



District heating modeling tools: A review based on design and simulation of renewable district heating networks

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ABSTRACT

To achieve net-zero greenhouse gas (GHG) emissions, the EU aims to fully decarbonize district heating (DH) by 2050. This work evaluates DH simulation tools based on their ability to support the operational requirements of renewable district heating (R-DH) systems, including thermal energy storage (TES), direct demand response (DR), and advanced control strategies such as model predictive control (MPC). Twelve tools were assessed using criteria derived from real-life R-DH operational needs. The methodology involved identifying the key operational requirements of R-DH systems through a comprehensive literature review and defining modeling criteria to assess the tools. These criteria include the ability to model TES across various timescales, simulate building thermal dynamics for DR scenarios, and integrate advanced control strategies. The tools were then evaluated and compared to provide insights for researchers and network operators, as well as recommendations for tool developers to address existing gaps. The results show that DH-dedicated tools are generally well-suited for network-specific studies and practical applications due to their user-friendly interfaces and built-in components. Non-DH-dedicated tools, offer greater flexibility and customization, excelling in TES modeling, building thermal dynamics, and secondary side configurations, but often require significant user expertise and additional effort to adapt to DH-specific applications. Notably, DH-dedicated tools like SIR3S and Fluidit Heat are bridging the gap between DH-dedicated and Non-DH-dedicated tools by incorporating features such as custom-scripting and co-simulation, offering enhanced flexibility for advanced research and practical applications. In conclusion, improving both DH-dedicated tools, and Non-DH-dedicated tools, will better support researchers and developers in driving the transition to efficient and sustainable R-DH systems.

1. Introduction

The continuous increase in global carbon emissions and the consequent global warming observed in recent decades necessitate substantial transformations across all fields of the current energy system [1]. In the heating sector, district heating (DH) has the potential to play a crucial role in reducing carbon emissions, when it relies primarily or exclusively on renewable and waste heat (RWH) sources. As documented in the latest [2] report, Europe had 19,037 district heating networks (DHNs) in operation in 2022, providing heat to over than 77.3 million citizens. In Austria, DH accounts for 17 % of the heating demand for residential and service sectors, with a total installed DH capacity of 11.2 GWth [2].

Despite the progresses over the past decades, RWH sources accounted for only 42.6 % of the DH energy mix in Europe, remaining well below the European goal of reaching climate neutrality by 2050 [2].

Achieving a fully renewable DH (R-DH) supply by 2050 [3], will require a profound change in the planning of new DH networks as well as in the management and operation of the existing ones.

DH systems have evolved over time, with each generation marked by advancements in technology and reductions in temperature levels, leading to lower heat losses and improved efficiency [4]. The 1st Generation (1GDH) was introduced in the 1880s in the USA, these systems used steam as the heat carrier to replace local heating installations in multifamily houses. They suffered from high heat losses, explosion risks, and corrosion in return pipes. Starting from the 2nd Generation (2GDH), steam was replaced by pressurized water (above 100 °C) to save fuel. Following the oil crises of the 1970s, the 3rd Generation (3GDH) was introduced. Supply temperatures were lowered below 100 °C to further reduce heat losses. In the fourth generation (4GDH), supply temperatures are decreased to a range between 30 and 70 °C. Recently introduced 5th Generation (5GDHC) networks are systems designed to

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Nomenclature			
CF-VT	Constant Flow Variable Temperature	R-DH	Renewable District Heating
CHC	Consumer-side Hydraulic Connection	R-DHN	Renewable District Heating Network
CHP	Combined Heat and Power	RWH	Renewable and Waste Heat
DH	District heating	RtR	Return to Return
DHC	District heating and cooling	RtS	Return to Supply
DHN	District heating network	SHPs	Sorption Heat Pumps
DHNI	District Heating Network Inertia	StS	Supply to Supply
DR	Demand Response	TES	Thermal energy storage
EH	Excess Heat	VCHPs	Vapor-compression Heat Pumps
GHG	Greenhouse Gas	VF-CT	Variable Flow Constant Temperature
GUI	Graphical User Interface	VF-VT	Variable Flow Variable Temperature
HOB	Heat only Boiler	WH	Waste Heat
HP	Heat pump	WtE	Waste to Energy
LCOH	Levelized Cost of Heat		
MILP	Mixed Integer Linear Programming	<i>Symbols</i>	
MO	Merit Order	\dot{Q}	Heat flow rate [W]
MPC	Model Predictive Control	\dot{V}	Volumetric flow rate [m ³ /s]
MSW	Municipal Solid Waste	ρ	Density [kg/m ³]
PDEs	Partial Differential Equations	T_{sup}	Supply temperature [°C]
		T_{ret}	Return temperature [°C]

simultaneously supply heating and cooling. These systems operate with ultra-low temperatures, with hot pipe temperatures ranging between 13–20 °C and cold pipe temperatures between 8–16 °C. However, terminology for 5GDHC is not yet standardized, with terms like “ultra-low temperature networks” ([5,6,7,8], “anergy networks” ([9]), and “bidirectional networks” ([10]) also being used.

1.1. Literature review

Over the last decade, numerous reviews have explored various aspects of district heating (DH) systems, providing valuable insights into their technical [11], environmental, and legislative fields [12]. A recurring theme across these studies is the integration of renewable heat sources (RWH) into DH systems, which is facilitated by strategies such as demand-side management, thermal energy storage (TES), and the reduction of operating temperature levels. Vandermeulen et al. [13] underscored the importance of flexibility in DH systems to address the challenges posed by intermittent heat generation from RWH sources. Similarly, Angelidis et al. [14] identified opportunities and barriers for DHC networks that rely on sector coupling via heat pumps (HPs) and TES devices. Guelpa et al. [15] demonstrated that supply temperature reductions can be achieved without requiring major infrastructural modifications, further enabling the integration of RWH sources.

In addition to these thematic reviews, several studies have specifically addressed district heating network (DHN) simulation tools. Allegrini et al. [16] and Xu et al. [17] reviewed modeling approaches and software tools for simulating district-level energy systems, emphasizing the importance of balancing the level of detail in building data with the reliability of results. Kuntuarova et al. [18] provided a comprehensive overview of modeling approaches and tools for DH network design and simulation, offering guidance for both academic and industrial users in selecting suitable options.

1.2. 4GDH and 5GDHC

The evolution of DH systems has led to the development of 4GDH and 5GDHC networks, which aim to integrate low-temperature RWH sources. These generations differ significantly in their design, operating principles, and suitability for various applications.

4GDH networks focus on reducing supply and return temperatures to maximize energy efficiency and facilitate the integration of RWH

sources. Supply temperatures can range from 30–50 °C for space heating (SH) only, depending on the heating technology used in buildings, or at least 65 °C when domestic hot water (DHW) preparation is included to prevent Legionella growth [[19,20]].

Several studies have demonstrated the energy and economic benefits of transitioning from 3GDH to 4GDH. A case study in Aalborg Municipality showed that transitioning to 4GDH reduced annual heat losses from 21 % to 15 % and increased the coefficient of performance (COP) of heat pumps (HPs) from 2.9 to 3.9 [21]. On a national scale, Sorknæs et al. [22] found that transitioning to 4GDH in Denmark reduced system costs by €220 million/year and thermal losses by 1.05 TWh/year.

5GDHC networks operate at near-ground temperatures (hot pipe: 13–20 °C, cold pipe: 8–16 °C) and rely on decentralized heat pumps (HPs) installed at connected buildings to provide the required temperatures for space heating (SH), space cooling (SC), and domestic hot water (DHW) [23]. Unlike 4GDH systems, which deliver heat directly to consumers at higher temperatures, 5GDHC networks provide low-temperature water that requires additional heating or cooling at the consumer level. The stable, near-ground temperature range of 5GDHC networks enhances the efficiency of evaporation and condensation processes in heat pumps (HPs), compared to air-source HPs, improving overall system energy efficiency. As a result, HPs in 5GDHC networks achieve high Seasonal Performance Factors (SPFs), typically ranging from 3 to 6, depending on the network’s temperature levels and the building’s heating and cooling demand [[24,25]].

A key feature of 5GDHC is its dependence on the electricity system, which directly impacts both the renewability of the network—determined by the carbon intensity of the electricity mix—and its economic competitiveness, which is strongly influenced by electricity prices [26].

Opportunities and barriers of 5GDHC. 5GDHC networks offer several advantages but face significant challenges. Their low operating temperatures reduce heat losses compared to higher-temperature DH systems. Saini (2022) et al. [27] reported heat losses as low as 4 % in 5GDHC networks. These systems can also meet both heating and cooling demands using the same infrastructure, making them ideal for mixed-use areas. However, 5GDHC networks face barriers to implementation. Volkova et al. [26] highlighted the incompatibility of existing DH infrastructure, which is mostly based on third-generation DH (3GDH) systems. The low temperature difference in 5GDHC networks requires higher flow rates to deliver the same thermal power, making it difficult

to reuse existing pipelines. High-efficiency buildings are also necessary to minimize energy demand, limiting their use in areas with older or poorly insulated buildings. Additionally, the bidirectional energy flow introduces control complexity, requiring advanced management systems.

Volkova et al. [26] and Lund et al. [28] concluded that 5GDHC networks are unlikely to replace 4GDH systems soon. They are better suited for specific applications, such as mixed-use areas with simultaneous heating and cooling needs.

Hybrid DH-HP systems, which combine central DH networks with locally installed HPs at consumer buildings, have been proposed as an intermediate solution between 4GDH and 5GDHC. Soleimani et al. [29] reviewed these systems and found that they can achieve operational cost savings of 5–27 % and CO₂ reductions of up to 32.3 % compared to conventional DH-only approaches, i.e., 4GDH.

1.3. DH modeling techniques

DHNs are complex thermohydraulic systems. Various modeling approaches have been proposed, designed for different application areas, objectives, and boundary conditions. Modeling techniques can be divided in two groups: black-box models and white-box models.

Black-box models do not consider the physical thermohydraulic dependencies between a system's inputs and outputs. Outputs are derived by data interpolation that usually comes from experimental data or results from white-box models simulations [30]. Different algorithms have been proposed, including Kalman filters, Autoregressive Moving Average (ARMA) models and artificial neural networks (ANN) [31]. The strength of black-box models is the relatively low computational time required to obtain solutions. However, the limited transferability hinders their broader application in real-world scenarios [32–30].

White-box models are typically based on one-dimensional models where the main direction of flow in the pipes is considered [30]. The hydraulic and thermal behavior of the system is physically described by partial differential equations (PDEs) that are typically numerically solved. Depending on the application scenarios and problems of interest, simplifying assumptions are applied to the nonlinear PDEs system for the best compromise between accuracy and computational time.

Both black-box and white-box models can be steady-state, quasi-dynamic and dynamic [33].

Steady-state approach.

In the steady-state approach, both hydraulic and thermal conditions are time-invariant, so the temperature distribution is not time-dependent. The solution of the PDEs for the thermal hydraulic behavior can be coupled or decoupled. In the decoupled solution, the hydraulic part is calculated first by using a Newton-Raphson method, Jacobi method or Hardy-Cross method ([33,18,34]). The thermal part is solved once the flow rates are determined, consequently, the matrix required to calculate the hydraulic part is smaller than for a coupled approach, where both parts are calculated in parallel. This makes the matrix for the problem solution smaller but the iteration steps for calculation increase [33]. The coupled thermo-hydraulic calculation solves both parts in a single system using the Newton-Raphson method and an integrated Jacobian matrix, reaching a faster convergence through fewer iterations [18].

Quasi-dynamic approach.

