meteorological information on an hourly basis for a specified year. Within the framework of the Heat4Future Tool, NASA's MERRA-2 dataset is used due to its global coverage. Simulated

Table 1
Available building use types based on [15].

Abbreviation	Description
SFH	Single-family house, if annual heat demand < 50 MWh
SFH_old	Single-family house 1969–1978
SFH_new	Single-family house after 2002
MFH	Multi-family house, if annual heat demand > 50 MWh
MFH_old	Multi-family house 1969–1978
MFH_new	Multi-family house after 2002
WnR	Wholesale and retail
GnR	Guesthouses and restaurants
AIO	Local authorities, insurance, organizations and public facilities, other
MnA	Metal construction and automotive workshop
OOS	Other operational services
ACM	Accommodation
BK	Bakery
LND	Laundry
HRT	Horticulture
PnP	Paper and printing
HLC	Household-like commercial enterprises
CTS	Summed profile commercial/trade/service

monthly river temperature data is obtained from [10]. This source stores open-source data of water temperature estimates worldwide, generated using the Dynamical Surface Water Quality model (DynQual) by [11]. The data is available for the period from 1980 to 2019, with a monthly temporal resolution and a 5 arcmin spatial resolution.

In the Heat4Future tool, ambient air temperature is the primary data source for generating hourly heat demand profiles. It is also used, along with irradiance data, to generate an hourly generation profile for solar thermal units. Additionally, river temperature data is employed to create an hourly generation profile of river heat pumps. To initiate the data acquisition process in the Heat4Future tool, the user must input the latitude and longitude of the study site, the desired dataset year, and a personal token for [9]. For user convenience, the module offers an autonomous download feature that saves the data in a predefined directory. Additionally, the tool integrates several free and open-source Python packages that facilitate data acquisition and processing. For example, the *requests* package is used to download Zenodo records and their corresponding files. Given that the simulated river temperatures from the DynQual model are stored in a netCDF format at a spatial resolution of approximately 10 km and considering the potential unavailability of exact data for every coordinate, the *xarray* package is employed to perform a linear interpolation and estimate temperatures for the specified coordinates. It is worth highlighting that for years outside the range of 1980 and 2019, monthly average temperatures for the period of 1980–2019 are calculated, which offer approximate estimations for the project simulations.

It is important to note that MERRA-2 is widely used due to its high temporal resolution (1h), making it suitable for the Heat4Future tool and energy system analysis across various geographical areas. However, some studies have shown that MERRA-2 has limitations and drawbacks, as it may exhibit annual average biases in specific meteorological parameters depending on the region, elevation, and other factors. Water temperature estimates from the Dynamical Surface Water Quality model (DynQual) are used in the Heat4Future tool due to the frequent unavailability of river temperature data, especially in areas with insufficient temporal or spatial resolution, which are needed for energy system modeling. In this context, the DynQual model outputs capture the interactions among hydrological, meteorological, and thermal dynamics, providing water temperature data for modeling river heat pumps. One limitation of this dataset is its spatial resolution of approximately 10 km, which requires the use of interpolation techniques to estimate temperatures at specific coordinates.

Thermal load module

The load module within the Heat4Future framework enables the generation of hourly thermal load profiles for the DHS containing various building types. The calculations for generating the profiles are based on the method developed by Hellwig [12] and further enhanced with additional concepts outlined by the German Research Society for Energy Economics [13]. This approach, called the standard load profile method, is mainly used in the gas industry to forecast gas deliveries for heating purposes. The thermal load module also incorporates the functionalities of the stand-alone Python tool developed by [14] called “Thermal Load Profile Generator” (TLP Generator).

In this module, the aggregated annual heat demand for domestic hot water and space heating and information on building types are used to calculate the hourly thermal load profile. Depending on the daily mean ambient air temperature, the aggregated annual heat demand is distributed over the hours of the year using an empirical regression function. The empirical regression function includes hourly empirical factors, which differ due to different building use types. The available building use types of the load module are listed in Table 1.

The empirical factors were derived from real data of gas delivery companies from different parts of Germany to accurately represent a wider range of building types under different climatic zones. The data on residential buildings were gathered from delivery nodes for co-called household collectives. A total of 20 household collectives were investigated, while one collective includes at

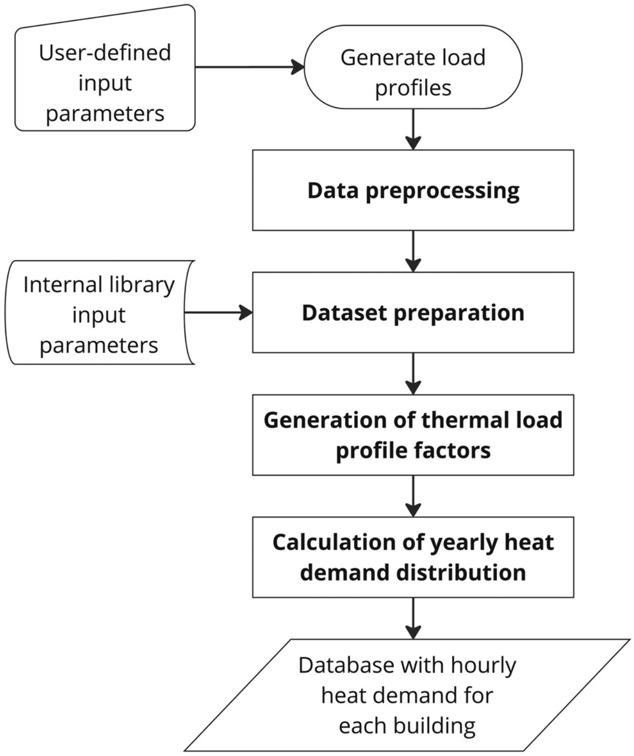

Fig. 2. Flowchart of load module.

least 20 residential buildings. The various types of building use, including commerce, trade, services, and industry, needed to be analyzed separately because of their distinct operating hours and specific operational needs specifications. A total of more than 130 measurement data points were used to develop the regression function [12]. Other factors, such as thermal inertia of the building mass, distribution heat losses, and holidays of the considered site, can be included in the calculations to obtain a more realistic representation of the heat demand distribution over the year. The distribution heat losses considered in this module correspond to the energy losses in the distribution pipeline network, while the absolute heat losses of each building are already factored in the annual heat demand.

The load profile generation process is divided into four sequential operations, as shown in Fig. 2. The first operation is "Data preprocessing", which involves creating and validating a unique list of input building use types defined by the user. The ambient air temperature retrieved using the Weather and Environmental Data module is read during the pre-processing step. The temperature data and the user-defined building use types form the basis of the dataset that will later be used for all calculations. The next three operations, "Dataset preparation", "Generation of thermal load profile factors" and "Calculation of yearly heat demand distribution" are described in more detail in the following subsections.

Dataset preparation

The flowchart in Fig. 3 depicts the "Dataset preparation" process. All subsequent calculations are carried out within the dataset, which is based on the daily mean values of ambient air temperature data. The primary hourly temperature data gathered from the weather and environmental data module is transformed into a dataset with daily resolution. In the case of considering the building mass thermal inertia, the allocated ambient air temperature of the past three days is calculated by Eq. (1) [15] and used instead of daily temperature data.

$$T_{alloc} = \frac{t_{day} + 0.5 \cdot t_{day-1} + 0.25 \cdot t_{day-2} + 0.125 \cdot t_{day-3}}{1 + 0.5 + 0.25 + 0.125} \tag{1}$$

The hourly thermal load is influenced not only by the ambient air temperature but also by the heat consumption behavior of residents and the heat consumption patterns due to work schedules or building use processes. It is, therefore, essential to consider the weekdays and hours of the day and their respective factors. The weekday factors are defined in [12] depending on the building type. The sum of all weekday factors for one week should be equal to 1 to ensure that the total energy balance remains intact. In addition to the daily temperature values, the weekdays are represented as numbers from 0 to 6 corresponding to the weekday inside the dataset. All holidays are defined as Sundays and set to number 6. To represent the hours of the day as numbers from 0 to 23, the

