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Hydrothermal challenges in low-temperature networks with distributed heat pumps

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ABSTRACT

Low-temperature networks (≤60 °C) combined with heat pumps allow for efficient heating and cooling of buildings and thermal energy exchange between buildings. Thus, such networks are a key technology to reduce the carbon footprint of urban areas. However, they are far more complex in operation than traditional district heating networks at high temperatures (>60 °C). To simplify future network planning, we present various challenges of low-temperature networks and offer solutions. We study the dependency of heat pump efficiencies on flow rates across the evaporator and present methods to cope with flow variations through heat pumps during operation. We introduce the concept "agent authority" and show that for an agent authority >≈0.7, flow variations during dynamic operation are within ≈20%. In a first case study, the total electricity consumption of a thermal network is minimised by reducing the flow rates through the heat pumps by ≈ 14%, however having only minor impact (0.3%) on the total electricity consumption. In a second case study, a decision matrix for selected network types is developed. We show that apart from quantifiable parameters such as energy efficiency or costs, qualitative criteria such as control and resilience are relevant in decision making.

1. Introduction

On a global scale, cities are responsible for 71%–76% of CO_2 emissions and between 67% and 76% of global energy use, as per United Nations (UN) estimates [1]. Energy consumption is expected to rise further as more than two-thirds of the world population are expected to live in an urban area by 2050. A combination of population growth and migration from rural areas is expected to add another 2.5 billion to the population of cities [1]. As a result, the rise in energy demand in high-density urban areas will pose enormous challenges to existing and future energy systems. Successful energy distribution management could play a pivotal role in sustainable development [2].

District heating and cooling systems (DHCS)s are generally more efficient at providing heating and cooling in urban areas than stand-alone systems [3] and can be a promising solution for meeting the growing demand for smart and sustainable cities [4,5]. However, traditional district heating systems offer poor prospects at integrating renewable energy sources or waste heat while also being prone to considerable thermal losses due to their high network temperatures. Reducing operating temperatures accompanied by higher system efficiency characterised each generational leap in district heating and cooling systems [6–8]. The 4th generation DHCSs, working at temperatures close to 60 °C, offer potential in waste heat recovery but are limited to waste heat or renewable heat with large temperatures, e.g. from industrial processes [9]. When the temperature is reduced to below 60 °C, more of the low-temperature renewable thermal energy sources like large-scale solar thermal and geothermal energy can be integrated, and more low-grade waste heat can be recovered [10]. The system may also provide cooling with decreasing network temperatures, which becomes increasingly relevant with climate warming [11–15]. At network temperatures below 60 °C, heat pumps are required to provide domestic hot water, and, at network temperatures below 30 °C, heat pumps must upgrade the thermal energy also for space

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Nomenclature

Abbreviations *(SI Units)*

AA	Agent authority,
BN	Bidirectional network
CN	Classical network
COP	Coefficient of performance,
COP_{Car}	Coefficient of performance of the Carnot cycle,
DHCS	District heating and cooling system
RN	Reservoir network
VA	Valve authority

Variables

C	Hydraulic resistance, Pa m^{-6} s^2
E	Electricity consumption, J
n	Number of buildings,
p	Pressure, Pa
P	Electric power, W
Q	Thermal energy, J
Q′	Thermal power, W
T	Temperature, K
v	Velocity, m s^{-1}
V′	Volume flow, m^3 s^{-1}

Parameters

c	Wave speed, m s^{-1}
η	Effectiveness of the heat pump,
ρ	Density, kg m^{-3}

Sub- and Superscripts

A	agent
con	condenser
CP	circulation pump
D	design
el	electric
eva	evaporator
exp	experiment
HP	heat pump
in	inflow
out	outflow
PL	partial load
R	remaining section
r	reference
OC	optimised control
tot	total
V	valve
VR	remaining section without the valve

heating. Thermal networks below 60 °C are the focus of this work and are simply called low-temperature networks here [16]. Other terms like “ultra-low-temperature networks” [17,18] or “5th generation district heating and cooling networks” [4,19] are avoided as there is no internationally agreed terminology [20].