The quasi-dynamic approach simulates the hydraulic part as steady-state and the thermal one as dynamic. This strategy is justified by the fact that pressure waves propagate at around 1500 m/s, while temperature variations travel at flow velocity in pipes ([35,36]). Quasi-dynamic models calculate temperatures at nodes accounting for thermal losses and transmission delay while the temperature distribution along pipes is neglected [37]. The flow field can be analyzed following a Lagrangian or an Eulerian specification. The Eulerian specification consists of the observation and description of a fixed portion of the flow field through which water particles enter and leave. In contrast, the

Lagrangian specification consists in following the water particles while they flow in the system [33]. Various methods have been proposed in literature for the solution of the thermal problem [18]. Benonysson et al. [38] presented the “node method”. The principle of this Eulerian-specification method is to keep trace of the movement of water mass from one network node to the following one. The “element method” is based on spatial discretization of the pipe, allowing to determine a temperature profile along the pipe. Other Eulerian specification methods like the “characteristic method” [39] and the “function method” [40] have been proposed in literature aiming to improve the trade-off between accuracy and computational time compared to the “node-method”. The “plug flow method”, used in ([41,42,33]), models the heat transfer fluid as a series of non-mixing plugs that move through network's pipes at the flow velocity, mimicking a Lagrangian specification. This method is considered accurate and computationally efficient [18].

Dynamic approach.

In the dynamic approach, both hydraulic and thermal problems are considered time-dependent. Dynamic approaches typically use an Eulerian specification [33]. In dynamic models, the pipes are spatially discretized, allowing to calculate the temperature of each pipe section, considering both thermal losses and transmission delay [37]. As in quasi-dynamic approaches, the solution of the thermal problem can be determined by applying the “elemental method”, the “node method” or other methods [18].

Comparison of approaches.

In steady-state approaches the calculation of temperature distribution in the network is time-invariant. This makes them suitable for design and planning [43], particularly for multi-energy systems ([44,45,46]). Quasi-dynamic and dynamic approaches are used for operational analysis ([41,47,37]). The quasi-static approach is considered accurate and limited time-consuming ([35,36]). As reported by [37], compared to the dynamic approach, the quasi-dynamic approach reduces computation burden, but its error and numerical diffusion still increase with time step increment and mass flow changes.

1.4. Research gap, research questions and scope of the work

Recent literature focusing on software tools for district heating (DH) network simulation primarily focus on conventional DH systems or provide general comparisons of tools without explicitly considering the unique operational requirements of highly renewable district heating (R-DH) systems. To date, no publication has comprehensively evaluated the ability of existing tools to simulate the optimal operation of R-DH systems, which aim to achieve near-100 % renewable heat production, maximize energy efficiency, and minimize CO₂ emissions. This study addresses this gap by introducing a novel analytical framework that links the real-life operational requirements of R-DH systems to specific modeling criteria for simulation tools. By doing so, this work provides a targeted evaluation of tools in the context of R-DH, offering insights that go beyond existing classifications and descriptions.

This work is guided by the following questions:

- Which specific real-operation abilities should a near-100 % R-DH possess?
- To what extent are the currently available DH simulation tools able to simulate the operation of a R-DH? What are the main features and limitations of these tools?

The novelty of this paper lies in three key contributions:

1. Identification of R-DH operational requirements
This study identifies a comprehensive list of operational abilities required for the real-life operation of R-DH systems, derived from an extensive review of technologies, strategies, and practices aimed at achieving highly renewable DH.

2. Evaluation of DH simulation tools using a novel analytical framework

Twelve DH simulation tools were evaluated and compared using a set of criteria directly derived from the identified operational requirements of R-DH systems. This approach goes beyond existing comparative studies, by systematically linking the operational needs of R-DH systems to modeling requirements, enabling a more application-oriented evaluation of tools.

3. Recommendations and Guidelines for Researchers and Tool Developers

Based on the evaluation, this paper provides clear recommendations for researchers to select tools aligned with their specific needs, whether for network-specific studies or advanced research requiring flexibility and multi-domain modeling. Additionally, it offers guidelines for tool developers to address existing gaps. By addressing these gaps, this work aims to support the transition to more sustainable and renewable DH systems.

2. Identification of R-DH real operation characteristics and needs

This section provides a comprehensive review of the technologies, strategies, and operating practices that support the transition to renewable district heating (R-DH) systems. Subsections 2.1 to 2.8 explore key aspects of R-DH systems, including renewable and waste heat (RWH) integration, flexibility and storage solutions, optimization of heat production, hydraulic configurations, temperature reduction strategies, and advanced control techniques. Based on this review, Section 2.9 derives a list of real-life operational requirements essential for the optimal functioning of R-DH systems.

2.1. Renewable and waste heat sources

In this section, the main types of RWH sources for DH are presented, analyzing the characteristics, potential, and limitations of each source.

As defined by Tran and Smith [48] in relation to electrical power generation, dispatchable generation is a type of generation that can be delivered based on the demand. Dispatchability measures the degree of flexibility of a certain plant in real time responsiveness. It is related to technical metrics like: start-up time, ramp-up (down) time, operational power range (maximum and minimum output), and minimum run time. Unlike electrical systems, where frequency and voltage control are required on a time-horizon in the order of seconds [49], the regulation of DH systems typically occurs on a timeframe in the order of minutes (or hours), reflecting their slower dynamics and considerable storage capacity.

The “scheduling” of a heat source is defined as the extent to which the heat output can be reliably forecasted and scheduled in advance, regardless the operational dispatchability in real time operation.

Biomass.

Biomass is currently the heat source with the highest share (34.4 % in 2022) in the European DH energy mix [2]. It is used in district heating (DH) systems through two main technology options: heat-only boilers (HOB) and combined heat and power (CHP) plants, both of which are well-established and frequently employed ([24,50,51,52,53]). Due to its high combustion temperature (above 200 °C), biomass can be used in 2GDH, 3GDH, and 4GDH systems.

In terms of dispatchability, biomass-based CHP plants have relatively long start-up times, ranging from 40 to 60 min for a hot start to 120–170 min for a cold start, and can operate at partial loads down to 30 % of nominal capacity [54]. HOBs offer slightly greater flexibility, with a regulation range of 25–100 % of full capacity and ramp rates between 4–10 % of nominal load per minute, depending on the specific plant [55]. Compared to gas boilers and electric boilers, biomass plants exhibit longer start-up times and lower ramp rates, making them more suitable for base-load or intermediate load operation [[56,55]].

The schedulability of biomass-based plants is high when fuel availability is ensured, as their heat output can be reliably forecasted and scheduled [24]. However, if a CHP plant prioritizes electricity production, the dispatchability and schedulability of heat production must be considered null.

Direct use of Geothermal.

Geothermal heat can be connected to district heating (DH) systems either directly, by injecting geothermal water into DH pipelines, or indirectly, using heat exchangers to separate geothermal water from the DH heat transfer fluid [57]. In 2022, geothermal energy accounted for 2.5 % of the European DH energy mix, with significant variability across countries [2]. Its economically viable use is limited to specific geological sites where shallow geothermal heat can be extracted at low cost and technological complexity [58].

Examples of geothermal DH applications include Iceland [59], France [60], and Turkey [61,62]. In Slovenia, Stegnar et al. [63] found that while 54 % of the technical DH potential remains untapped, shallow geothermal energy is more suited to individual systems than DH applications. In contrast, deep geothermal energy can be exploited without geographical limitations, as demonstrated by DH systems in Munich [64] and Vienna [65].

When available, geothermal heat sources are generally both schedulable and dispatchable, although dispatchability may be constrained by specific applications.

Waste heat.

Waste heat (WH) sources for district heating (DH) can be classified into two categories: (i) heat generated from waste-to-energy (WtE) technologies, and (ii) excess heat (EH) released by industrial and service sector processes [66]. In 2022, WtE and EH contributed 6.4 % and 3.6 %, respectively, to the European DH energy mix [2].

WtE technologies use municipal solid waste (MSW) incineration in heat-only boilers (HOB) or combined heat and power (CHP) plants, with examples found in many countries [[67,66]]. Fruergaard et al. [68] demonstrated that replacing fossil-fuel boilers with WtE incinerators can significantly reduce CO₂ emissions, saving up to 48 and 43 kg CO₂/GJ for two case studies. Since MSW can be stored at the plant, WtE heat sources are highly schedulable, similar to biomass-based plants [56]. However, their dispatchability is limited by long start-up times (up to 12 h for a cold start) and low ramp rates (1 % per minute) [56].

Excess heat (EH) is a byproduct of industrial [69] or service-related activities, such as supermarkets, power substations [70], and data centers [[71,72,73]]. While EH production is not dispatchable, as it depends on the primary activity of the industrial or service process, its schedulability is high when production processes are regular [[70,73]].

Use of Heat Pumps.

Heat pumps (HPs) are a heat production technology used to supply heat to district heating networks (DHNs), accounting for approximately 1 % of the heat supply in DH systems [74]. HPs require a heat source (e. g., air, ground, groundwater, or waste heat) and an additional energy input, which can be either electrical energy for vapor-compression heat pumps (VCHPs) or thermal energy for sorption heat pumps (SHPs) [75]. HPs play a key role in renewable-driven DH (R-DH) systems by enabling the integration of RWH sources into DHNs, particularly when the temperature of the heat source is insufficient for direct injection into the network.

The HEATLEAP European project has demonstrated the environmental and economic benefits of integrating large-scale HPs into DH systems, particularly for waste heat recovery [76]. For example, in Berlin, an 8 MW high-temperature HP recovers waste heat from a cooling plant, supplying heat to the DH network at temperatures between 85 °C and 120 °C, resulting in annual CO₂ savings of 6,500 tons [77]. Similarly, Wang et al. [78] studied the use of high-temperature HPs to recover waste heat from data centers, showing that a 1 MW HP can reduce CO₂ emissions by approximately 33 tons annually. Many DHNs are transitioning from combustion technologies to large HPs, with examples in Denmark, Germany, Austria, and the Netherlands [79].

A quantitative description of dispatchability of vapor-compression heat pumps (VCHPs) is reported in [80]. Air-to-water and seawater-source VCHPs exhibit a cold start-up time of 0.5–1 h and a hot start-up time of 6–10 min, making them significantly more responsive than other base load technologies like biomass or waste-to-energy plants. VCHPs also have a regulation capability of 10 % per minute and can operate at a minimum load of 25 %.

In terms of schedulability, HPs depend on the availability and schedulability of the energy input, which varies based on the type of heat pump and its energy source. For VCHPs connected to the electricity grid, the energy input is generally available and schedulable, but its renewable nature depends on the CO₂ intensity of the electricity mix. SHPs, on the other hand, rely on thermal energy, whose schedulability depends on the characteristics of the heat source.

Solar thermal.

Solar thermal systems convert solar radiation into thermal energy and accounted for only 0.2 % of the European DH energy mix in 2022 [2]. Studies have highlighted the potential of integrating solar thermal energy into DH networks, particularly for reducing CO₂ emissions. Winterscheid et al. [81] demonstrated that increasing the annual solar fraction reduces emissions, though none of the scenarios studied achieved a solar fraction above 20 %. Similarly, Rämä and Mohammadi [82] evaluated centralized and decentralized solar collector systems in a Finnish DH network, finding that the maximum solar fraction reached 21 % for centralized systems at low supply temperatures.

Solar thermal energy is inherently non-dispatchable and non-schedulable due to its dependency on weather conditions and the strong seasonal and daily imbalances in production [83]. While forecasting methods can provide reliable intra-day and day-ahead predictions, uncertainty increases significantly for longer time horizons [84]. The dispatchability and schedulability of solar thermal systems improve significantly when coupled with thermal energy storage (TES).

Table 1 summarizes the dispatchability and schedulability of RWH sources. Most sources, such as biomass, waste heat, and solar thermal, SHPs have low dispatchability, while geothermal and VCHPs are highly dispatchable. Notably, the renewability of VCHPs depends on the electricity mix. In terms of schedulability, most sources, except solar thermal, exhibit high reliability when production processes or fuel storage are predictable.

2.2. Flexibility in DH

The low dispatchability of many RWH sources, as highlighted in Section 2.1, can lead to temporal mismatches between heat production and consumption, potentially compromising the reliability of DH services. To address this challenge, R-DH systems must leverage alternative flexibility options to ensure a better alignment of heat supply and demand.

Flexibility is a frequently used term referred to energy systems and it

Table 1
Dispatchability and schedulability of RWH sources.