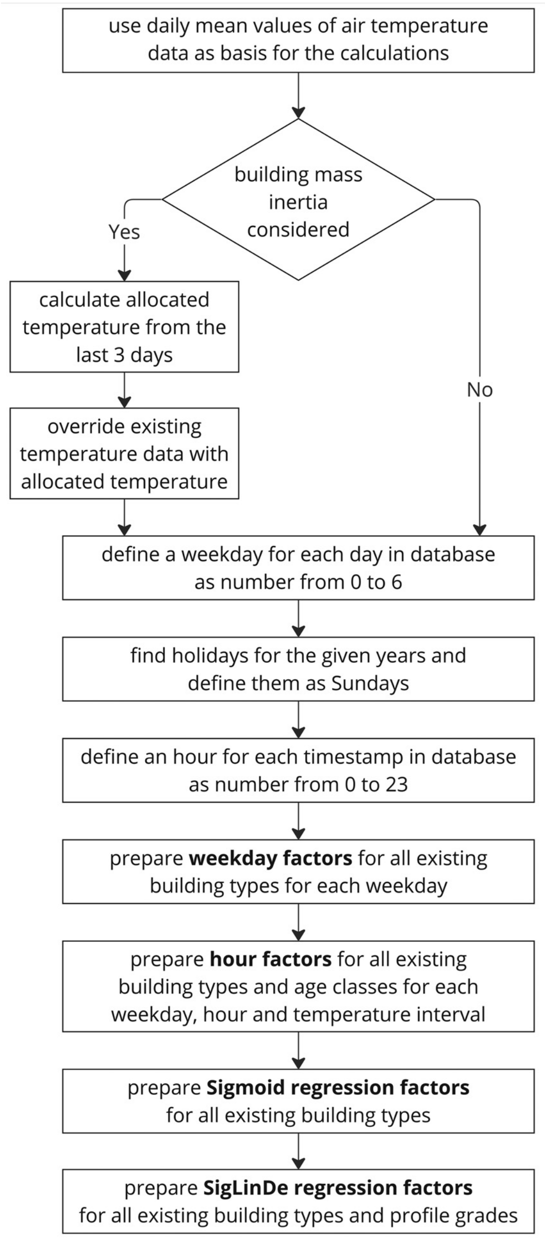

Fig. 3. Flowchart of the dataset preparation process.

dataset is transformed back from daily to hourly resolution. The hourly factors are also defined based on empirical estimates provided in [12] and depend not only on building use type but also on building age class, ambient air temperature and weekday. In addition to the dataset for further calculations, dictionaries of weekday and hourly factors are created, and factors for empirical regression functions are imported from the internal module library.

Thermal load profile factors

The process of generating thermal load profile factors is depicted in Fig. 4. In the Heat4Future tool, it is possible to choose between two possible empirical regression functions (Sigmoid or SigLinDe). The Sigmoid regression function represents the correlation between heat consumption and ambient air temperature while considering building type, as presented in Eq. (2).

$$h(\upsilon) = \frac{A}{1 + \left(\frac{B}{\upsilon - \upsilon_0}\right)^C} + D \quad (2)$$

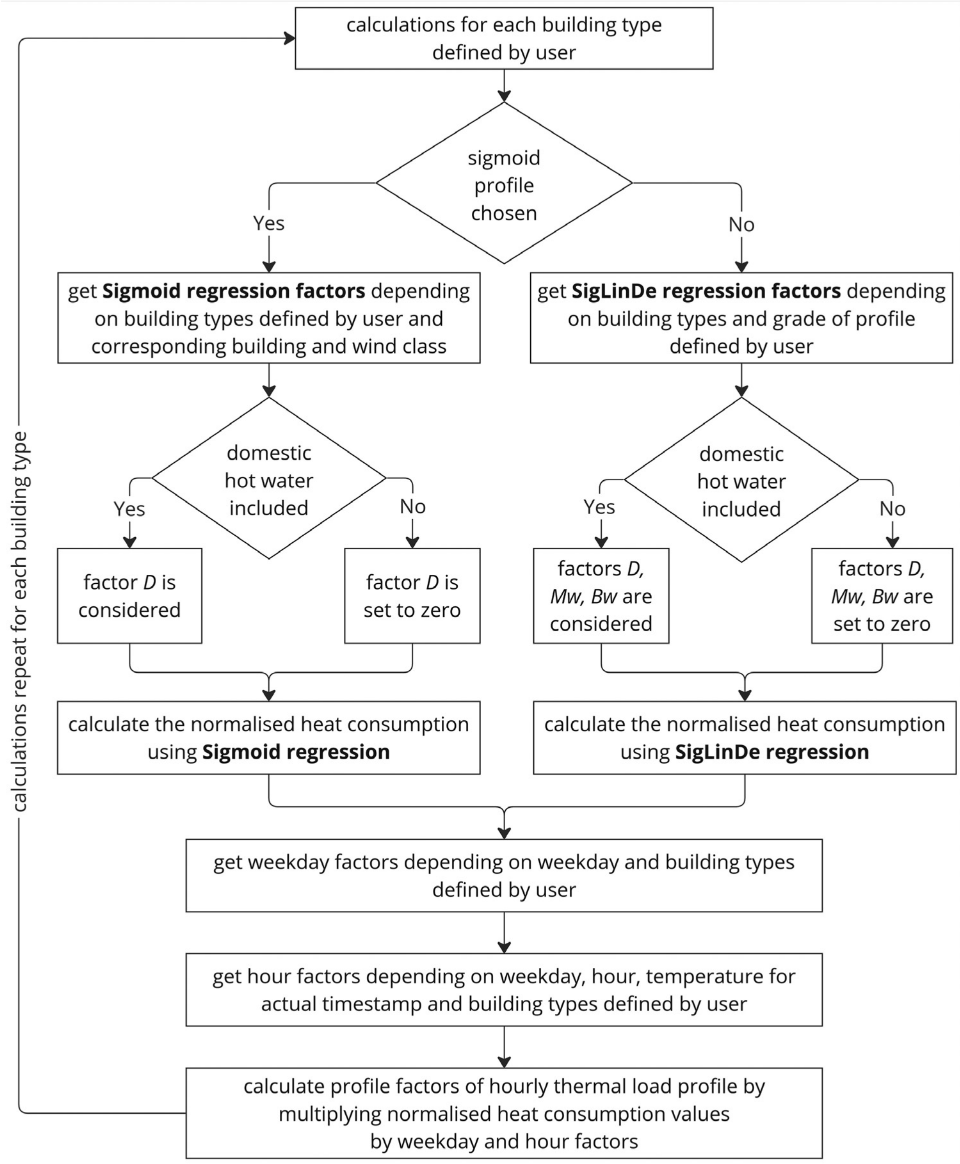

Fig. 4. Flowchart of generation thermal load profile factors process.

The coefficients A, B, C, and D of the Sigmoid function for different building types are based on empirical data provided by [12]. υ is the ambient air temperature and υ_0 is the reference temperature representing the return flow temperature of the buildings.

The SigLinDe regression function is an extension of the Sigmoid function and can be of 3rd or 4th order. It takes into account, in addition to the Sigmoid function, the linear continuation of the function, allowing for a better representation of the heat load during extreme temperatures in winter or during the summertime, when only the base load for domestic hot water supply should be taken into account, as shown in Eq. (3).

$$h(\upsilon) = \left(\frac{A}{1 + \left(\frac{B}{\upsilon - \upsilon_0} \right)^C} + D \right) + \max\left(m_h \cdot \upsilon + b_h, m_w \cdot \upsilon + b_w \right) \tag{3}$$

The SigLinDe function contains additional coefficients m_h, b_h, m_w and b_w. The coefficients m_h and b_h represent the superimposed function of the heating gas supply, while m_w b_w represent the superimposed function of the domestic hot water supply.