Heat pumps and chillers allow for the electrification of the heating and cooling sector. By linking the heating and cooling sector to the power network, low-temperature networks allow cross-sector synergies to be identified and optimisations to be developed, which would not be otherwise possible within individual sectors [21]. The enormous challenge of decarbonizing the heating and cooling sector requires technological progress and systemic innovation. This paper tries to address the challenges occurring in low-temperature network operation as well as considerations during the system design. The physical mechanisms of the challenges are not new. For example, heat pumps have been a well-known technology for decades. However, with decreasing network temperatures, distributed heat pumps have been used in district heating only recently. When network temperatures are reduced, flow rates increase, and the electricity consumption of circulation pumps may become relevant for total network efficiency. However, flow rates influence the efficiency of heat pumps. The quantitative dependency of flow rates on the coefficient of performance is rarely studied. We provide new insights by recapitulating theory, conducting an experiment, and applying the findings in a case study in sections 2 and 5. Another challenge becoming increasingly relevant in low-temperature networks is varying flow rates. Dynamic flow rates are present in all hydraulic systems with varying differential pressures across individual components (valves, pumps). These dynamic transition states are usually not of concern in high-temperature networks featuring heat exchangers in energy transfer stations. However, in low-temperature networks with heat pumps instead of heat exchangers, flow rate fluctuations may cause shut-down of heat pumps or, at low network temperatures, even freezing evaporators. We present strategies to cope with flow variations during the design and operation phase in sections 3 and 4. In general, the challenges in low-temperature networks with distributed heat pumps are, to a large extent, related to operation, robustness, and resilience. These parameters are difficult to measure and often neglected in decision-making. Section 6 suggests criteria to be included in decision-making and how they could be weighted to choose between various network types.

2. Heat pumps in low-temperature networks

Traditional high-temperature networks with heat exchangers in the energy transfer stations of buildings are robust in operation. Deviations from the optimum set points of flow rate and temperature may decrease the system's energy efficiency but usually do not cause any operational malfunctions or damage to the network components. In low-temperature networks, however, the heat pumps in the energy transfer stations are sensitive to specific flow rates and temperature regimes. Deviations from those regimens may cause, apart from a decrease of energy efficiency, malfunction or damage to the heat pumps and eventually result in a shortage of heating energy. Therefore, careful planning, control, and monitoring flow rates and temperatures are essential for the secure operation of low-temperature networks. In the following sections, we first provide background knowledge on the physical properties of heat pumps and their restrictions regarding flow rate and temperature ranges. Then we analyse how heat pump performance depends on the flow rate through the evaporator by revising theory and illustrating the effects using a laboratory experiment. The flow dependency of heat pump performance should be considered when optimising low-temperature networks with rather large flow rates compared to high-temperature networks. From the heat consumer perspective, billing is sometimes based on water volume instead of energy consumption. Hence, minimising flow rates through heat pumps is in the interest of the low-temperature district heating clients. We limit our analysis to water-water or brine-water heat pumps.

2.1. Physical properties of heat pumps

Heat pumps absorb the thermal power Q'_{eva} (W) at the evaporator and release the thermal power Q'_{con} (W) at the condenser. The electric power P_{el} (W) is required to compress the refrigerant, which is necessary to release Q'_{con} at a higher temperature than the temperature at which Q'_{eva} is supplied to the heat pump. Neglecting thermal losses of the heat pump, the energy balance holds

$$Q'_{con} = Q'_{eva} + P_{el}. \quad (1)$$

The coefficient of performance (COP) of the heat pump is defined by

$$COP = Q'_{con}/P_{el} \quad (2)$$

and is often expressed as

$$COP = \eta_{HP} COP_{Car}. \quad (3)$$

Here η_{HP} (−) is the effectiveness of the heat pump, which mainly depends on heat pump design and the refrigerant. The maximum achievable COP, named here COP_{Car}, is based on the Carnot cycle and holds

$$COP_{Car} = T_{con}/(T_{con} - T_{eva}). \quad (4)$$

Here, T_{con} (K) and T_{eva} (K) are the condensation and evaporation temperatures of the heat pump, respectively. For example, a groundwater heat pump used for space heating or domestic hot water may have parameters of $\eta_{HP} = 0.5$, $T_{eva} = 10$ °C, $T_{con} = 40$ °C or $T_{con} = 65$ °C, respectively. The resulting COPs are 5.2 and 3.1, respectively. The larger the temperature difference between T_{eva} and T_{con}, the more electrical power must be supplied to the compressor, resulting in a lower COP.