Heat Source	Dispatchability	Schedulability
Biomass	Low (long start-up times, low ramp rates)	High (fuel can be stored, ensuring reliable scheduling)
Geothermal	High (output can be adjusted by varying geothermal fluid flow rate)	High (reliable and predictable in suitable geological sites)
Waste-to-Energy	Low (long start-up times, low ramp rates)	High (MSW can be stored, ensuring reliable scheduling)
Excess Heat	Low (dependent on primary industrial/service process)	High (if production processes are regular and predictable)
Heat Pumps	VCHPs: High (short start-up times, high ramp rates) SHPs: Low	VCHPs: High (if connected to the electricity grid). SHPs: Depends on source.
Solar Thermal	Low (due to weather dependency)	Low (forecasting methods offer limited reliability)

is often used in relation to electrical systems. Lechl et al. [85] solved the ambiguities regarding flexibility definitions, providing a flexibility taxonomy applicable to all types of energy systems. The authors give a mathematical definition for terms like: “flexibility requirement”, “flexibility potential”, “flexibility source” and others. In the field of DH, Vandermeulen et al. [13] defined flexibility as the ability of shifting heat production and/or consumption in time and/or magnitude. Flexibility options consider actions that occur in a timespan below 24 h, i.e., intraday [86], or for several days.

In DH, three categories of **flexibility** options can be identified:

- Use of central thermal energy storages for intraday (daily) operation
- Use of demand-side flexibility (Demand Response)
- Use of the network itself as a thermal storage

a) Use of central thermal energy storages.

Centralized thermal energy storage (TES) systems can be connected to the network and be utilized for valley filling and peak shaving of the thermal demand (consumption-flexibility). Centralized TES can also allow to store intermittent production of renewable ([87,88]) and waste heat [89] for a later use, maximizing RWH exploitation (production-flexibility). TES systems can be used for both long- and short-term storage. Gadd and Werner [90] conducted an analysis reporting the relative size of storage units (m³/TJ) as a function of the annual energy demand of the network. Results show that most of the TES installed in DH systems are short-term storages.

TES can be divided in three categories based on the physical phenomenon used to store heat: sensible, latent and chemical. While sensible storage is a mature technology used in various DH networks, latent and chemical storage are still at an early research stage. [57].

Fazlollahi et al. [91] and Du et al. [92] demonstrated the benefits of integrating central TES into DH systems. Fazlollahi et al. showed that incorporating daily TES tanks in high- and low-temperature DH networks improved overall system efficiency, reduced environmental impacts, and lowered total costs by 4.7 %, 5 %, and 2 %, respectively. Similarly, Du et al. [92] proposed a framework for integrating waste heat from data centers with dual short-term TES, achieving a 2.1 % increase in load shifting, a 10 % reduction in peak demand, and a 3.2 % decrease in operational costs. Both studies highlight that larger TES sizes enhance peak shaving and cost reduction, although the impact on load shifting capacity is limited.

The review by Guelpa and Verda [57] extensively examined the implementation of thermal energy storage (TES) in DHC systems. It evaluated both short-term and long-term storage options, highlighting their respective advantages and disadvantages. The analysis assessed energetic, economic and environmental aspects.

b) Use of demand-side flexibility (Demand Response).

Demand Response (DR) consists in shifting the thermal load of consumers in time. The main benefits of this practice are a reduction in peak heating demand, as well as a reduction in the cost of heat supply and CO₂ emissions in cases where fossil peak-heating plants are used ([93,94]).

Two types of DR can be identified [94]:

• Indirect DR

It consists in the application of different tariffs for different time of the day. This is widely used in the electricity market and attempts are done also for the thermal one. The main limitation of this method is the uncertainty in the outcomes due to the hardly forecastable user behavior. In this regard, Mokhtari et al. [95] proposed a methodology for designing day-ahead dynamic price profiles for DH, aimed at encouraging customers to participate in DR purposes activities. Results show that the change in demand profile matched a pre-defined load-shifting profile with 16.6 % mean absolute percentage error (MAPE) with an associated peak load reduction of up to 84.4 % in a typical winter day. Knudsen et al. [93] presented an iterative

methodology for assessing price-driven DR during the development of the heating solution of new building areas with DH and available WH. Results show a potential of 13 % reduction in operational cost at the expense of 1 % increase in energy consumption. The operation cost reduction derives from a minor use of costly, carbon-emitting peak-heating plants.

- **Direct DR**

It consists in a direct load control. Demand profiles are managed to make them as close as possible to the optimal ones (desired benchmark) while keeping comfort conditions inside the buildings. Direct DR can rely on optimization processes, real time analysis and day-ahead analysis.

When Direct DR is used, “flexible consumers” can adjust their consumption at the request of the network operator, to achieve a specific goal. For example, if the goal is the minimization of thermal peaks, the consumption of the flexible consumer can be increased (valley filling) to store heat before an expected demand peak. During peak demand, the consumption of the flexible consumer can be reduced (peak shaving), exploiting the heat previously stored. For non-industrial consumers, flexibility potential can be identified in the use of:

1. A distributed TES.
2. The building mass as a virtual thermal storage.

In the first case, a TES is installed at the consumer’s site, on the secondary side of the DH substation [57].

In the second case, a similar demand-side flexibility concept is performed, with the difference that the storage capacity exploited is the building’s thermal mass. Flexibility lies in the variation of the room temperature within the building, which can be increased at times of high availability of heat production and reduced at times of low availability. The range of room temperature variation is constrained by the preservation of comfort conditions inside the building [96,97].

Industrial utilities can also shift in time their consumption, providing demand-side flexibility.

As highlighted by Lind et al. [98], the building’s thermal mass has the ability to shift loads on short term. This ability can be utilized for reducing costs to end-users or energy providers, reducing the primary energy demand of peak boilers and CO₂ emissions. Van der Zwan and Pothof [97] formulated an operational MPC optimization model for a DH system with capacity- and temperature-limited renewable sources. The test case shows that the peak heating demand can be reduced by 50 %, if the thermal inertia of the buildings is used and the heating setpoints for sources’ supply temperatures are adapted. A comprehensive review on building flexibility for DH has been realized by Guo et al. [99]. The review considers quantification of energy flexibility, the realization of thermal flexibility, and the use of building thermal mass in demand side management.

- c) **Use of the network itself as a thermal storage.**

Unlike the electric grid, district heating networks (DHNs) inherently possess a higher degree of flexibility due to their ability to store thermal energy. This flexibility, often referred to as District Heating Network Inertia (DHNI), allows the network to be “charged” during periods of high renewable heat (RWH) availability and “discharged” during low availability, providing short-term flexibility without additional infrastructure investment. However, this approach increases heat losses and thermal stresses in the network [100].

DHNI is typically activated by varying the supply temperature at heating plants while ensuring minimum supply temperatures for consumers and avoiding excessive temperature change rates. Alternatively, overflow valves can increase return temperatures by bypassing flow from supply to return lines, though this also increases heat losses. The concept of network preheating further exploits the heat transportation delay in DHNs, allowing high supply temperatures at low flow rates before a demand peak, followed by increased flow rates during the peak

to avoid production spikes [101].

Several studies have demonstrated the potential benefits of utilizing DHNI:

- a. **Peak Power Reduction:** Basciotti et al. [102] showed a 15 % reduction in daily peak power with only a 0.3 % increase in heat losses. Turski and Sekret [103] found that using both buildings and the DHN as thermal storage reduced peak production by 16.2 MW in a case study.
- b. **Cost Savings:** Kouhia et al. [100] reported a 2 % reduction in operating costs through optimized control strategies.

However, the practical storage potential of DHNs is limited. Zhang et al. [104] found that Swedish DHNs can store less than 0.8 % of daily heating demand with a 10 K temperature increase, while Chinese DHNs, due to oversized pipes, can store up to 4 %. Additionally, intensive use of DHNI can increase the frequency of pipe ruptures due to thermal stresses, as noted by Vandermeulen et al. [86] and Liu et al. [105].

2.3. Seasonal thermal energy storage

Seasonal thermal energy storage (STES) enables heat generated during one season to be stored and used in the following one. STES systems are often coupled with renewable and waste heat (RWH) sources, such as solar thermal plants, to store excess heat produced in summer and provide it in winter when demand is higher [57]. Depending on the storage temperature relative to the operating temperatures of the district heating network (DHN), the heat transfer fluid can either be directly used as the storage medium (direct usage) or require auxiliary systems, such as heat pumps, to increase the storage temperature (indirect usage) [57].

STES technologies are typically divided into three categories: Tank and Pit TES (TTES and PTES), Borehole TES (BTES), and Aquifer TES (ATES).

Tank and Pit TES. TTES uses insulated containers filled with water, while PTES stores heat in excavated ground enclosed by watertight covers. These systems have low energy density and high thermal losses (up to 30 %), making them less suitable for urban areas with limited space availability [[57,106]]. PTES systems have been studied in combination with solar thermal plants and absorption heat pumps (AHPs), achieving solar fractions of up to 20 % in DH systems [107].

Borehole TES. BTES stores heat in the thermal capacity of the soil using pipes installed in boreholes to form a closed-loop system. While BTES offers potential for integration with solar thermal systems, it comes with high investment costs, low energy density (3–5 times lower than water TES), and sensitivity to soil thermal properties [[57,106]]. Studies show that the effectiveness of BTES in DHC networks depends on a balanced cooling-to-heating demand ratio, typically between 0.4 and 1.0, to optimize environmental and economic performance [[108,109]].

Aquifer TES. ATES uses natural aquifers as storage media, with groundwater acting as the heat carrier. However, ATES faces challenges such as high heat losses due to the lack of thermal insulation and potential interference with other groundwater uses [[106,57]]. In Freiburg, Germany, simulations of shallow low-temperature ATES systems showed potential greenhouse gas (GHG) emissions savings of up to 70,000 tCO₂eq/year, corresponding to 40 % of current emissions from space heating and domestic hot water preparation in the area [110].

STES technologies offer significant potential for integrating RWH sources into DHNs, particularly in regions with seasonal heating and cooling demand. However, their adoption is limited by challenges such as low energy density, high thermal losses, and site-specific constraints (e.g., soil properties or aquifer availability). Among the three technologies, TTES and PTES are more suitable for areas with abundant space, while BTES and ATES are better suited for regions with balanced cooling-to-heating demand ratios or favorable geological conditions. Future research should focus on improving the efficiency and cost-

effectiveness of STES systems, as well as exploring their integration with advanced DH tools such as heat pumps and solar thermal systems.

2.4. Optimization of heat production portfolio

The achievement of R-DH requires the integration of un-evenly distributed RWH sources [111]. The scarcity and non-dispatchability of RWH sources require the implementation of an optimal control strategy to fully exploit their potential. In the context of energy (electricity and heat) production, portfolio optimization aims at finding the optimal operation of a portfolio of multiple plants, to satisfy a given energy demand within a set of boundary conditions and constraints ([112,113]). Modeling approaches for portfolio optimization can be stochastic or deterministic. In DH, deterministic approaches are more commonly spread [112], even though examples of stochastic methods exist ([114,115,116]). Deterministic approaches include linear programming, merit order (MO), mixed integer linear programming (MILP) and mixed integer non-linear programming ([117,118,112]). MILP and MO are the most used methods. The MILP approach is able to include an accurate description of the technology behavior, accounting for minimum run-time, maximum ramp-time, start-up and down times [112]. The MO is a rule-based algorithm that determines the activation and the thermal output of the plants in the portfolio according to their ascending marginal cost of production. A conceptual representation of the MO is reported in Fig. 1.

While the MILP approach guarantees a higher accuracy, it is more time-consuming and computational-intensive. This aspect becomes important with the integration of several RWH sources. Gonzalez-Salazar et al. [112] compared four different versions of MO with a MILP approach for a case-study DH system. Results showed small difference in heat production between the most accurate MO model and the MILP approach. The authors suggest the use of a combination of MO and MILP models for faster and more robust decision-making.

2.5. Hydraulic circuits for RWH sources

The local scarcity of RWH sources (Section 2.1) requires their optimal integration into DHNs.

A heating plant can supply heat to the network in three different hydraulic circuits configurations (Fig. 2) [119].

Return-to-Supply (RtS) (Fig. 2a): the heating plant increases the

temperature from the return to the supply line. This setup requires high pumping power, as the pump must overcome the pressure difference between the return and supply lines.