In this way, the normalized heat consumption values $h(\upsilon)$ can be calculated for different temperature values throughout the year. It is important to note that in this module, the inclusion of domestic hot water is optional. If domestic hot water is not included in the calculations, the coefficient D of the Sigmoid or D and m_w of the SigLinDe regression functions are set to zero.

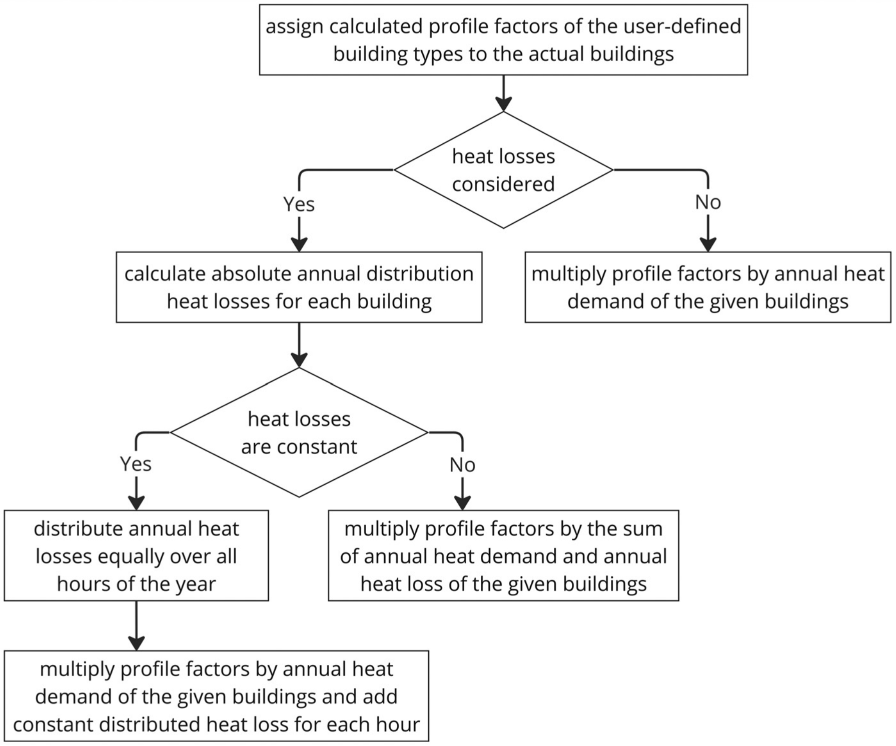

Fig. 5. Flowchart of calculation of yearly heat demand distribution process.

For each building use type defined by the user, the corresponding factors from the dictionaries are assigned, taking into account the temperature, day of the week, and hour. The profile factors for each building use type are calculated for each hour by multiplying the normalized heat consumption by the weekday and hour factors, as defined in Eq. (4). Lastly, the calculated profile factors for each building type are normalized.

$$F_{hour} = h(\upsilon) \cdot f_{hour} \cdot f_{day} \tag{4}$$

Yearly heat demand distribution

The process employed to calculate the yearly heat demand distribution is shown in Fig. 5. The profile factors of the unique building types are assigned to the actual buildings. In order to calculate the hourly thermal load, the annual heat demand of the buildings is multiplied by the profile factors obtained in the previous step, as expressed in Eq. (5).

$$Q_{hour} = Q_{annual} \cdot F_{hour} \tag{5}$$

An additional feature of this module is the ability to provide an estimate of the annual heat grid distribution losses. The user specifies the distribution heat losses as a percentage of the total heat demand. The absolute annual distribution heat losses are calculated by multiplying the user-defined loss percentage with the annual heat demand of each building. The distribution of heat losses over the year may be either constant or variable. In the case of constant heat losses, they are distributed equally throughout the year, resulting in a uniform profile. The constant heat loss of each hour is added to the annual heat demand multiplied by the profile factor. For variable heat losses, the sum of absolute losses and annual heat demand of buildings is multiplied by profile factors, resulting in heat losses that are proportional to the heat demand.

The thermal load hourly profile serves as a starting point and an essential basis for all further calculations, including the sizing of the buffer TES and the creation of a scheduling plan for heat generators, as described in the following sections.

Buffer thermal energy storage module

The objective of the buffer TES module is to provide an initial estimate of the short-term storage capacity required for the stable and cost-efficient operation of the DHS. In the Heat4Future tool, the buffer TES aims to reduce or offset heat load variations within a chosen interval (e.g., 1 hour), allowing for the continuous operation of heating plants and reducing the need for auxiliary/peaking boilers [16]. This type of storage generally has a small volume and high power, especially relative to its size, and is used when

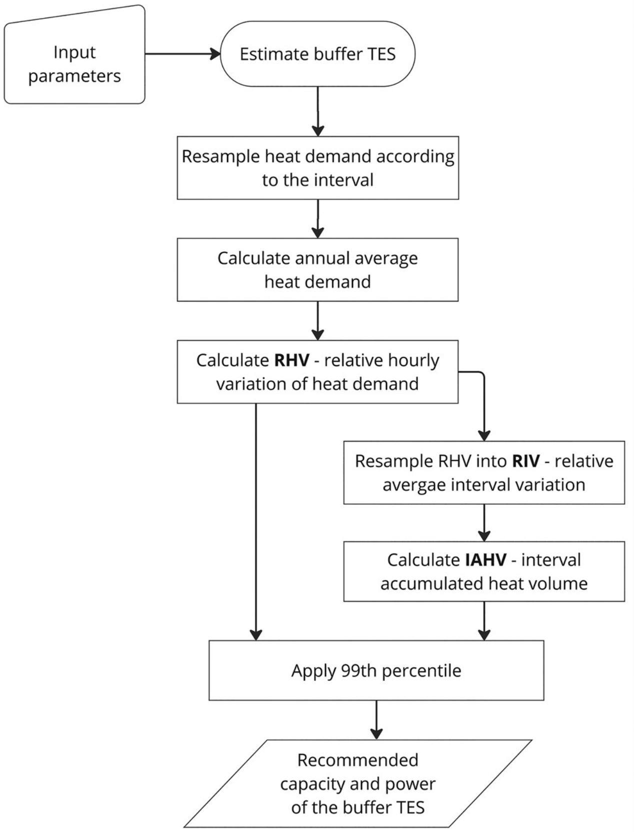

Fig. 6. Flowchart of buffer TES sizing process.

plants have operational restrictions such as minimum run time requirements. The sizing method for the buffer TES is based on the methodology proposed by [16] to reduce peak loads in DHS with CHP-TES systems, as summarized in Fig. 6. However, users also have the option to set the desired capacity of the storage manually.

This module determines the recommended capacity (thermal power) for the buffer TES in the given DHS based on the variation of the heat demand profile within a specified time interval. The module employs the heat load time series to compute three descriptive parameters: relative hourly variation RHV, relative average interval variation RIV, and interval accumulated heat volume $IAHV$. Note that by employing this sizing method to calculate these three parameters, it is possible to estimate the capacity of the TES independently of the heating plants' capacities while relying solely on the heat load time series. The equations describing the parameters for the assessment of the thermal load variation are as follows:

$$RHV = \frac{|L_h - L_i|}{L_a} \cdot 100 \tag{6}$$

$$RIV = \frac{\frac{1}{2}\sum_{h=1}^{i} |L_h - L_i|}{L_a \cdot i} \cdot 100 \tag{7}$$

$$IAHV = \frac{1}{2}\sum_{h=1}^{i} |L_h - L_i| \tag{8}$$

where, L_h, L_i, L_a represent the heat load for three different time intervals (hourly, individually chosen interval average, and annual average). Ideally, buffer TES sizing should be based on the maximum variation value to eliminate fluctuations. However, it is recommended to disregard extreme values (typically 1%), as they are considered outliers, and can result in oversized buffer TES. Therefore, the module only considers the 99th percentile of the relative hourly variation $|L_h - L_i|$ for determining the buffer TES power and the 99th percentile of the accumulated heat volume in one interval $IAHV$ for determining the buffer TES capacity. Considering values less than the 99th percentile may lead to undersizing of the storage, reducing the flexibility of the overall system [17]. Furthermore, the module incorporates a mechanism for integrating the storage into the calculation of the generation profile. If the buffer TES interval is set to more than one hour, the algorithm modifies the setpoint for production plants from the determined hourly heat