2.2. Flow rate and temperature restrictions

A heat pump shuts down when the heat pump's specific flow rate or temperature design boundaries are violated. Such shutdowns primarily protect the heat pump from damage. However, frequent shut-downs and restarts accelerate the wear and tear of heat pumps on the long term and should be avoided.

Flow rate requirements: The flow rate must exceed a minimum threshold to ensure turbulent flow through the evaporator and, for low network temperatures, to avoid cold spots and freezing of the supply fluid in the evaporator. If the flow rate falls below the critical threshold, an error signal stops the heat pump's operation. The flow rate thresholds are specific to each heat pump design.

Temperature restrictions: The inflow temperatures $T_{eva,in}$ (K) and $T_{con,in}$ (K) to the heat pump on the evaporator and condenser side, respectively, must be kept within the design temperature range, which depends on the operation field of the compressor, physical properties of the refrigerant and freezing temperature of the evaporator's supply fluid. If those temperatures are outside the tolerated regime, the pressure of the working fluid increases or decreases beyond accepted thresholds. In this case, the pressure sensors of the heat pumps cause an emergency shut down. If $T_{eva,in}$ is too high, a recirculation loop may be activated to redirect the cold outflow to the inflow of the evaporator [22].

2.3. Dependency of the COP of the heat pump on the flow rate through the evaporator

The control of low-temperature networks must ensure the robust operation of heat pumps, keeping temperatures and flow rates in the evaporator within the tolerated ranges to ensure reliable service. Given a robust DHCS's operation, the system energy efficiency can be optimised. Here, we investigate the dependency of the COP of the heat pump on the flow rate V'_{eva} through the evaporator. The inflow temperature $T_{eva,in}$ is mainly set by the energy balance of the network and is therefore assumed constant. The flow rate V'_{eva}, however, is an optimisation variable in a thermal network. The dependency of the COP on V'_{eva} is often ignored. However, the flow rate V'_{eva} affects the heat transfer across the evaporator, which affects the evaporation temperature and therefore the COP. This can be understood by first assuming an initial state with large V'_{eva} and full evaporation (plus a certain degree of overheating) of the working fluid. If V'_{eva} is decreased, the heat transfer across the evaporator will decrease. Consequently, the degree of overheating is reduced and, in case V'_{eva} was further reduced, the working fluid would not be fully evaporated anymore. To counteract this, a sensor registers reduced overheating of the working fluid and consequently the opening degree of the expansion valve (Fig. 1a) is reduced to lower the evaporation pressure and thus the evaporation temperature T_{eva}. This increases the temperature difference between working fluid and network fluid and therefore the heat transfer across the evaporator, again guaranteeing full evaporation and the required overheating of the working fluid. However, by (4), reducing T_{eva} reduces the COP of the heat pump. This effect is illustrated in the following laboratory heat pump experiment. In this experiment, we kept the inflow temperature to the evaporator constant at $T_{eva,in} = 15$ °C (±0.1 K) (constant parameters are marked green in Fig. 1a). The condenser's inflow temperature and flow rate were also kept constant at $T_{con,in} = 35$ °C (±1 K) and $V'_{con} = 3'500$ l h^{-1} (±200 l h^{-1}), respectively. The compressor was operated at a constant speed. During the experiment, the flow rate through the evaporator V'_{eva} stepwise varied between 400 l h^{-1} to 4'200 l h^{-1}. After moving to a new operation state, we waited for 10 to 15 min to reach steady state.