Return-to-Return (RtR) (Fig. 2b): the heating plant pre-heats the return line, operating efficiently at low temperatures. Pumping power is provided by network pumps to overcome the pressure loss in the heat exchanger and connecting pipes. The higher return temperature raises network heat losses and slightly reduces the efficiency of the primary heat generator.

Supply-to-Supply (StS) (Fig. 2c): the heating plant heats the supply line, operating at low efficiency due to the high required temperature. Network pumps provide the pumping power to overcome the pressure loss in the heat exchanger and connecting pipes. The primary heat generator's efficiency remains unchanged.

The choice of the hydraulic configuration depends on the type of renewable technology and the supply and return temperature of the DHN.

HPs. A detailed review regarding the integration of HPs in DH was conducted by Barco-Burgos et al. [120]. Their work reviewed the integration of HPs in 3GDH, 4GDH and 5GDHC, describing 12 placement options and connection modes of a HP unit. Due to the significantly lower temperature lift, RtR configuration has a higher COP compared to RtS configuration. In the same framework, [121] compared five generic configurations of HPs in DH systems considering different DHN temperatures, different fuels and different production technologies. For lower DH temperatures (70 °C and 35 °C supply and return temperature respectively), the RtR configuration exhibited the best performance when considering both cost of fuel and coefficient of system performance (COSP). Specifically, the COP for RtR and RtS configuration was 5.30 and 4.11 respectively. Supercritical HPs (e.g., CO₂ as refrigerant) can reach high temperature lifts on the heat sink side and therefore be used in RtS configuration [122].

Biomass plants and Waste-to-Energy (WtE). Burning technologies are typically used in RtS configurations as they are not limited by maximum temperatures and their energy conversion efficiency is not strongly dependent on return and supply temperature [119,123]. For burning technologies, a considerable efficiency improvement is possible if flue gases condensation is achieved. To achieve flue gases condensation, the DH return temperature should not exceed 45–50 °C. Burning technologies can be used in StS configuration, coupled with a heat source installed in RtR.

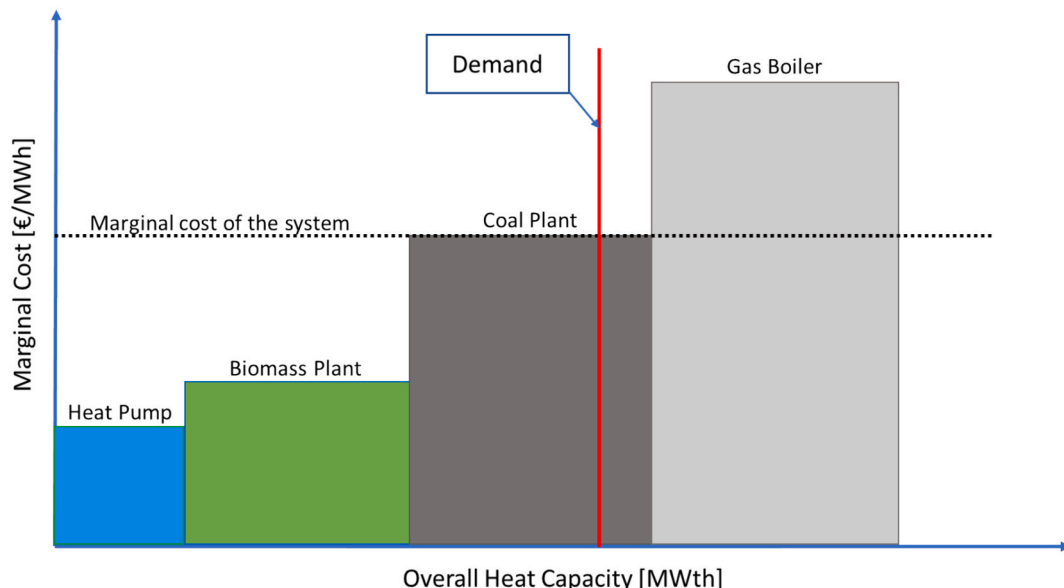


Fig. 1. Conceptual Representation of Merit Order, based on [112].

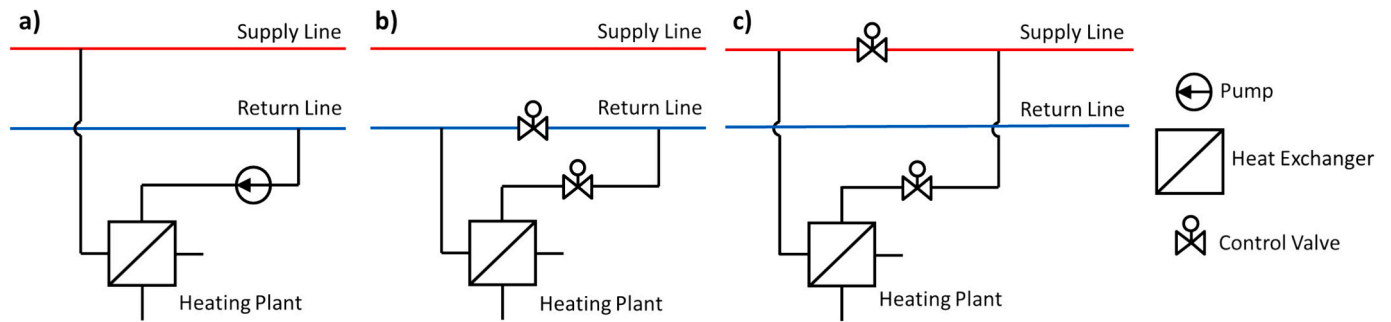


Fig. 2. Schematic representation of hydraulic circuits for heating plants: a) Return-to-Supply Configuration; b) Return-to-Return Configuration; c) Return-to-Supply Configuration [119].

Solar thermal. Solar thermal collectors are limited in the maximum temperature they can reach [124]. Solar collectors exhibit higher efficiency at lower operating temperatures due to reduced thermal losses, as the temperature difference between the collector and the ambient environment is minimized [125], the RtR is the most efficient connection. If network's required supply temperature is low enough, they can be operated also in RtS and StS configuration.

Geothermal and Excess Heat (EH). The outlet temperature produced by geothermal and excess heat depends on the specific heat source exploited. In some cases, RtR is forced by the low-temperature of geothermal or excess heat source. If the heat source temperature is high enough in relation to the required supply temperature in the DH network, RtS or StS configurations can be adopted. EH can be coupled with HPs, if the temperature of the EH source is too low.

While the RtR configuration offers advantages for HPs and solar thermal plants, it also presents notable drawbacks. When a source is installed in RtR, an additional heat source downstream must be installed in RtS to achieve the required supply temperature. However, this downstream source may operate at lower efficiency due to the higher return temperature caused by the upstream RtR source [[119,123]]. Furthermore, the higher return temperature downstream of the source connected in RtR increases heat losses in the network. These opposing effects underline the importance of optimization to identify the most suitable hydraulic configuration for specific applications.

Table 2, reports the adopted hydraulic configurations for the diverse RWH sources presented in Section 2.1.

2.6. Reduction of temperature levels in DH

As explained in the Introduction (Section 1), the historical succession of DH generations is characterized by a trend towards lower operating

Table 2
Hydraulic Connections for RWH sources.

Renewable Heat Source	Return-to-Supply (RtS)	Return-to-Return (RtR)	Supply-to-Supply (StS)
Biomass	F; ME	NF	F**
Solar Thermal	F	F; ME	F
Geothermal	F*	F	F*
Waste Heat (Excess Heat)	F*	F	F*
Waste Heat (Waste-to-Energy)	F*	NF	F**
Heat Pumps	F	F; ME	F

Legend:

F	Feasible
NF	Not Feasible
ME	Maximum Efficiency
*	Feasibility depends on the temperature level of the heat source
**	Feasible if a better suited heat source is attached in RtR

temperatures. Literature shows that the reduction of operating temperature is still an important area of research. Several procedures and techniques have been proposed in literature aiming to reduce the return temperature.

These include optimizing domestic hot water (DHW) tank charging through advanced control concepts [126], implementing adaptive control systems for radiator circuits to address oversizing issues [127], and utilizing cascade systems to repurpose return flows from high-temperature consumers for low-temperature consumers [128]. Additionally, reviews have highlighted the importance of pricing strategies, maintenance practices, and other non-technical measures in achieving lower return temperatures [129].

Lowering the return temperature in DH has implications on the hydraulic and thermal performance. When the return temperature is reduced while maintaining a constant supply temperature, the temperature spread increases. This allows the same thermal power to be transmitted with a lower volumetric flow rate, thereby either reducing the required pumping power or enabling the supply of more customers with the same flow rate [128].

As discussed in Section 2.5, reducing the return temperature also enhances the efficiency of certain heat production technologies, such as condensing boilers, which require low return temperatures below 45 °C to maximize condensation and energy recovery [123].

Lower return temperatures are essential for reducing supply temperatures, which help further minimize thermal losses in the network. Additionally, lower supply temperatures enable the integration of low-temperature renewable heat sources (RWH) into R-DH systems [130].

2.7. Heat production control strategies

In DH systems, supply temperatures and volumetric flow rates are the two primary decision variables used to control the thermal power at heat sources. Three main control strategies are commonly employed in DH [18]:

1. Constant Flow – Variable Temperature (CF-VT),
2. Variable Flow – Constant Temperature (VF-CT), and
3. Variable Flow – Variable Temperature (VF-VT)

Among these, the VF-VT strategy has been shown to achieve the best performance in terms of cost reduction and renewable energy integration [131]. However, dynamically controlling both the supply temperature T_{sup} and flow rate \dot{V} introduces significant challenges, due to the non-linear and non-convex nature of the problem. Non-convexities arise from both the thermo-hydraulic calculations and the control logic. The thermo-hydraulic calculations involve non-linear relationships between flow rates, temperatures, pressures, and heat transfer, as well as temperature mixing at network nodes [18].

The control logic for VF-VT requires dynamically adjusting both the supply temperature T_{sup} and the flow rate \dot{V} . Without additional rules or

constraints, the system is underdetermined, as infinite number of combinations of T_{sup} and \dot{V} can satisfy the power equation:

$$\dot{Q} = \dot{V} \cdot \rho \cdot c_p \cdot (T_{sup} - T_{ret})$$

Where ρ is the water density and c_p is its specific heat at constant pressure. To resolve this, additional rules can be defined to link T_{sup} or \dot{V} to other parameters. For example, T_{sup} can be defined as a function of ambient temperature. Alternatively, optimization algorithms can be used to determine the optimal combination of T_{sup} and \dot{V} (e.g., minimized energy consumption for pumping power and heat losses). However, these approaches introduce further complexity, as the optimization problem must account for time delays, temperature dynamics, and interactions between variables. In many cases, this results in a Mixed-Integer Nonlinear Programming (MINLP) formulation, which is computationally expensive and difficult to solve for large systems [18].

2.8. Model predictive control optimization

In renewable-driven district heating (R-DH) systems, the substitution

of flexible fossil-fuel-based heating plants with low-dispatchable and low-programmable renewable heat (RWH) sources increases the risk of mismatch between production and consumption, which cannot be fully compensated by flexibility options (Sections 2.2 and 2.3). To mitigate this risk and optimize the use of RWH sources, Model Predictive Control (MPC) has emerged as a widely used control strategy that integrates forecasts of exogenous variables, such as future thermal demand and RWH availability [132], into an optimization algorithm [133,134].

MPC requires a digital network model to predict the future outputs of a system over a finite time horizon. The process involves several steps, which can be summarized as follows (Fig. 3):

1. Current State Estimation

Calculation of the current state of the system (e.g., temperatures, mass flows, storage levels), using available measurements and a digital network model to estimate unmeasured states.

2. Forecasting of exogenous variables

Forecast of exogenous variables (e.g., thermal demand, outdoor temperature, intermittent RWH availability, electricity prices) over the prediction horizon.