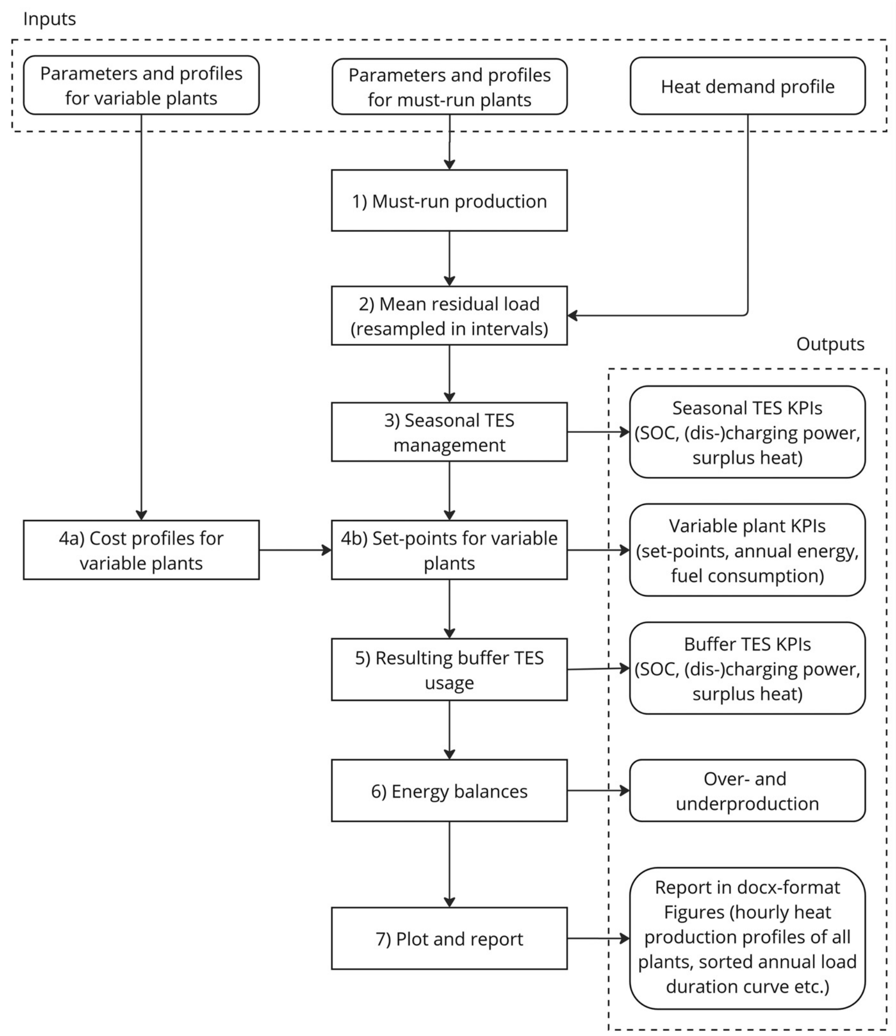

Fig. 7. Overview of the calculation process.

demand to the mean value of the heat demand within this particular interval. This is done to align the intervals of the heat demand and the buffer TES.

Strategic heat planning module

The strategic heat planning module is the central component of the proposed tool. It generates hourly heat production profiles for each heating plant within the DHS, which are presented in various plots and are summarized in a report. This module uses the outputs from the previously described modules and user-defined parameters as inputs and rules for the heat supply hierarchy for the different heating plants, seasonal and buffer thermal energy storages. Fig. 7 shows a flow chart depicting an overview of the inputs, the outputs, and seven internal steps of the calculation.

Inputs

In the first step, the module requires general input data such as the project's name, the location (longitude and latitude) of the respective DHS, and the year considered to retrieve the necessary input data. The input data for weather, load and storage parameters can either be generated with the previously presented modules or read from individual time series.

The module also requires additional input data for the system's technical configuration. The heating plants and their thermal capacities can be freely selected by the user from the heat supply options in the tool. The heating plants are divided into must-run and variable plants. Furthermore, buffer and seasonal TES capacities can also be freely defined by the user. To keep the operation of

Table 2
User-defined input parameters for strategic heat planning module.

Technical parameters	Seasonal TES	Capacity
		Power
		Set point
		Annual loss
	Buffer TES	Capacity
		Power
		Set point
		Annual loss
	Minimum run-time	Interval
	Must-run plants (optional)	Plant types and their parameters
	Variable plants (optional)	Plant types and their parameters
Must-run plants optional parameters	Waste Incineration plant	Max. capacity
	Industrial surplus heat plant	Max. capacity
	Deep geothermal plant	Max. capacity
	Urban waste heat plant	Max. capacity
	Solar thermal plant	Total annual production
		Irradiation profile
Variable plants optional parameters	Heat pump plant	Max. capacity
		Supply temperature
		Source temperature
		Limit source temperature
		Conversion efficiency
	Biomass boiler plant	Max. capacity
		Thermal efficiency
		Conversion factor
		Limit of annual biomass usage
	Biomass combined heat and power plant	Max. capacity
		Thermal efficiency
		Electrical efficiency
		Conversion factor
		Limit of annual biomass usage
		Price ratio between electricity production price and electricity consumption price

the DHS balanced, it is recommended to set the buffer TES parameters according to the results of the Buffer thermal energy storage module. An overview of these parameters is provided in Table 2.

Production from must-run heating plants (1)

The must-run heating plants are assumed to operate continuously. In the first calculation step, the heat production of all must-run plants is summed up for each hour.

The following must-run heating plants are modelled in the tool:

- Waste incineration heating plant
- Urban waste heating plant
- Industrial heating plant
- Deep geothermal heating plant
- Solar thermal heating plant

The hourly heat production profiles of these heating plants are defined by constant values that equal their maximum capacity, as defined by the user, except for the solar thermal heating plants, whose generation profile is calculated based on the solar irradiance. In the event that a solar thermal plant is selected for production, the user is prompted to define the expected annual heat production Q_{total} instead of its maximum capacity.

$$Q_t = E_t \cdot Q_{rel} \tag{9}$$

$$Q_{rel} = \frac{Q_{total}}{\sum_{t=1}^{8760} E_t} \tag{10}$$

The hourly heat production profile for the solar thermal plant is calculated using Eq. (9), which considers the hourly solar irradiance E_t of the respective location and the relative solar heat production Q_{rel}. The relative solar heat production Q_{rel} is defined as the ratio of the total heat production of the solar thermal plant Q_{total} and the total solar irradiation $\sum_{t=1}^{8760} E_t$ over the year, as shown in Eq. (10).

Mean residual load (2)

In the second step, the production of the must-run heating plants is subtracted from the heat demand profile for each hour of the year. This difference, defined as the “residual load” in the Heat4Future tool, can be either positive or negative.

To achieve a more accurate and realistic representation of the DHS, a global minimum run-time for the variable plants is introduced in the form of a parameter called “interval”. To manage this minimum run-time, an internal variable called “production set point” is used alongside the residual load variable. The production set-point is calculated as the inverted mean residual load (resampled according to the interval duration) and provides information on the quantity of thermal energy that must be further produced to cover the total heat load of the interval. The production set-point is defined in Eq. (11).

$$\text{production set point} = \frac{\sum_{i=1}^{\text{interval}} \text{residual load}}{\text{interval}} \tag{11}$$

For any remaining positive residual load, where heat demand exceeds production from the must-run plants in the respective time step, the tool calculates the necessary heat supply from the seasonal TES and variable plants to meet the remaining heat demand. In addition, the module provides an initial estimate for the necessary capacity of the seasonal TES. Any surplus heat from the must-run heating plants that exceeds the heat demand in the respective hour is accumulated. The maximum accumulated value defines the capacity of the seasonal TES.