With increasing V'_{eva} (marked in red in Fig. 1a) the temperature difference ΔT_{eva} across the evaporator $\Delta T_{eva} = T_{eva,in} - T_{eva,out}$ decreases (Fig. 1b). Thus, the thermal powers Q'_{eva} and Q'_{con} increase, whereas the electric power P_{el} remains approximately constant (Fig. 1c). As a result, the COP increases with increasing V'_{eva}, which relates to an increase in the heat pump's evaporation temperature. The increase of the COP is steep at small V'_{eva} and flattens out at large V'_{eva}. This finding signifies that heat pumps are operated most efficiently at large flow rates through the evaporator. However, large flow rates through the evaporator result in large flow rates in the transmission and distribution pipes of the thermal network and consequently increase the electricity consumption of the network's circulation pumps. The qualitative responses of Q'_{eva}, Q'_{con}, P_{el} and the COP to changing V'_{eva} apply to every heat pump. However, the quantitative responses (the steepness of the increases of the COP as function of V'_{eva}) is heat pump specific. In low-temperature networks, flow rates and temperatures should thus be monitored and controlled during operation to ensure the operational function of heat pumps and to optimise DHCS's efficiency. An example of how to control and optimise system efficiency is presented in the case study in Section 5.

3. Flow variations and agent authority

Section 2 introduced temperature and flow rate regimes for robust heat pump operation in low-temperature networks and showed how evaporator flow rates influence heat pump efficiency. This section analyses flow variations caused by interactions between network agents, where “agent” refers to any participant of

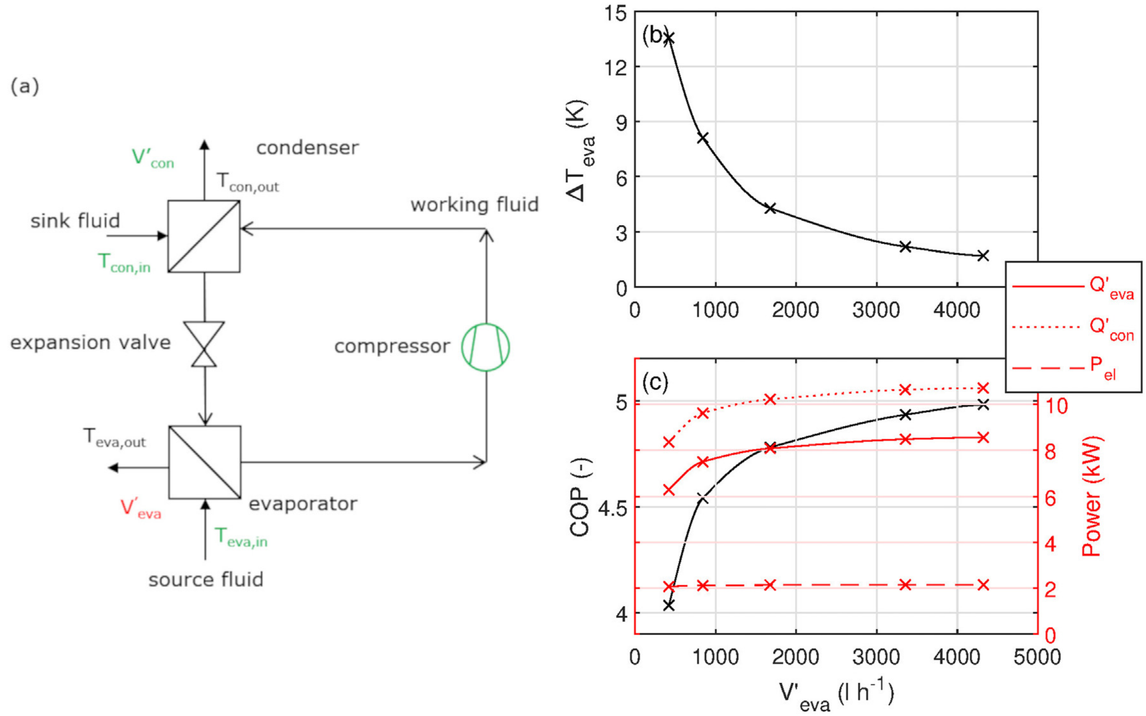

Fig. 1. Heat pump efficiency as function of the flow rate through the evaporator. **a**, Schematic of the relevant parameters of the heat pump experiment. **b**,**c**, Temperature difference across the evaporator, thermal powers, electric power and COP of the heat pump as a function of the flow rate across the evaporator. Crosses indicate the measurement points.

the network, no matter whether prosumer, plant or storage [23]. To quantify flow variations, the concept of "agent authority" is introduced. The physical principles required for defining the agent authority are well known and similar to the concept of "valve authority" [24]. However, using a parameter that is easily computable from design conditions during design phase is new and will help to ensure robust and resilient operation of low-temperature networks in the future.