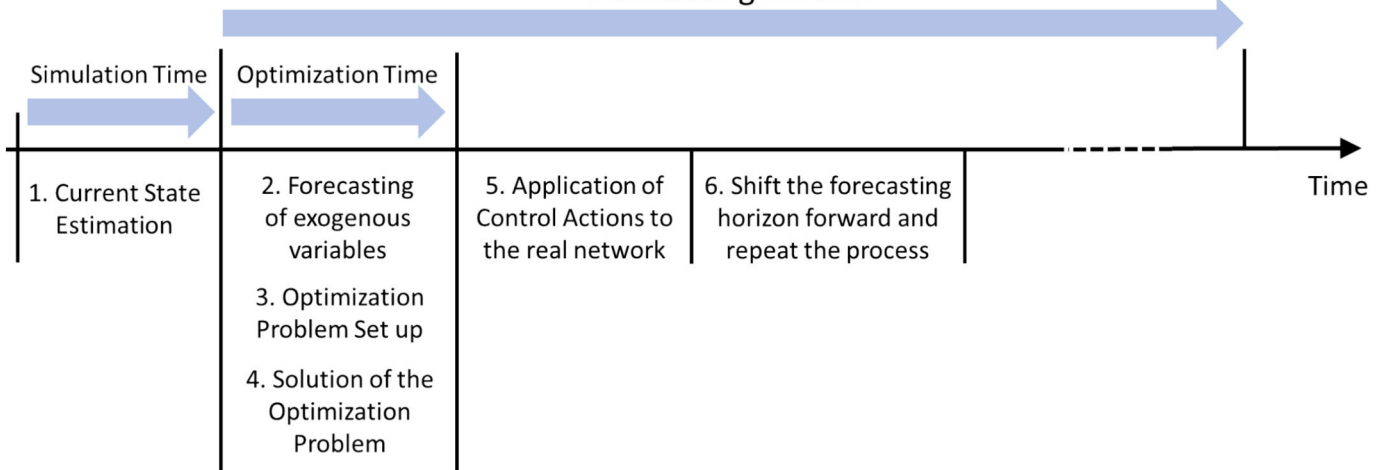
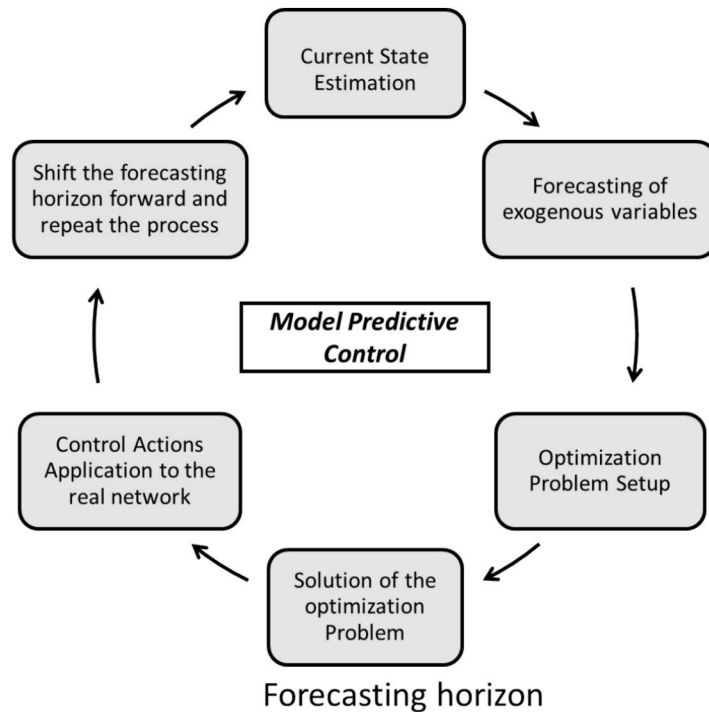


Fig. 3. MPC Cyclic Procedure and related Timeline.

3. Optimization Problem Setup

Formulation of a constrained optimization problem to minimize a target function (e.g., CO₂ emissions, cost of heat), based on:

- the predicted system behavior,
- forecasted exogenous variables, and
- system constraints (e.g., temperature and pressure limits).

4. Solution of the Optimization Problem

At each timestep, the solver computes the optimal sequence of control inputs over the time horizon. MPC applies only the first element of the optimized control sequence, as the optimization is re-evaluated at the next timestep using updated measurements and forecasts.

5. Control Actions Application to the real network

Application of the previously computed control actions to the real system.

6. Shift the forecasting horizon forward and repeat the process

The forecasting horizon is shifted forward and the process is repeated from Step 1.

Academic literature demonstrates that MPC can optimize several aspects of DH operation, including reducing heat production costs [135], minimizing total energy demand [136], lowering peak consumption [137], and improving the utilization of RWH sources [136,138]. For most applications, the forecasting horizon ranges between 6 and 24 h.

The computational efficiency of MPC is critical for its feasibility in real-time control applications. The time required to simulate the current network state and solve the optimization problem must be significantly lower than the forecasting horizon. Studies have shown that while MINLP-based MPC approaches offer broader applicability due to reduced parameter tuning, they are computationally expensive. NLP-based MPC methods, on the other hand, are 7–9 times faster and provide similar control performance [139]. Computational efficiency is particularly important for large systems, where real-time control is essential.

2.9. List of R-DH real-life operational requirements

The literature review carried out in the previous sections (Sections 2.1 to 2.8), allowed to identify and describe the technologies, measures and operating conditions currently adopted to achieve a R-DH. All the considered aspects can be summarized in a list of functional and operational abilities that a R-DH should possess.

1. Storing heat in central TES for both short and long-term storage
2. Adopting DR techniques for short-term flexibility
3. Exploiting the network as a thermal storage for short-term flexibility
4. Optimally control the heat production portfolio
5. Integrating heating plants considering different hydraulic attachments to the network
6. Reducing the operation temperatures
7. Optimally control the thermal production at heat sources by controlling both flow and supply temperature
8. Application of MPC for optimal control

3. Methodology

This chapter outlines the systematic approach adopted to evaluate district heating (DH) simulation tools for their ability to support the optimal operation of R-DH systems.

3.1. Overview of the Methodological approach

The methodology is structured into several phases:

- *Sources research.* In the beginning, a systematic search of academic sources, including research and review articles, was conducted across multiple scientific databases (e.g., Scopus, ScienceDirect, and others). The search strategy involved the use of keyword categories and Boolean operators to identify studies focusing on technologies, measures, and operating conditions that promote an increased share of renewable and waste heat (RWH) sources in the DH source mix. The search process was guided by key research topics, which are detailed in the “Selection and categorization of sources” section.
- *Definition of R-DH.* A renewable-district heating (R-DH) is defined as a DHN that is supplied with near-100 % RWH energy mix to satisfy the heating demand of residential (SH and DHW), non-residential and industrial customers.
- *Selection and categorization of sources.* The sources found were selected and categorized by research topic.
 - The research topics considered are:
 - Renewable and waste heat sources
 - Flexibility in DH
 - Seasonal thermal energy storage
 - Optimization of heat production portfolio
 - Hydraulic circuits for heating plants
 - Control strategies for heat production
 - Reduction of operating temperature levels
 - Model predictive control optimization

As the purpose of this work is to evaluate DH tools for the simulation of the optimal operation of R-DH, the selection of sources focused on 3GDH, and 4GDH which are currently the most widely implemented technologies. Nevertheless, sources addressing 5GDHC have been included for certain topics.

- *Identification of list of operational requirements for R-DH.* Based on the literature review, a list of functional and operational required for R-DH is identified.
- *Definition of criteria for DH simulation tools evaluation.* The criteria for evaluating DH tools are based on two key aspects:
 - Satisfaction of pre-requisites: the tool’s ability to simulate the quasi-dynamic operation of a DHN, including dynamic thermal modeling and steady-state hydraulic modeling (explained in Section 3.2).
 - The satisfaction of a R-DH specific modeling requirements: the tool’s ability to satisfy modeling requirements, such as TES integration and custom-scripting, that are directly derived from the list of abilities identified in the previous phase and summarized in Table 3.
- *DH tools’ selection.* An extensive online search, combined with the analysis of both review and research academic articles, was conducted to identify DH modeling tools for evaluation. Twelve tools were selected, representing a diverse range of commercial, educational, and freeware software to ensure a comprehensive assessment across different types of tools used in the field.
- *DH tools’ evaluation and comparison.* The selected tools were individually evaluated based on the defined criteria, focusing on their ability to simulate the optimal operation of R-DH systems. Following this evaluation, the tools were compared to identify their relative strengths and weaknesses. This comparative analysis provided the basis for deriving recommendations for researchers on tool selection and guidelines for tool developers to address existing gaps in simulation environments.

A detailed disclaimer regarding the variability and limitations of the reported information is provided in Section 4.2.

3.2. DH Tools’ evaluation criteria

This section outlines the evaluation criteria used to analyze DH simulation tools. The criteria are designed to assess the tools’ ability to simulate the optimal operation of R-DH systems. The evaluation

Table 3
Derivation of modeling requirements and implementation options from R-DH real-life operational requirements.

R-DH real-life Operational Requirement	Purpose	Modeling Requirements	Implementation Options
1. Storing heat in central TES for both short- and long-term storage	Maximize use of intermittent RWH sources (solar thermal, wind, PV + HP).	1. TES model analysis (with thermal stratification and thermal losses) 2. Control strategy for TES charging/discharging: a. Simple Rule-based; b. Complex Rule-based; c. MPC (custom scripting or co-simulation)	<ul style="list-style-type: none"> • TES model; • Conditional control; • Custom scripting; • Co-simulation;
2. Adopting DR techniques for short-term flexibility	Maximize use of intermittent RWH sources (solar thermal, wind, PV + HP).	1. TES modeling at consumer level (secondary side) 2. Building thermal model (secondary side) 3. DR control strategy: a. Simple Rule-based; b. Complex Rule-based; c. MPC (custom scripting or co-simulation)	<ul style="list-style-type: none"> • TES model; • Building thermal model; • Conditional control; • Custom scripting; • Co-simulation;
3. Exploiting the network as a thermal storage for short-term flexibility	Maximize use of intermittent RWH sources (solar thermal, wind, PV + HP).	1. Evaluate network "SOC" and transportation delay; 2. Control strategy for network charging/discharging: a. Simple Rule-based; b. Complex Rule-based; c. MPC (custom scripting or co-simulation)	<ul style="list-style-type: none"> • Quasi-dynamic modeling; • Temperature and pressure in pipes; • Conditional control; • Custom scripting; • Co-simulation;
4. Optimally control the heat production portfolio	Maximize overall integration of RWH sources, or minimize overall cost of heat production.	1. Embedded Merit Order control logic 2. User's implemented control strategy for heat sources: a. Simple Rule-based; b. Complex Rule-based; c. MPC (custom scripting or co-simulation) <u>Note:</u> Tools can support either one or both options.	<ul style="list-style-type: none"> • Integrated Merit Order control logic; • Conditional control; • Custom scripting; • Co-simulation;
5. Integrating heating plants considering different hydraulic attachments	Maximize efficiency or allow integration of intermittent RWH sources (solar thermal, wind, PV + HP). Meaningful for	Attach heat sources in RtR and StS configurations (alternative to standard RtS).	<ul style="list-style-type: none"> • Supported RtR, RtS, and StS hydraulic configuration for heat sources

Table 3 (continued)

R-DH real-life Operational Requirement	Purpose	Modeling Requirements	Implementation Options
6. Reducing operation temperatures	waste heat, solar thermal, HPs. Favor integration of low-temperature heat sources (RWH sources). Reduce distribution heat losses.	Possibility to import "load-files" for supply and return temperatures.	No specific implementation option. <u>Note:</u> All tools support import of load-files.
7. Optimally control the thermal production at heat sources by controlling both flow and temperature	Achieve optimal energy efficiency, cost reduction, and maximize RWH integration.	1. Rule-based control of both T_{sup} and \dot{V} 2. Optimization framework to determine the optimal combination of T_{sup} and \dot{V} (VF-VT) <u>Note:</u> Tools can support either one or both options.	<ul style="list-style-type: none"> • Quasi-dynamic modeling; • Temperature and pressure in pipes; • Conditional control; • Custom scripting; • Co-simulation;
8. Application of MPC for optimal control	Integrate intermittent RWH sources (solar thermal, wind, PV + HP). Forecasting and optimization of intermittent RWH sources, TES, network storage, DR.	1. Embedded modules for MPC application 2. Interface for co-simulation with external tools (MPC can be implemented) <u>Note:</u> Tools can support either one or both options.	<ul style="list-style-type: none"> • Integrated forecasting algorithms; • Integrated optimization algorithms; • Custom scripting AND/OR co-simulation supported;

framework is based on the real-life operational requirements of R-DH systems, which are linked to specific modeling requirements that the tools must fulfill. Table 3 provides an overview of the key operational requirements for R-DH systems (defined in Section 2.9), the motivations behind these requirements, the corresponding modeling needs, and the specific implementation options available for simulation tools. This table serves as a framework for understanding how real-life operational challenges in R-DH systems can be addressed in the evaluation of DH modeling tools.