Charging and discharging the seasonal TES (3)

In the third step – after considering the must-run plants and the iterative adjustment of the production set-point – the module considers the seasonal TES to compensate for the seasonal discrepancy between heat production and consumption. The parameters influencing the charging and discharging processes of seasonal TES are its available capacity and its input and output power.

These parameters, “maximum capacity”, “maximum power”, “TES set-point” and “annual heat loss” of seasonal TES are defined by the user. The parameter “annual heat loss” represents the ratio of heat energy loss over the course of a year to the maximum capacity of the TES. For each step of the calculation, the heat losses are considered in relation to the current state-of-charge (SOC). The “TES set-point” describes the initial SOC of the TES for the first step of the calculation.

The integration of the seasonal TES addresses two cases involving production set-points and storage limiting factors:

1. Charging
   In the event that the production set-point is positive, indicating that the production from the must-run plants exceeds the heat demand within the specified interval, and the seasonal TES has available capacity, the storage is charged with the excess energy up to the maximum input power or the available capacity of the storage.
2. Discharging
   In the event that the production set-point is negative, indicating that the must-run plants are unable to satisfy the heat demand within the specified interval, and there is available energy in the seasonal TES, the storage is discharged in order to cover the remaining heat demand up to the maximum output power or the stored energy amount.

Production from variable heating plants (4)

In the fourth step, the production from variable heating plants is calculated. For the intervals where the residual load combined with the contribution of the seasonal TES is still positive, the unmet heat demand is satisfied by variable heating plants. The contribution of the variable heating plants follows a heat merit order based on their cost profiles. The cost profiles are determined by a cost ratio based on primary energy consumption costs, as these constitute the largest portion of the total variable costs compared to other operation and maintenance costs. The cost ratio allows to rank the variable plants without knowing the exact fuel and electricity prices. The heat generators with the lowest cost-ratio of each time step are selected first, followed by the next least expensive heat generator until the remaining heat demand is satisfied. The variable plants, in contrast to the must-run plants, can operate at partial load depending on the current production set point.

The variable heating plants considered in this module consume either fuel or electricity to produce the heat. They are assumed to cover medium and peak loads and can be shut down by the network operator. The following variable heating plants are available in the tool:

- Heat pump
- Biomass boiler
- Biomass CHP

Cost profiles for variable heating plants (4a)

In order to operate the plants in a cost-effective manner, the plants are ranked by their cost ratio $r_{el/th}$. This ratio is introduced to avoid relying on exact electricity and fuel prices (e.g., €/kWh$_{th}$), which must be forecasted over a horizon of more than 10 years. Instead, the module uses the ratio of electrical costs to thermal costs, as this can often be determined from technical parameters. For example, an electrical boiler with an efficiency of 99 % has a cost ratio of 1.01 kWh_{el}/kWh_{th}, while a heat pump with a COP of 3 has a cost ratio of 0.33 kWh_{el}/kWh_{th}. The key point of this approach is that heat pumps exhibit lower variable costs compared to electrical boilers.

Each variable heating plant type is programmed using a black box approach. For heat pumps, the heat source can be selected between river and wastewater. The cost ratio for each hour of operation for heat pumps is dependent on their COP and is calculated using Eq. (12).

$$r_{el/th} = \frac{1}{\epsilon_{hp,t}} \tag{12}$$

$$\epsilon_{hp,t} = \epsilon_{carnot,t} \cdot \eta_{hp} \tag{13}$$

$$\epsilon_{carnot,t} = \frac{T_{hot}}{T_{hot} - T_{source,t}} \tag{14}$$

The COP is calculated by multiplying the heat pump conversion efficiency η_{hp} by the Carnot COP $\epsilon_{carnot,t}$, as defined in Eq. (13). The Carnot COP depends on the system's supply temperature T_{hot}, assumed to be constant throughout the year, and the temperature of the heat source $T_{source,t}$, which can be either constant for wastewater or vary over the year for river water Eq. (14).

The ranking of variable plants using the introduced cost ratio is based on their thermal output per invested kWh_{el}. An additional conversion factor is introduced to evaluate heating plants that are not powered using electricity. The conversion factor $f_{biomass/el}$ represents the ratio between the prices of biomass and electricity as defined by the user. If necessary, the cost ratios for other fossil fuels can also be introduced by the user. This factor allows the user to evaluate different scenarios regarding the price development of biomass and electricity. For example, a conversion factor of 0.5 indicates that the price for 1 kWh of electricity is twice as expensive as 1 kWh biomass. Using this factor, the value of the necessary energy input from biomass can be converted into its equivalent value in electrical energy. This way, all biomass-fueled heating plants can be compared to electricity-based heating plants in terms of their variable cost ranking. The calculation of cost ratio for biomass boilers depends on the conversion factor $f_{biomass/el}$ and the thermal efficiency of the boiler η_{th}, as shown in Eq. (15).

$$r_{el/th} = \frac{f_{biomass/el}}{\eta_{th}} \tag{15}$$

Similarly, the cost ratio for CHP plants is calculated using the same conversion factor $f_{biomass/el}$ and thermal efficiency η_{th}. Since CHP plants produce both electricity and heat, it is assumed that the revenues from electricity generation reduce the variable costs of heat production. These revenues are determined by the electrical efficiency η_{el} of the CHP plants and a price ratio between the selling price of electricity and the buying price of electricity $pr_{el.sell/el.con}$. This price ratio must be defined by the user and indicates the expected (assumed) ratio between the price that can be achieved from selling electricity and the price that has to be paid to buy electricity. For example, a price ratio of 0.5 would indicate that the selling price per kWh of electricity is assumed to be half the price that has to be paid per kWh electricity. The calculation of the cost-ratio for CHP plants is represented in Eq. (16).

$$r_{el/th} = \frac{f_{biomass/el} - \eta_{el} \cdot pr_{el.sell/el.con}}{\eta_{th}} \tag{16}$$

Set-points for variable heating plants (4b)

The maximum hourly heat production for the variable plants is determined by the maximum capacity of each heating plant. In addition, the production of the river heat pump is restricted to periods when the river temperature is above a specified minimum value to prevent freezing.

The variable heating plants run continuously during the user-defined interval, taking into account their minimum run times. Since the hourly heat demand can fluctuate within the interval, it is necessary to integrate a buffer TES to compensate for the differences between the operating set-points of the plants and the heat demand, therefore ensuring the operational reliability of the DHS.

In the event of hourly underproduction, the remaining heat demand is met by thermal energy from the buffer TES, and in the case of hourly overproduction, the buffer TES captures the surplus thermal energy. The module accounts for the technical limitations of buffer TES, including its input and output power, as well as its free capacity or the amount of stored energy in each hour. To ensure stable operation and prevent the occurrence of extreme states of charge (either completely full or empty), the SOC of the storage is maintained at a designated level, typically set at 50%.

Charging and discharging the buffer TES (5)

Once the hourly production set point is satisfied, it is also necessary to ensure that the system's energy balance is maintained. The TES plays a crucial role in meeting the demand by supplying heat up to its maximum input or output power, free or available capacity, and residual load, depending on the system's operational circumstances. The parameters "maximum capacity", "maximum power", "storage set point", as well as "annual heat loss" of buffer TES, are defined by the user. To ensure a well-balanced DHS,