Valves and circulation pumps cause fluctuating pressure conditions in networks [25]. This section introduces a method to estimate flow variations caused by pressure variations. A numerical example is provided in Appendix A2. The order of magnitude of the expected flow variations is estimated from the pressure differences at design conditions. To illustrate the concept, we use the classical and bidirectional network design [3,10,26–30] shown in Fig. 2a and b. The definition of the agent authority is based on a particular hydraulic circuit. The hydraulic circuit consists of (i) a circulation pump that creates the pressure difference Δp_{CP} (Pa), (ii) an agent with the pressure loss Δp_A (Pa) and (iii) the remaining network section with pressure loss Δp_R (Pa) (green lines in Fig. 2a and b). For the bidirectional network type, design condition refers to the operation state with maximum flow rate through the remaining section. The ellipsoid arrow indicates the hydraulic circuit of agent A1 in both Fig. 2a and b. A closed hydraulic circuit holds

$$\Delta p_{CP} = \Delta p_A + \Delta p_R. \quad (5)$$

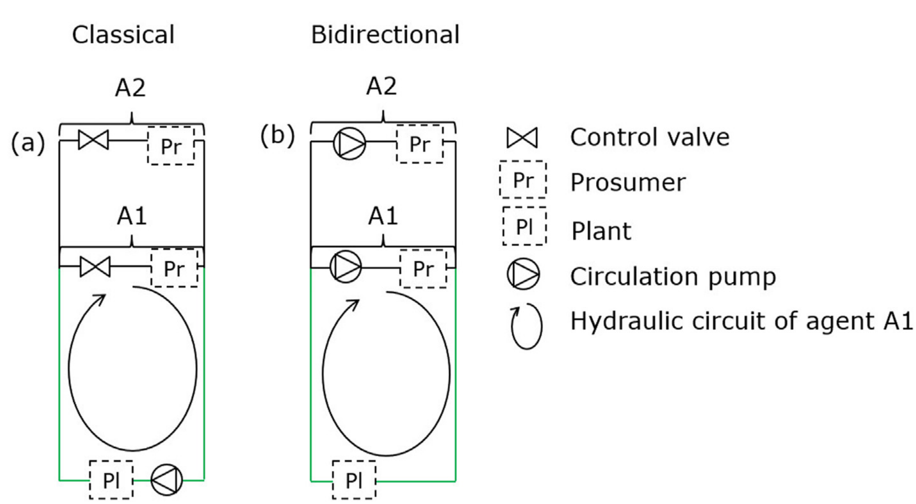

Fig. 2. Hydraulic schemes of low-temperature networks. **a,** In the classical network, the circulation pump transports the fluid from the plant to the agents A1 and A2 and back. **b,** In the bidirectional network, agents A1 and A2 operate their own circulation pumps. The green lines indicate the remaining section of agent A1.

The agent authority (AA) is defined as the ratio of the agent's pressure drop to the total pressure drop of the hydraulic circuit at design conditions (index "D").

$$AA = \frac{\Delta p_{A,D}}{\Delta p_{A,D} + \Delta p_{R,D}} \quad (6)$$

The definition of AA is similar to the definition of the valve authority VA [24].

$$VA = \frac{\Delta p_{V,D}}{\Delta p_{V,D} + \Delta p_{VR,D}} \quad (7)$$

Here, $\Delta p_{V,D}$ (Pa) is the pressure drop across the control valve in the fully open position at design condition and $\Delta p_{VR,D}$ (Pa) is the pressure drop across the remaining section of the hydraulic circuit excluding the control valve. By definition, both AA and VA are smaller than 1 and larger than 0. For a valve authority VA of 0.5 reasonable control of flow rates by opening or closing the valve is expected [24]. In bidirectional networks without control valves, the valve authority is not defined. In classical networks VA $\leq$ AA, because the pressure drop across a single valve is always smaller than the sum of the pressure drops in the agent, which includes valves, filters, heat exchangers, heat pumps, etc. In the following, we use AA to estimate flow variations. Later, we again refer to VA when discussing flow variations in classical networks.