3.2.1. Prerequisites

The evaluation considers the assessment of two fundamental prerequisites (P), which are necessary for any tool to be considered suitable for R-DH simulation:

P1: Quasi-dynamic simulation. The tool must support a quasi-dynamic modeling approach, which combines dynamic thermal modeling with steady-state hydraulic modeling. Dynamic thermal modeling is essential for capturing time-dependent phenomena such as temperature variations, heat losses, and transmission delays in the network. Steady-state hydraulic modeling is sufficient for simulating pressure and flow in the network, as transient hydraulic effects (e.g., water hammer or surge phenomena) are not relevant for thermal DH simulations.

Quasi-dynamic simulation is critical for enabling the evaluation of both network as a storage (Section 2.2) and VF-VT heat production control (Section 2.7). For network as a storage, quasi-dynamic simulation is required to model transmission delays and the dynamic behavior of temperature in the pipes, which are key to understanding the network's state of charge (SOC) and its ability to provide short-term flexibility. For VF-VT heat production control, quasi-dynamic simulation is necessary to capture the time-varying behavior of heat production and demand, ensuring that the system can respond dynamically to changes

in operating conditions.

P2: Calculation of time-dependent temperature and pressure in network's pipes. The tool must provide time-dependent simulation results for both temperature and pressure levels in the network. Accurate temperature calculations are necessary for modeling heat transmission delays, heat losses, and the effects of time-varying inputs such as consumer demand and heat production. Pressure calculations are essential for identifying hydraulic bottlenecks and determining the pumping energy required to operate distribution pumps.

This prerequisite is also essential for both network as a storage and heat production control scenarios. For network as a storage (Section 2.2), the calculation of time-dependent temperature and pressure is necessary to evaluate the thermal and hydraulic behavior of the network, including the distribution of stored heat and the feasibility of using the network as a storage system. For VF-VT heat production control (Section 2.7), these calculations are required to optimize energy efficiency and maximize the integration of renewable and waste heat (RWH) sources by accurately determining flow rates and temperature levels throughout the network.

3.2.2. Modeling requirements

The modeling requirements (MRs) are derived from the operational needs of R-DH systems and represent the specific capabilities that simulation tools must possess (Table 3). These requirements are:

MR1: TES Model. The tool must include a built-in TES model or allow user-defined TES models through custom scripting or co-simulation. The TES model should account for thermal stratification and thermal losses. TES models are essential for simulating both short-term storage for daily operation (Section 2.2) and long-term seasonal storage (Section 2.3).

MR2: Building Thermal Model. The tool must allow the integration of building thermal models to simulate the use of building thermal mass for direct demand response (DR) (Section 2.2). For large networks with many connected consumers, simple thermal models, such as RC models, are preferred to avoid excessive simulation times. For smaller networks, particularly in research applications, more detailed building thermal models can be used to achieve higher accuracy.

MR3: Conditional Control. The tool must support conditional control strategies, either through built-in functionality or user-defined scripting. Conditional control is based on "If + statement" logic, where specific actions are triggered when predefined conditions are met. This type of control is essential in various operational strategies in R-DH systems, including: TES charging and discharging strategies, direct DR, network as a storage, heat production control at plants, merit order control logic.

MR4: Custom-scripting. This refers to the ability of the user to access a programming environment (either integrated within the tool or external, such as Python or MATLAB) to define and implement control logic. Custom-scripting allows for the development of a wide range of control strategies, from simple conditional control "IF + statement" logic to more complex algorithms, such as optimization-based control. The tool must provide an API or similar interface to enable communication with external programming environments. It can be applied to TES management, direct DR implementation, use of the network as a storage, and optimization of the heat production.

MR5: Integrated Merit Order control logic. The tool must include an embedded merit order control logic to optimize the heat production portfolio. Merit order control is a standard strategy for prioritizing heat sources based on criteria such as cost, availability, and efficiency (Section 2.5). An embedded merit order control logic simplifies the implementation of this strategy, allowing users to quickly and efficiently optimize the integration of RWH sources. While advanced users can implement merit order control logic manually using conditional control (MR3) or custom-scripting (MR4), having it as an embedded feature ensures ease of use, standardization, and time efficiency.

MR6: Hydraulic Schemes for Plants. The tool must support the

integration of heating plants with different hydraulic schemes, such as return-to-supply (RtS), return-to-return (RtR), and supply-to-supply (StS) configurations (Section 2.5). These configurations are critical for optimizing the performance of various heat source in R-DH systems. For example, integrating a HP in an RtR configuration can significantly improve its coefficient of performance (COP). Additionally, the tool must support Customer-side Hydraulic Connections (CHC), such as HPs located on the customer side, which are typical of 5GDHC networks. To model such decentralized configurations, the tool must allow for the simulation of the secondary side (behind the district heating substation), enabling the representation of customer-side components and their interaction with the primary network.

MR7: Integrated Forecasting and Optimization Algorithms. The tool must include built-in forecasting and optimization algorithms to support model predictive control (MPC) strategies (Section 2.8). These algorithms are essential for forecasting time-varying inputs, such as consumer demand and renewable heat availability, and for optimizing the operation of R-DH systems in real time. The availability of built-in forecasting and optimization algorithms simplifies the implementation of MPC and reduces the need for external tools or custom development.

MR8: Co-Simulation. This refers to the coupling of two or more simulation tools to model different subsystems or components. Each tool runs its own simulation engine, and they exchange data during runtime, often using standardized protocols like FMI/FMU. Co-simulation can be used for tasks that require specialized tools, such as simulating detailed TES models or building thermal models (Sections 2.2, 2.3), or for integrating external forecasting and optimization tools to perform MPC logic (Section 2.8). Unlike custom-scripting (MR4), which focuses on implementing control logic within a single programming environment, co-simulation involves the integration of multiple simulation tools to model different aspects of the system.

MR9: Heat Production Control (VF-VT). The tool must support the simulation of heat production control strategies at plants with variable flow and variable temperature (VF-VT), enabling dynamic boundary conditions for these parameters. It should also allow rule-based control based on system conditions, such as heating demand or weather. Optimization of \dot{V} and T_{sup} can be implemented through custom scripting (MR4) or co-simulation (MR8), provided the tool supports quasi-dynamic modeling (P1), time-dependent temperature and pressure calculations (P2), and conditional control (MR3).

Support is considered **complete (CS)** if the tool allows dynamic adjustment of both T_{sup} and \dot{V} and supports optimization frameworks natively or via custom-scripting or co-simulation. **Partial (PS)** is defined as the tool allows dynamic adjustment of T_{sup} and \dot{V} only through rule-based control. **No support (NS)** is assigned if the tool does not allow dynamic adjustment of T_{sup} and \dot{V} .

4. Results

This section presents the evaluation of district heating (DH) simulation tools in the context of their ability to support the operational requirements of renewable district heating (R-DH) systems. Section 4.1 introduces the 12 selected tools, providing details about their developers, licensing models, and key references. Section 4.2 discusses the evaluation of these tools based on the defined prerequisites and modeling requirements.

4.1. List of considered DH tools

This section presents the software tools considered. The 12 software tools evaluated and the respective sources are reported in Table 4.

4.2. DH tools evaluation

The results of the DH tools evaluation are reported in Table 5 and

Table 4
List of evaluated DH tools.

No	Software Name	Developer	License	Sources
1	Fluidit Heat	Fluidit Oy	Commercial, educational	[140,27]
2	Leanheat Network	Danfoss A/S	Commercial, educational	[141,142]
3	Dymola	Dassault Systemes	Commercial, educational	[143,144,145]
4	SIR 3S	3SConsult	Commercial	[146]
5	STANET	Fischer-Uhrig Engineering GmbH	Commercial, educational	[147,148]
6	AD Net Heat	Fraunhofer-Institut für Techno-und Wirtschaftsmathematik ITWM – Kaiserslautern	Commercial, educational	[149]
7	Pandapipes	Fraunhofer Institute for Energy Economics and Energy System Technology (IEE), Kassel	Open source	[150,151]
8	TRNSYS	Solar Energy Laboratory (SEL), University of Wisconsin	Commercial, educational	[152,27]
9	Polysun	Vela Solaris AG	Commercial, educational	[153]
10	nPro	nPro Energy	Commercial, academic	[154,155]
11	ROKA³	RZVN Wehr GmbH	Commercial, educational	[156,157]
12	SimScape	The MathWorks, Inc.	Commercial, educational	[158]

Table 5
DH tools Evaluation – Prerequisites.

Software Name	P1. Dynamic Thermal Behavior	P2. Calculation of time-dependent pressure and temperature
Fluidit Heat	✓	✓
LeanHeat Network	✓	✓
Dymola	✓	✓
SIR 3S	✓	✓
STANET	×	✓
AD-Net Heat	✓	✓
Pandapipes	×	✓
TRNSYS	✓	✓
Polysun	✓	✓
nPro	×	✓
ROKA ³	✓	✓
SimScape (Matlab)	✓	✓

Legend:

✓	Satisfied
×	Not Satisfied

Table 6. Table 5 reports the tools evaluation with respect to Prerequisites P1 and P2. Table 6 reports the DH tools evaluation with respect to Modeling Requirements (MR1 to MR9).

Disclaimer: The capabilities and features of the tools reported in this section are based on a combination of publicly available information and, where applicable, direct access to licenses and documentation, and direct information exchange with tools' developers. These capabilities may vary depending on the specific version, configuration, or licensing options of the tool. While every effort has been made to ensure the accuracy and completeness of the information presented, the authors cannot guarantee that all details are up-to-date or exhaustive. Readers are encouraged to consult the official documentation or contact the

software providers for the most current and accurate information.

Fluidit Heat is a district heating network (DHN) simulation tool developed by Fluidit Oy [140]. The software is equipped with a Graphical User Interface (GUI), which facilitates user-friendly modeling and analysis of DH systems. The tool includes a built-in sensible TES model, consisting of 10 horizontal layers, where water movement is modeled using a plug-flow approach. Users can define the total storage volume and specify either the height or diameter of the tank, with the other dimension automatically constrained. Heat losses through the tank's envelope are calculated based on a user-defined heat loss coefficient $[W/(m^2K)]$, and heat transfer between stratified sections is modeled using a heat transfer coefficient. These features make Fluidit Heat suitable for simulating both short-term and long-term TES scenarios.

The tool supports conditional control through a non-physical scenario component called Control Station, which allows users to define rule-based control strategies. Additionally, custom-scripting is supported via Control Station, enabling users to implement control logic in EPANET, Python [159], JavaScript [160], and Ruby [161]. This functionality can be used to simulate direct DR scenarios, such as the use of decentralized TES or building thermal mass as a virtual TES. Custom-scripting also allows users to implement advanced control strategies, such as forecasting and optimization algorithms for model predictive control (MPC). The tool includes an embedded merit order control logic, called "Production Plans", allowing users to optimize the heat production portfolio by prioritizing heat sources based on cost.

Fluidit Heat provides support for alternative hydraulic connections for heating plants, including return-to-return (RtR) and supply-to-supply (StS) configurations, which can be implemented using the Heat Exchanger object. While the tool does not include built-in forecasting and optimization algorithms, users can implement these functionalities externally using custom-scripting in Python. Information about co-simulation capabilities and building thermal models was not found.