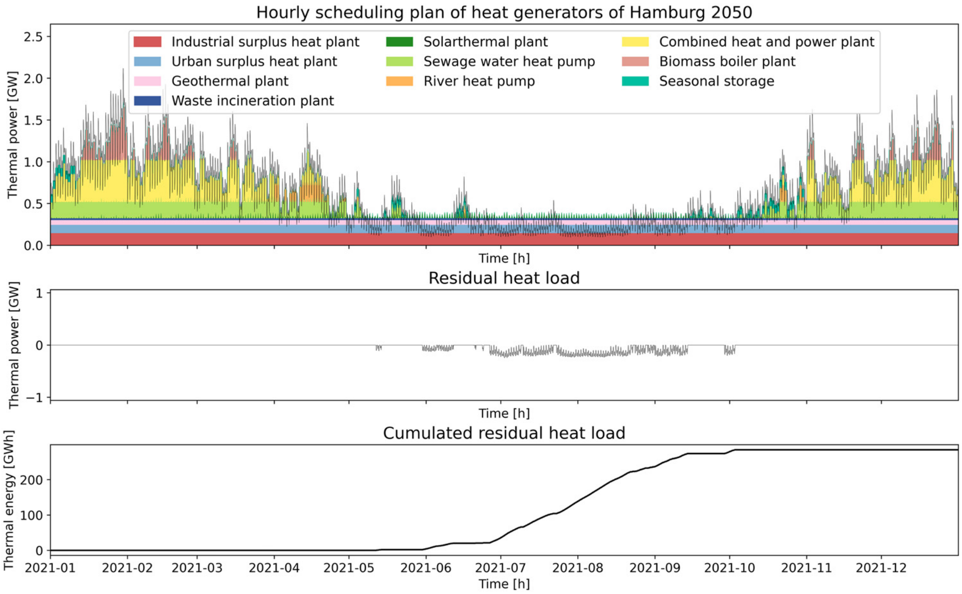

Fig. 8. Exemplary plot of hourly scheduling plan and residual load in Heat4Future tool.

it is recommended that the buffer TES parameters be set to the results from the buffer TES module. For each calculation step, the heat losses are considered in relation to the current SOC. The storage set point indicates the initial SOC for the first calculation step. Similar to the seasonal TES, two operational cases are implemented for the buffer TES:

1. Charging
   If the residual load is positive, indicating a surplus of thermal energy, and the buffer TES has an available capacity, the storage is charged with the surplus energy up to its maximum input power or available capacity.
2. Discharging
   If the residual load is negative, indicating that the heat demand is not fully met, and there is heat energy available in the buffer TES, the storage is discharged to satisfy the demand, up to its maximum output power or the amount of energy stored.

Energy balances (6)

If the available must-run and variable plants, along with the seasonal TES, cannot meet the heat demand in the given time step, the remaining residual load is printed out as a graph. The user can use this information to manually adjust the design and sizing of the selected heat generators to better meet the heat demand.

Reporting (7)

The tool provides a series of graphs, including those of the hourly schedules for the heating plans, the residual load, the charging and discharging processes for both storages, and a pie chart illustrating the overall production of the heating plants. Additionally, it includes a representation of the annual sorted load duration curve for one selected year. Moreover, a key performance indicator (KPI) report is automatically generated, providing an overview of the outgoing situation with user-defined input parameters, output results, and diagrams. For the biomass-fueled heating plants, the module also calculates the overall biomass usage, enabling the user to plan the DHS in compliance with annual biomass resource limitations. Figs. 8-11 illustrate a collection of plots from the report.

Method validation

The proposed tool is based on the strategic heat planning approach developed by [18]. To assess and validate the Heat4Future tool, the case study results for Hamburg 2050 from [18] were utilized. To ensure comparability, the same input parameters for heat demand time series and thermal power for heat generators, as used in [18], were applied to the Heat4Future tool. The values used for validation are shown in Table 3.

The limiting factor for must-run heating plants is their annual thermal energy potential. As a result, the thermal power values for these plants are derived from the total heat energy in [18]. The same thermal power values for thermal generation reported in [18] are applied in the validation simulation. The resulting hourly scheduling plan of heat generators for Hamburg 2050 from [18] is presented in Fig. 12, and the corresponding results generated by the Heat4Future tool are depicted in Fig. 13.

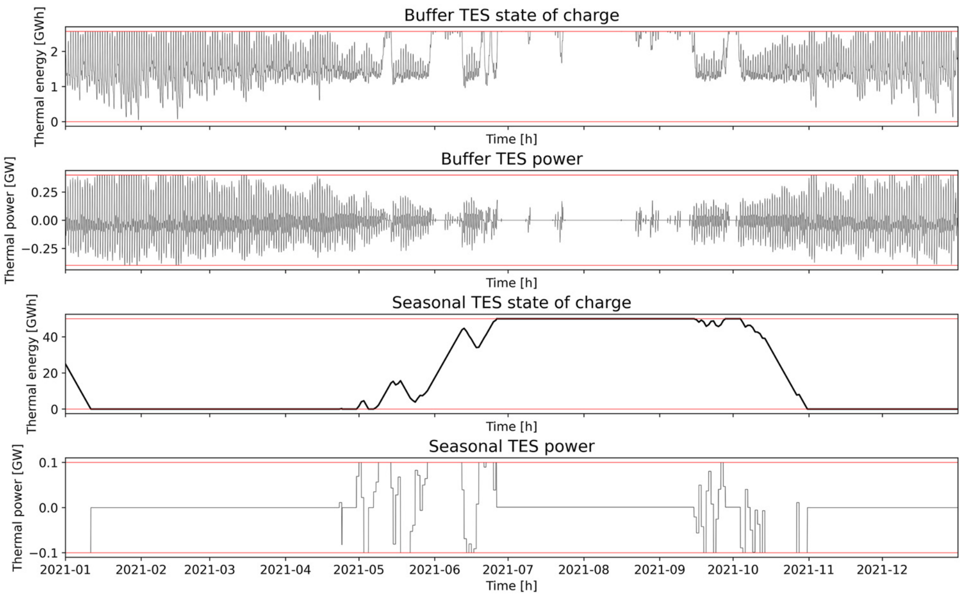

Fig. 9. Exemplary plot for thermal energy storage in Heat4Future.

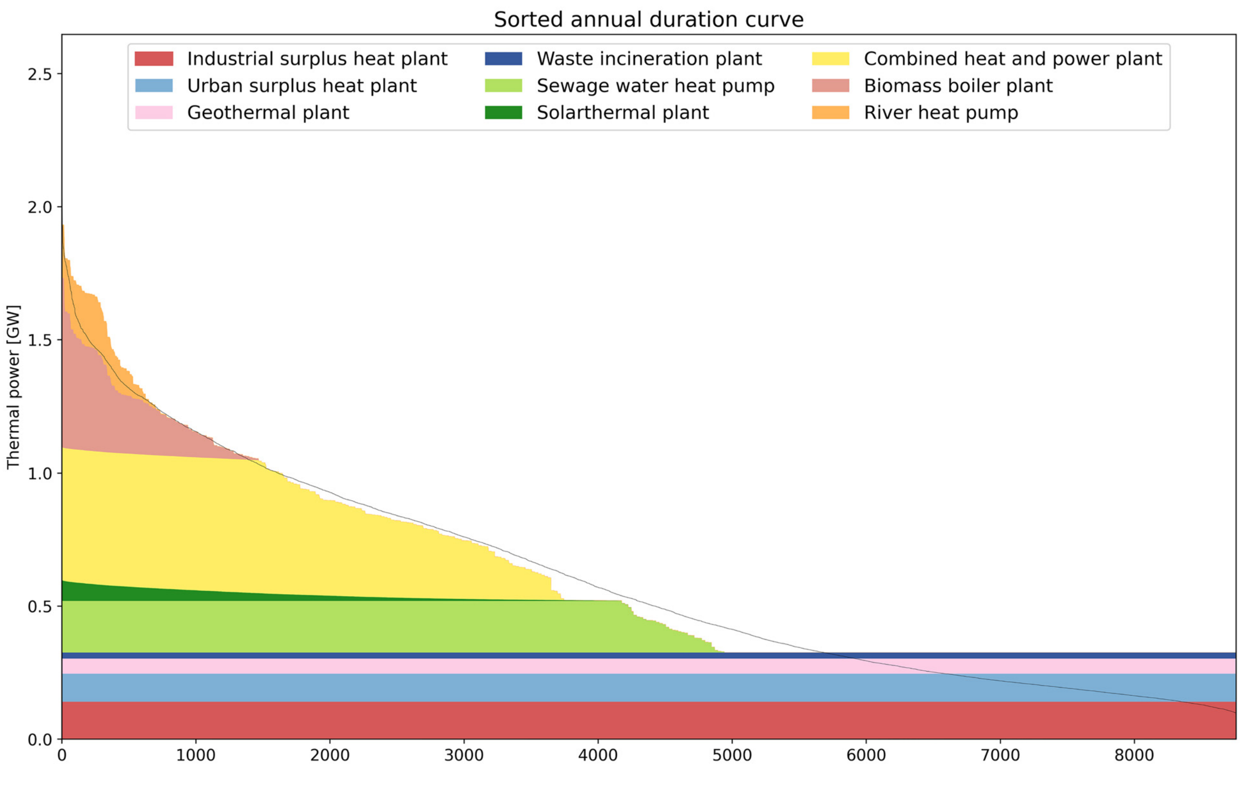

Fig. 10. Exemplary plot of sorted annual duration curve in the Heat4Future tool.