Leanheat Network is a thermo-hydraulic modeling tool developed by Danfoss A/S [142] for district heating (DH) systems. The software is equipped with a GUI for user-friendly modeling and analysis. The tool includes a built-in sensible TES model with 2 horizontal layers. The total volume is the only geometrical parameter defined, and heat losses are modeled using a user-defined heat loss coefficient. An internal heater can also be installed in the tank. The tool does not support building thermal models, as the system boundaries are limited to the primary side of the DH substation. Conditional control is supported through the "Conditional Control" feature, which allows users to define rule-based control strategies. A software-specific language with built-in functions enables custom-scripting, though the scripting environment is embedded and limited compared to external programming environments. The tool includes an embedded merit order control logic, called "Production Plan", allowing users to optimize the heat production portfolio by prioritizing heat sources based on cost. RtR and StS configurations can be implemented using the "Heater" object. The tool supports cyclic simulations, that include real-time measurements for digital model validation, an embedded forecaster for thermal power demand, and an embedded cost-optimizer for adjusting temperature and pressure levels. Co-simulation with external tools and interfaces for external programming languages are not supported.

Dymola is a multi-domain programming environment for the Modelica language, equipped with a GUI [144]. The tool supports detailed modeling and simulation across various domains. The tool provides pre-built sensible, latent, and chemical TES models (MR1) as well as pre-built building thermal models (MR2) through Modelica-based libraries. These libraries include:

- EnergySystems Library [162]
- Modelica Buildings Library [163]
- IBPSA Library [164]
- AixLib [165]

Table 6
DH tools Evaluation – Modeling Requirements.

Software Name	MR1. TES Model	MR2. Building Thermal Model	MR3. Conditional Control	MR4. Custom-Scripting	MR5. Integrated Merit Order control logic	MR6. Hydraulic Schemes for Plants	MR7. Integrated Forecasting and Optimization Algorithms	MR8. Co-Simulation	MR9. Heat Production Control (VF-VT)
Fluidit Heat	✓ (BI); S (10Nodes); CuSc	×	✓	✓	✓	✓ (BI); RtS; RtR; StS; No CHC	×	×(?)	CS
LeanHeat Network	✓ (BI); S (2Nodes)	×	✓	✓ (embedded – limited)	✓	✓ (BI); RtS; RtR; StS; No CHC	EF; EO	×	PS
Dymola	✓ (BI); S, L, C; CuSc; CoSi	✓	✓	✓	×	✓ (IbU); RtS; RtR; StS; CHC	×	✓	CS
SIR 3S	✓ (BI); S	×	✓	✓	×	✓ (BI); RtS; RtR; StS; No CHC	×	×(?)	CS
STANET AD-Net Heat	×	×	✓	✓	×	Not evaluated for the lack of quasi-dynamic simulation ✓ (IbU); RtS; RtR; StS; No CHC	×	×(?)	CS
Pandapipes TRNSYS	✓ (BI); S, L, C; CuSc; CoSi	✓	✓	✓	×	Not evaluated for the lack of quasi-dynamic simulation ✓ (IbU); RtS; RtR; StS; CHC	×	✓	CS
Polysun	✓ (BI); S (12Nodes), L; CuSc; CoSi	✓	✓	✓	×	✓ (IbU); RtS; RtR; StS; CHC	×	×(?)	PS
nPro ROKA ³	×	×	✓	✓ (embedded – limited)	×	Not evaluated for the lack of quasi-dynamic simulation ✓ (IbU); RtS; RtR; StS; No CHC	×	×(?)	PS
SimScape (Matlab)	✓ (IbU)	×	✓	✓	×	✓ (IbU); RtS; RtR; StS; CHC	×	✓	CS

Legend:

✓	Available
×	Not Available
BI	Built-In
CHC	Consumer-side Hydraulic Connection Supported
C	Chemical TES
CS	Complete Support
CoSi	Co-Simulation Supported
CuSc	Custom Scripting Supported
EF	Embedded Forecaster
EO	Embedded Optimizer
IbU	Implementable by User
L	Latent TES
No CHC	Consumer-side Hydraulic Connection Not Supported
NS	Not Supported
PS	Partial Support
RtR	Return-to-Return
RtS	Return-to-Supply
S	Sensible TES
StS	Supply-to-Supply
UD	Under Development

- IDEAS Library [166]

Users can adapt the parameters of pre-built models to tailor them to specific applications. Additionally, Modelica-library developers can create custom components for TES and building thermal simulation. Conditional control (MR3) is supported through the Modelica language, which allows users to define rule-based control strategies. Custom-scripting (MR4) is enabled via Modelica, allowing users to develop advanced control strategies and tailor models to their needs. The tool does not include an embedded merit order control logic (MR5). RtS, RtR, and StS configurations are supported (MR6), as users can freely define the hydraulic connections of heating plants. Dymola does not include a pre-built module for forecasting and optimization algorithms (MR7). However, co-simulation enables the integration of external tools, such as MATLAB [167], Python [159], JModelica.org [168], or Julia [169], to develop and execute model predictive control (MPC) algorithms. While

Dymola excels in compiling and simulating models, its optimization capabilities are limited. Co-simulation capabilities (MR8) are supported through the Functional Mock-up Interface (FMI) standard [170], which allows model exchange and integration with external tools, or via the Dymola-specific dydosim executable file.

SIR3S is a hydraulic modeling software developed by 3SConsult [146]. The tool is equipped with a GUI and supports steady-state, quasi-dynamic, and dynamic simulation of water networks, heating and cooling networks, and gas networks. The tool includes two types of built-in sensible TES models: a simple model based on energy balance and a more detailed model capable of simulating thermal stratification inside the TES tank [171]. Direct DR scenarios can be simulated by modeling a secondary-side loop connected to the primary DH network via a heat exchanger. A building thermal model and user-specified TES model can also be defined using the Python interface [172], though the scalability of such custom definitions is challenging to evaluate. Conditional

control is supported through event-based control strategies, and custom-scripting is enabled via the Python interface [172], allowing users to implement advanced control strategies, including forecasting and optimization algorithms for model predictive control (MPC). RtR and StS configurations can be simulated using the Heat Exchanger object. The tool does not include embedded merit order control logic or built-in forecasting and optimization algorithms, but these functionalities can be implemented externally using the Python interface. Co-simulation capabilities are not supported, limiting the tool's ability to integrate with external simulation tools.

STANET is a software package developed by Ingenieurbüro Fischer-Uhrig [148] for the stationary and dynamic calculation of utility networks, including gas, water, electricity, sewage, and district heating. This analysis focuses exclusively on its district heating capabilities. The tool simulates subsequent network states as consecutive thermo-hydraulic equilibrium states, using a quasi-static approach. As a result, STANET does not support quasi-dynamic simulation, which is a prerequisite for this evaluation. Therefore, the nine modeling requirements are not examined.

AD-Net Heat is a district heating network (DHN) simulation tool developed by the Fraunhofer Institute for Industrial Mathematics ITWM, based in Kaiserslautern [149]. The tool can be operated either through its GUI or by setting boundary conditions in a Python script for execution. The tool does not currently include a built-in TES model (MR1), although this feature is under development. Information about the integration of building thermal models (MR2) is not available. Conditional control (MR3) and custom-scripting (MR4) may potentially be implemented by defining user-specific subroutines in Python [159]. These capabilities could allow for the simulation of direct demand response (DR) scenarios and event-based control, although this functionality has not been explicitly verified. The tool does not include an embedded merit order control logic (MR5). RtR and StS configurations are supported (MR6). The Python interface appears to provide the flexibility required to apply forecasting and optimization algorithms (MR7) through user-defined routines, including model predictive control (MPC). However, further investigation or testing is required to confirm the full extent of these functionalities. Information about co-simulation capabilities (MR8) is not available.

Pandapipes is a Python-based open-source tool for fluid system modeling, analysis, and optimization, developed by the Fraunhofer Institute for Energy Economics and Energy System Technology (IEE), Kassel [150]. The tool simulates subsequent network states as consecutive thermo-hydraulic equilibrium states, using a quasi-static approach [18]. As pandapipes does not support quasi-dynamic simulation, which is a prerequisite for this evaluation, the nine modeling requirements are not examined.

TRNSYS is a transient system, multi-domain simulation program with a modular structure, developed by the Solar Energy Laboratory at the University of Wisconsin-Madison [173]. The tool is equipped with a Graphical User Interface (GUI) and supports detailed transient simulations across various domains. The tool provides pre-built models of sensible, latent, and chemical TES (MR1) through the TESS Libraries [174], which are available as add-ons. These models allow for detailed simulation of TES systems. Additionally, users can customize built-in TES models or create new ones by writing custom scripts in Fortran or integrating TRNSYS with external tools. The simulation of building thermal models (MR2) is supported through built-in models such as Type 19 (a single-zone model) and Type 56 (a detailed multi-zone model) [[175,176]]. These models enable the simulation of direct DR scenarios, including the use of buildings as virtual TES. Conditional control (MR3) is supported through the modular structure of TRNSYS, which allows users to define rule-based control strategies. Custom-scripting (MR4) is also possible by writing custom code in Fortran or by integrating TRNSYS with external tools for advanced control strategies. The tool does not include an embedded merit order control logic (MR5). RtS, RtR, and StS configurations are supported (MR6), as the user

can freely define the hydraulic connections of heating plants. TRNSYS does not have a built-in module for forecasting and optimization algorithms (MR7). However, it can be coupled in co-simulation (MR8) with external tools such as MATLAB/Simulink [[167,177]] via Type 155 or Python [159], where model predictive control (MPC) algorithms can be performed [[178,179]].

Polysun is an energy modeling software tool developed by Vela Solaris [153] for designing systems for buildings and districts. The tool is equipped with a GUI that allows users to design and customize hydraulic circuits by connecting components. The tool includes latent and sensible TES models (MR1), with the latter represented using 12 horizontal layers. Users have access to a large library of TES types, enabling customization of parameters such as dimensions, insulation properties, and port connections. Custom TES models can also be defined using Polysun Designer. Polysun provides a pre-built single-zone building thermal model (MR2), which allows users to configure inputs such as building geometry, shading, thermal mass (as a lumped capacity), insulation properties, ventilation, and internal gains. This enables the simulation of direct DR scenarios using the building's thermal mass. However, the underlying building equations are not accessible or modifiable by the user. Conditional control (MR3) is supported through the tool's graphical interface, which allows users to define rule-based control strategies. Custom-scripting (MR4) is enabled via the Plugin Controller, which supports programming languages such as Java [180], Python [159], and MATLAB [167]. This functionality allows users to implement advanced control strategies, including forecasting and optimization algorithms for model predictive control (MPC). The tool does not include an embedded merit order control logic (MR5). RtS, RtR, and StS configurations are supported (MR6), and users can freely design hydraulic circuits for heating plants. Polysun does not include a pre-built module for forecasting and optimization algorithms (MR7). However, users can implement MPC algorithms by coupling Polysun with external tools via co-simulation (MR8). Co-simulation is supported with tools such as MATLAB/Simulink [[167,177]] and Python [159]. Data exchange can be achieved through file-based methods, such as CSV files in the standard version, or through the Plugin Controller [181]. Users have reported that Polysun simulations may experience slow runtimes or failures when modeling large-scale DHNs with many pipes or customers. The exact threshold is undocumented and likely depends on network complexity and available computational power.

nPro is a planning tool for buildings and districts developed by nPro Energy [154]. It is designed to support the dimensioning of pipe diameters in district heating networks (DHNs) and uses energy balances to model network components [155]. The tool performs quasi-static simulations by sequentially modeling hydraulic and thermal behavior [18]. Due to the lack of dynamic temperature calculations, nPro does not support quasi-dynamic simulation, which is a prerequisite for this evaluation. Therefore, the eight modeling requirements are not examined.

ROKA³ is a district heating network (DHN) planning and simulation tool developed by RZVN Wehr GmbH [156]. The tool is equipped with a GUI for network modeling and analysis. The tool does not include a TES model (MR1). Information about the integration of building thermal models (MR2) is not available. Conditional control (MR3) is supported through event-based control, and custom-scripting (MR4) is enabled using a syntax derived from the EPANET rule description language [[157,18]]. The tool also provides mathematical and logical functions and operators to define custom rules or attributes for network components [157]. The tool does not include an embedded merit order control logic (MR5). RtS, RtR, and StS configurations are supported (MR6), allowing users to simulate various hydraulic connections for heating plants. The simulation of direct DR scenarios and the application of forecasting and optimization algorithms (MR7) are hindered by the absence of an interface to external tools. Co-simulation capabilities (MR8) are not supported. System boundaries in ROKA³ include both the primary and secondary sides of the DH substation [18].