To facilitate a more accurate comparison of the resulting heat generation plans, Fig. 14 outlines the total heat production from all heating plants using both methods.

Due to the similar implementation of the must-run heating plants in both the original method and the Heat4Future tool, their total heat production remains consistent across both methods. However, for the variable heating plants, the Heat4Future tool yields different results compared to the original method. These differences can be attributed to the enhancements made to the original method that were incorporated into the Heat4Future tool. In the Heat4Future tool, the order of the variable heating plants is determined by

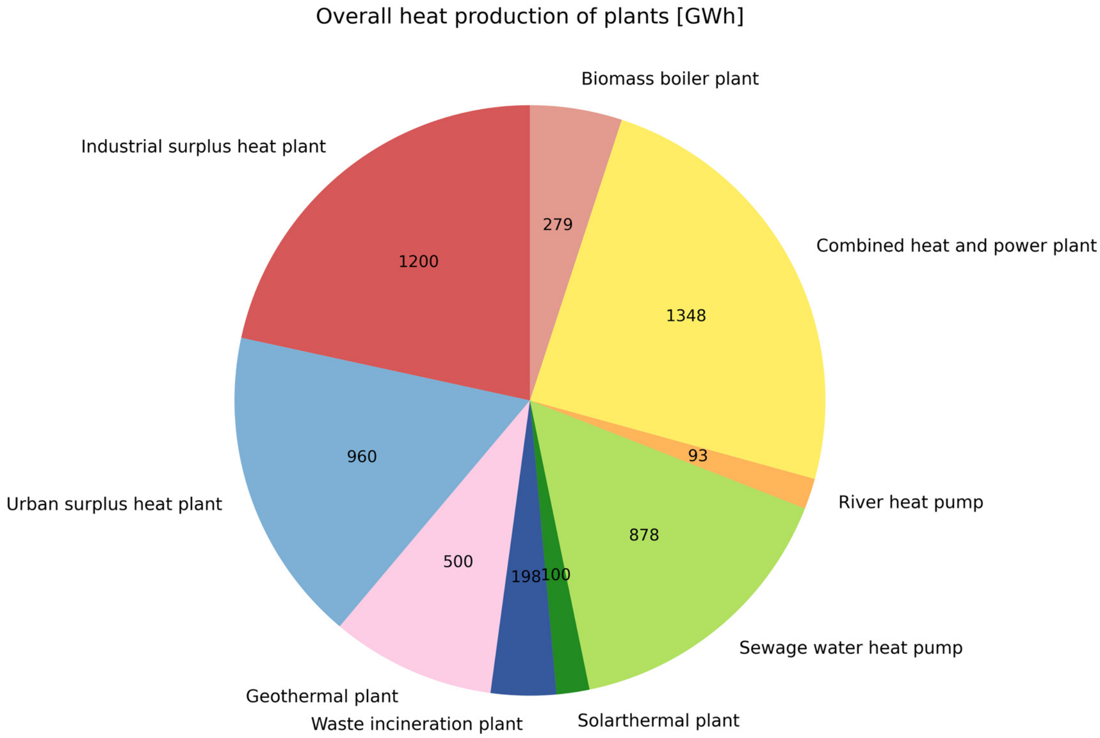

Fig. 11. Exemplary pie chart of energy production in the Heat4Future tool.

Table 3
Method validation assumptions.

Heating plant	Thermal energy in GWh	Thermal power in GW
Industrial surplus heat plant	1200	137
Urban surplus heat plant	1000	109.6
Geothermal plant	500	57
Waste incineration plant	198.5	22.7
Solar thermal plant	100	Depends on the radiation profile
Sewage water heat pump	1700	194
River heat pump	1281.6	200
Combined heat and power plant	2500	500

their cost profiles, with calculated cost-ratios as explained in Section Strategic heat planning module. In contrast, the original method utilizes a predefined fixed order based on the efficiency of the primary energy use of the generators [18].

Regarding the calculation of the river heat pump operation, the original method neglected the temperature losses and the terminal temperature difference in the heat exchangers. These technical restrictions were addressed in the enhanced heat pump model in the Heat4Future tool. The calculations using the improved models result in fewer days when the river heat pump can operate due to stricter restrictions on the source temperature.

It is also important to note that the input data for the river temperature in the Heat4Future tool differs from that used in the original study, as a more comprehensive database was employed. The mean temperatures estimated by the DynQual model are lower than those in the datasets used in the original paper, resulting in a greater number of days when the river heat pump cannot operate due to low source temperatures. It is, however, worth highlighting that the heat production from the sewage heat pump is comparable for both methods, given that a constant source temperature is employed for both calculations.

Further improvements have been made with regard to the quantitative consideration of peak load coverage and the introduction of biomass boilers, both of which were neglected in the original approach. Incorporating supplementary biomass generation to accommodate peak loads has resulted in a significant increase in heat generation from biomass in the Heat4Future tool. Moreover, the Heat4Future tool incorporates the implementation of both buffer and seasonal TES operations, whereas the peak load coverage and storage were addressed in [18] only theoretically. Furthermore, the Heat4Future tool enables the determination of the optimal capacity of buffer TES, which also enhances the operational planning.

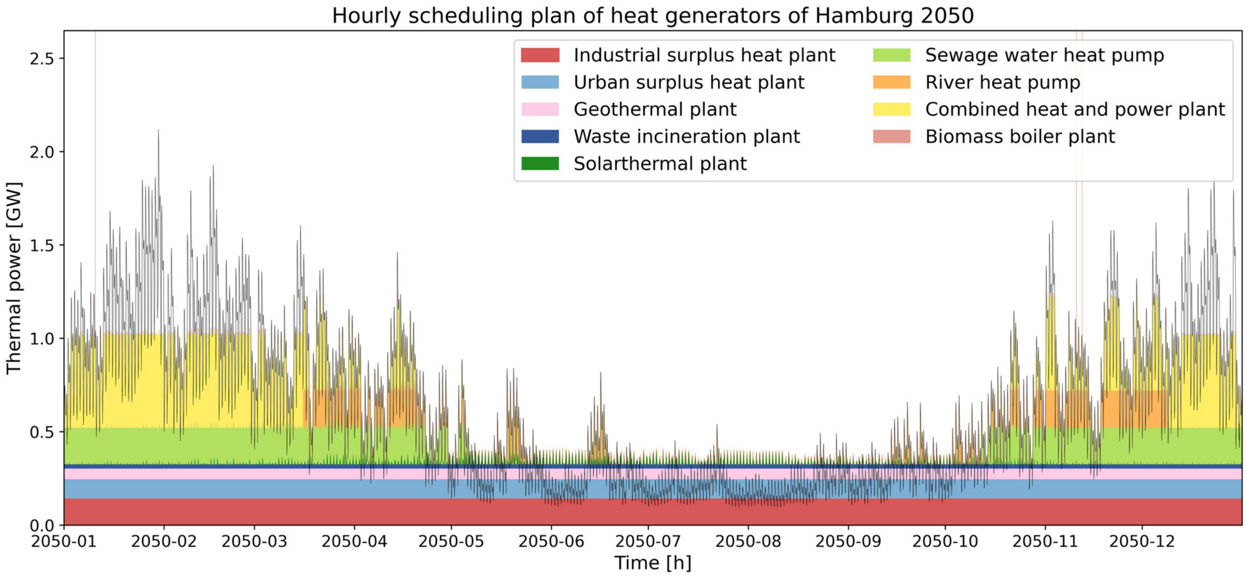

Fig. 12. Hourly scheduling plan from case study Hamburg 2050 as published in [18].