Simscape is a Matlab-based simulation software tool developed by The MathWorks, Inc. [158]. It enables the modeling of physical systems within the Simulink environment by integrating physical component models, based on physical connections, with block diagrams and other modeling paradigms. The tool does not include pre-built TES models (MR1). However, it provides built-in components for modeling sensible TES systems, such as thermal masses and various heat transfer blocks, available in the Simscape Foundation Library [182] and Simscape Thermal Library [183]. Advanced users can implement their own TES models, though this requires significant expertise and effort. Dedicated building thermal models (MR2) are not included, but simplified building thermal dynamics can be modeled using components such as thermal masses and heat transfer processes. Simscape can also be integrated with external building simulation tools, such as EnergyPlus [184], TRNSYS [173], and carnotUIBK [185], enabling the simulation of direct DR scenarios that incorporate the building's thermal mass. Conditional control (MR3) is supported through Simulink's block diagram modeling environment, which allows users to define rule-based control strategies. Custom-scripting (MR4) is enabled via Matlab and Simulink, allowing users to implement advanced control strategies, including forecasting and optimization algorithms. The tool does not include an embedded merit order control logic (MR5). RtS, RtR, and StS configurations are supported (MR6), as users can design hydraulic circuits by connecting components. Simscape does not include a built-in module for forecasting and optimization algorithms (MR7). However, it can be integrated with Matlab's Model Predictive Control Toolbox [186], which provides pre-built tools for designing and deploying MPC algorithms. Additionally, users can program custom MPC algorithms in Matlab or Simulink [167,177], enabling the definition of tailored optimization problems. Co-simulation capabilities (MR8) are supported, as Simscape can be integrated with external tools such as EnergyPlus, TRNSYS, and carnotUIBK, enabling advanced multi-domain simulations.

5. Discussion

This section discusses the findings from the evaluation of DH simulation tools. Section 5.1 highlights the key insights from the evaluation, providing recommendations for researchers based on the strengths and limitations of DH-dedicated and Non-DH-dedicated tools. Section 5.2 outlines guidelines for tool developers, emphasizing areas for improvement to better support the modeling and simulation of R-DH systems.

5.1. Key findings and recommendations for researchers

The tools' evaluation allowed to identify two distinct macro-categories:

- DH-dedicated tools (Fluidit Heat, Leanheat, ROKA³, SIR3S, ADNet Heat). These are tools specifically designed to model and simulate DHNs.
- Non-DH-dedicated tools (Dymola, TRNSYS, Polysun, SimScape). These tools can simulate a variety of systems, including thermal systems, but are not inherently specialized for DHNs modeling.

DH-Dedicated Tools. Among DH-dedicated tools, Fluidit Heat and SIR3S stand out for their detailed multi-nodes TES models, which include heat losses and thermal stratification, making them suitable for researchers focusing on seasonal TES studies. Leanheat Network offers a simplified TES model consisting of only two nodes, which may suffice for basic applications but is less suitable for detailed TES studies. ROKA³ lacks a TES model entirely, limiting its applicability for TES-related research, while for ADNet Heat a TES model is currently under development. None of the DH-dedicated tools include pre-built building thermal models, which restricts their ability to simulate direct DR scenarios or decentralized configurations. Fluidit Heat and Leanheat

Network are the only tools with embedded merit order control logic, making them suitable for heat production portfolio optimization. Leanheat Network is also the only tool with embedded forecasting and optimization frameworks, which makes it a strong candidate for researchers focusing on predictive control and optimization. In terms of custom-scripting, Fluidit Heat and SIR3S provide APIs for external programming languages, offering a higher level of freedom and customization, while Leanheat Network and ROKA³ are limited to tool-specific embedded programming languages, which may restrict flexibility for advanced modeling.

Researchers who prioritize flexibility and customization in their studies should consider using Fluidit Heat or SIR3S, as these tools provide APIs for external programming languages and detailed TES modeling capabilities.

Researchers focusing on direct DR scenarios or decentralized configurations should consider using Non-DH-dedicated tools, as DH-dedicated tools lack building thermal modeling and secondary side modeling capabilities.

Non-DH-Dedicated Tools. Non-DH-dedicated tools, such as Dymola, TRNSYS, Polysun, and SimScape, are highly versatile and capable of simulating a variety of systems, including thermal systems. While they are not inherently specialized for DHN modeling, they offer significant advantages in terms of flexibility, customization, and multi-domain modeling. Dymola, TRNSYS, and Polysun provide robust TES modeling capabilities, including sensible, latent, and chemical TES models, making them ideal for researchers investigating advanced TES configurations or seasonal TES. These tools also include pre-built building thermal models, enabling the simulation of direct demand response scenarios using the building's thermal mass. TRNSYS, Polysun, and Simscape support modeling of the secondary side (customer side), which is essential for simulating decentralized heat sources and 5GDHC networks. Dymola and Simscape excel in flexibility and customization, allowing users to create their own components and integrate external tools (e.g., MATLAB, Python) via co-simulation. TRNSYS and Polysun also provide significant customization options, but their interfaces are more user-friendly, making them accessible to a broader range of users.

Researchers requiring freedom in customization and access to detailed modeling of TES and building thermal dynamics should prioritize Dymola or TRNSYS, especially for studies focusing on the secondary side and decentralized configurations.

For researchers focusing on multi-domain modeling or integrating DHNs with other energy systems, Simscape is a strong candidate due to its co-simulation capabilities and flexibility. For researchers who value user-friendly interfaces and good customization options, Polysun and TRNSYS are recommended.

In summary, the choice of a simulation tool should align with the specific research focus. DH-dedicated tools are ideal for network-specific studies due to their user-friendly interfaces and built-in components, while Non-DH-dedicated tools offer greater flexibility for multi-domain modeling and advanced configurations. Researchers should weigh the trade-offs between accessibility and customization to select the tool that best meets their needs.

5.2. Guidelines for tools development

DH-Dedicated Tools. DH-dedicated tools are primarily designed for network operators and researchers, serving as essential platforms for modeling and simulating DHNs. While these tools are generally user-friendly and equipped with built-in components, several gaps have been identified:

1. Enhance TES models

Some DH-dedicated tools lack TES models or provide oversimplified versions (e.g., 2-node models). Developers should prioritize the inclusion of detailed TES models that account for heat losses and thermal stratification.

2. Incorporate secondary side modeling
The ability to model the secondary side (customer side) is essential for simulating direct demand response (DR) scenarios and decentralized configurations, such as customer-side hydraulic connections (CHC) in 5GDHC networks.
3. Support VF-VT control
While some tools provide complete support for VF-VT control, some DH-dedicated tools do not support dynamic optimization of both flow and temperature. Developers should focus on enabling VF-VT control through built-in optimization frameworks or enhanced co-simulation capabilities, which would allow for advanced operational strategies and temperature control optimization.
4. Expand Custom-control capabilities
Custom-scripting is often limited to embedded programming languages in some DH-dedicated tools, which restricts flexibility for advanced users. Providing APIs for external programming languages (e.g., Python, MATLAB) would significantly enhance the customization options for researchers and advanced users and offer the possibility for new features and relative testing by users and developers.
5. Integrated merit order control logic
While some tools, such as Leanheat Network and Fluidit Heat, include embedded merit order control logic, this feature is not universally available. Adding this functionality to more tools would benefit users who prioritize accessibility and need to optimize heat production portfolios without relying on custom-scripting.

Non-DH-Dedicated Tools. Non-DH-dedicated tools are designed for broader applications and are not inherently specialized for DHN modeling. While their flexibility and multi-domain capabilities make them highly valuable for advanced research, there are areas where improvements could make them more accessible and better suited for DH-specific studies.

1. Improve Accessibility
Non-DH-dedicated tools often require significant expertise to be set up and to be used effectively, which can be a barrier for less experienced users. Developers could consider providing pre-built modules (e.g., pipes, heat exchanges, pumps) and templates for common DHN configurations.
2. Enhance Import Functionalities
Many DHN researchers and operators rely on GIS or CAD data for network design and analysis. Adding robust import functionalities for these file types would make Non-DH-dedicated tools more practical for DHN modeling and reduce the time required for data preparation.

It is important to recognize that Non-DH-dedicated tools are designed for a wide range of applications, and achieving DH-specific user-friendliness may not always align with their broader purpose. However, targeted improvements in accessibility and import functionalities could make these tools more attractive to DH researchers without compromising their versatility.

6. Conclusions

This work presented a comprehensive evaluation of district heating (DH) simulation tools, focusing on their ability to support the operational requirements of renewable district heating (R-DH) systems. These requirements include the use of thermal energy storage (TES) for various timescales, leveraging building thermal mass for direct demand response (DR) scenarios, and implementing advanced control strategies such as model predictive control (MPC) and variable flow-variable temperature (VF-VT) control. Twelve DH simulation tools were evaluated and compared based on modeling requirements directly derived by the real-life operational abilities of R-DH. The evaluation aimed to guide

researchers and network operators in selecting appropriate tools and to provide guidelines for tool developers to address existing gaps.

The evaluation revealed that DH-dedicated tools are well-suited for network-specific studies and practical applications due to their user-friendly interfaces, built-in components, and the ability to simulate large DHNs. However, they often lack advanced features such as detailed TES models, secondary side modeling, and full support for VF-VT control, which limits their applicability for studies on direct DR scenarios, customer-side hydraulic connections (CHC), and advanced operational strategies. Researchers who prioritize network calculations and require accessible tools with moderate customization options are recommended to use Fluidit Heat or SIR3S, which offer detailed TES modeling and APIs for external programming languages. Leanheat Network offers embedded functionalities, such as merit order control logic and forecasting/optimization frameworks, which enhance accessibility for users who cannot or prefer not to implement custom controls.

Non-DH-dedicated tools, such as Dymola, TRNSYS, Polysun, and Simscape, provide greater flexibility and customization, making them ideal for research-oriented applications. These tools excel in modeling TES, building thermal dynamics, and secondary side configurations, enabling the simulation of direct DR scenarios and customer-side hydraulic connections (CHC) such as heat pumps installed at the customer side in 5GDHC networks. Researchers requiring freedom in customization and detailed modeling of TES and building thermal dynamics are recommended to use Dymola or TRNSYS, especially for studies focusing on the secondary side. For multi-domain modeling or integrating DHNs with other energy systems, Simscape is a strong candidate due to its co-simulation capabilities.

The evaluation also identified key areas for tool development. For DH-dedicated tools, developers should focus on enhancing TES models, incorporating secondary side modeling, supporting VF-VT control, expanding custom-scripting capabilities, and ensuring that merit order control logic is universally available. For Non-DH-dedicated tools, improving accessibility through pre-built modules and templates for DHN configurations, as well as enhancing import functionalities for DH-specific data, would make these tools more practical for DH researchers while maintaining their versatility for broader applications.

In conclusion, the choice of a simulation tool depends on the specific research focus. DH-dedicated tools are ideal for network-specific studies and practical applications of existing networks, while Non-DH-dedicated tools are better suited for advanced research requiring flexibility and multi-domain modeling. By addressing the identified gaps, tool developers can better meet the evolving needs of researchers and network operators, ultimately supporting the transition to more efficient and sustainable R-DH systems.

Declaration of generative AI use and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used the General ChatBot GPT4o of the “Academic AI of the University of Innsbruck”, which is an AI system based on OpenAI’s ChatGPT. The use has been limited to rephrasing text to improve clarity and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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CRediT authorship contribution statement

Luca Vittorio Valentini: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Sandra Forndran:** Writing – review & editing, Methodology, Conceptualization. **Fabian Ochs:** Writing – review & editing, Methodology, Conceptualization. **Alexander Thür:** Supervision, Methodology, Conceptualization. **Wolfgang Streicher:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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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