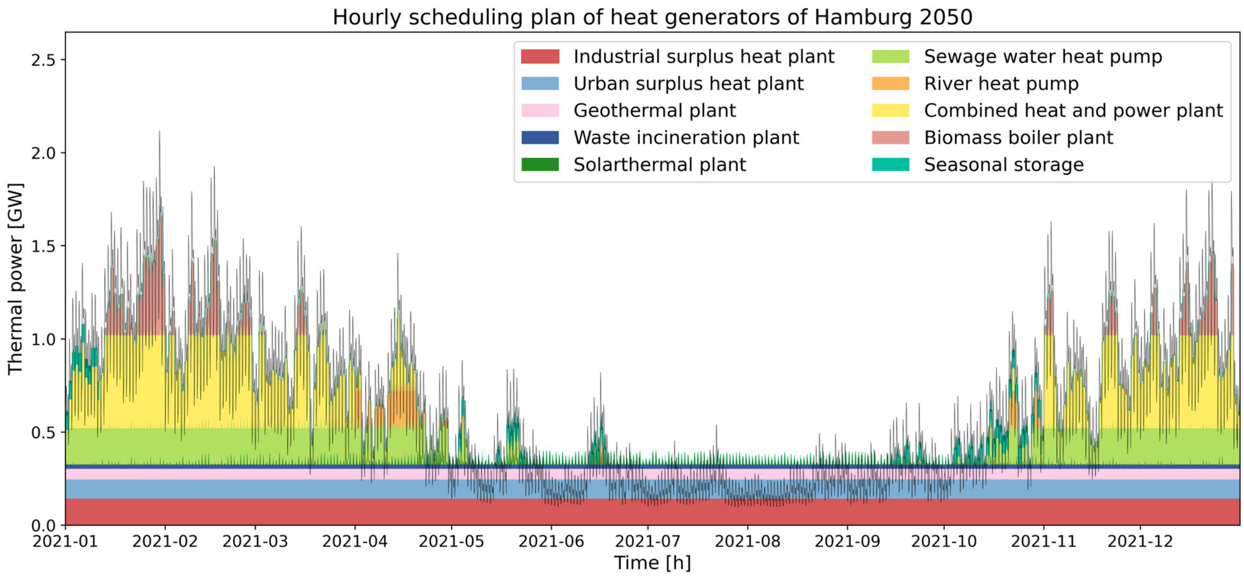

Fig. 13. Hourly scheduling plan from Heat4Future tool for case study Hamburg 2050.

Limitations

The intended application of the Heat4Future tool is to facilitate the preliminary planning of future supply for a given district heating system. Therefore, the tool requires a minimal set of input data that the user must provide, including the annual heat demand of the considered DHS, as well as the type and maximum capacity of the heating technologies to be included in the simulation. This means that prior to using the tool, the user must perform a potential analysis for renewable heat generation, as the Heat4Future tool does not offer this feature. Additionally, the tool does not account for capital costs associated with generators or the grid; instead, it assumes the provided generator types and the DHS are fixed.

Due to its broad approach, the Heat4Future tool is not intended for detailed planning of a district heating system's layout and/or operation. The method does not account for hydraulics and grid dimensions and it lacks sequential optimization of the heat generators, as this would require detailed data sets, such as variable electricity prices, which are unavailable in the early stages of planning DHS.

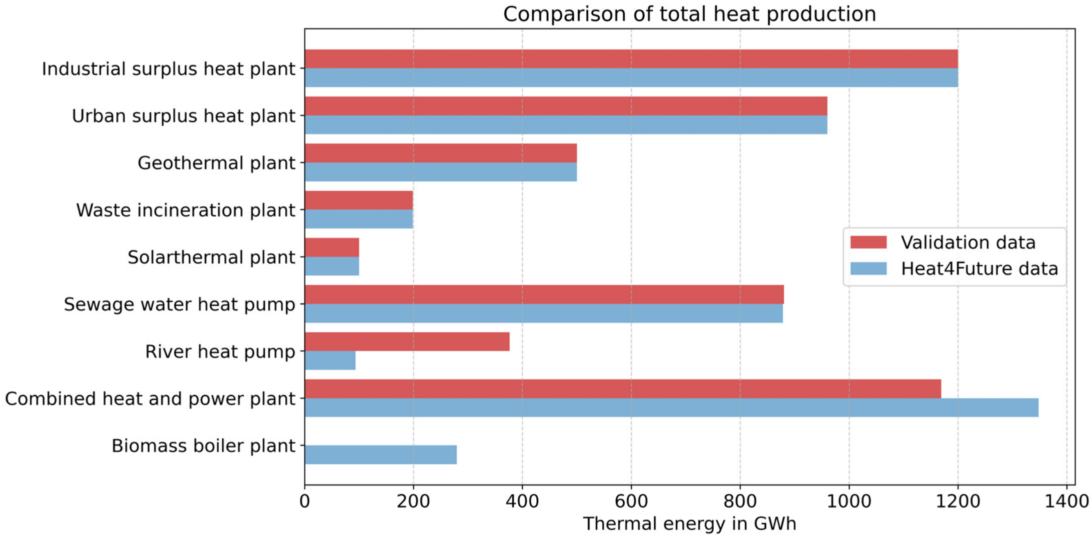

Fig. 14. Comparison of heat production between results from the original case study and from the Heat4Future tool.

It should be noted that the method itself relies on various simplifications, particularly regarding the technical operation of the heating plants, as presented in Section Method details. For the intended application of the tool, this level of detail and abstraction is sufficient; however, it makes the tool unsuitable for detailed operational planning of heating plants within an actual DHS. Overall, the Heat4Future offers a straightforward, yet effective approach for exploring various options for renewable heat supply in a DHS. Therefore, it is a valuable contribution to existing planning approaches, which often require a more detailed knowledge base and thus more suitable for a later stage of the DHS planning process.

Conclusions

The methodology presented for the Heat4Future tool offers a data-friendly and computationally efficient approach for the preliminary planning of renewable DHS. The tool's calculations are based on publicly available data sources, making it applicable even when users have very limited data about the future demand and supply of DHS. The core of the heat generation simulation is the proposed approach of ranking the heating plants based on a cost ratio that indicates the relationship between electrical costs and thermal costs. This ratio can be calculated using technical parameters, allowing for the ranking of heating plants based on their operational costs without the need for cost projections. This method simplifies the tool's usability and enhances its applicability to highly uncertain price forecasts, particularly concerning the long-term horizons for which district heating system (DHS) planning is typically conducted. The open-source nature of the tool offers various avenues for enhancing its usability, thus ensuring its broad future applicability. Potential future developments may include the implementation of a simple graphical user interface to enhance usability, the addition of new features to account for investment costs (e.g., decision-making through multi-criteria analysis methods), and the incorporation of additional data sources for potential analysis of the heating plants.

Ethics statements

Not applicable

CRediT author statement

Nina Kicherer: Conceptualization, Methodology, Resources, Writing- Original draft preparation, Writing -Review & Editing, Project administration. **Pablo Benalcazar:** Conceptualization, Methodology, Software, Resources, Writing - Original draft preparation, Writing - Review & Editing. **Peter Lorenzen:** Conceptualization, Methodology, Software, Formal analysis, Validation, Writing - Original draft preparation, Writing - Review & Editing. **Olessya Kozlenko:** Software, Data curation, Visualization, Formal analysis, Writing - Original draft preparation, Writing - Review & Editing. **Sadi Tomtulu:** Software, Data curation, Visualization, Formal analysis, Writing - Original draft preparation. **Jan Trosdorff:** Methodology, Resources, Software, Writing - Review & Editing.

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.

Data availability

Data will be made available on request.

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