We assume that the circulation pump supplies a constant differential pressure. Consequently, the circuit's pressure drop (i.e. agent plus network section pressure losses) remains the same at design and partial load state (Index "PL" for partial load).

$$\Delta p_{CP,D} = \Delta P_{CP,PL} \quad (8)$$

Referring to agent A1, this equation can be written as

$$C_{A1} V'^2_{A1,D} + \Delta p_{R1,D} = C_{A1} V'^2_{A1,PL} + \Delta p_{R1,PL} \quad (9)$$

Here, $V'_{A1,D}$ ($m^3\ s^{-1}$) and $V'_{A1,PL}$ ($m^3\ s^{-1}$) are the flow rates through the agent A1 at design and partial load conditions, respectively, and C_{A1} ($Pa\ m^{-6}\ s^2$) is the hydraulic resistance of agent 1. The two terms on the left of (9) refer to design conditions and are therefore both constant. The two terms on the right of (9) are load dependent and thus variable.

At design condition, both agents A1 and A2 are active (Fig. 2). We assume that at partial load, agent A2 has disconnected from the network and only agent A1 is active. After the disconnection of A2, the flow rate through the remaining section (green in Fig. 2) decreases and consequently, $\Delta p_{R,PL}$ is reduced. To keep the right side of (3) equal to the left side of (3) without adjusting C_{A1}, the flow rate $V'_{A1,PL}$ must increase. That means that even though agent A1 has neither changed its control valve position (Fig. 2a) nor the speed of its circulation pump (Fig. 2b), the flow rate through agent A1 increases, caused by the deactivation of A2. The maximum flow variation in A1 is approached when $\Delta p_{R,PL}$ tends to zero. Such an operation is approached if most of the flow in the remaining section (Fig. 2, green lines) was caused by A2, before A2 had been disconnected. In the extreme case of $\Delta p_{R,PL} = 0$, (9) transforms to

$$C_{A1} V'^2_{A1,D} + \Delta p_{R1,D} = C_{A1} V'^2_{A1,PL} \quad (10)$$

or, using (6)

$$\frac{C_{A1} V'^2_{A1,D}}{AA1} = C_{A1} V'^2_{A1,PL}. \quad (11)$$

The ratio of the flow rates at partial load and design condition (neglecting the index "1" now) is

$$\frac{V'_{A,PL}}{V'_{A,D}} = \sqrt{\frac{1}{AA}}. \quad (12)$$

Equation (12) is the central equation for estimating flow variations. In a system where the agents have AA = 1, the agents are hydraulically decoupled, and agent/agent interactions do not occur. If the flow variations shall, e.g., be smaller than 20%, meaning $V'_{A,PL}/V'_{A,D} < 1.2$, then the agent authority must be larger than 0.69, i.e. AA > 0.69. This theory initially assumed constant differential pressure control of the circulation pump. In reality, the differential pressure of the circulation pump depends on the operation state, i.e. positions of the control valves and the activity of the circulation pumps (Fig. 2b) in the system. The pump and network characteristic curves describe this dependency [24]. Thus, the theory described here should only be applied to regimes where the characteristic pump characteristic curve is flat, i.e. where the differential pressure created by the circulation pump only weakly depends on the flow rate.

In the classical network (Fig. 2a), the flow rates through the agents are adjusted by control valves. As mentioned before, the control valves are generally designed to satisfy VA = 0.5. Because AA > VA = 0.5, flow variations are, by (12), smaller than ≈ 40% in classical networks. That is why classical networks, by the simple presence of control valves, are less affected by flow variations than bidirectional networks.

In the reservoir network, which will be introduced later in section 6.2, all agents have an agent authority close to 1, and the flow rates through the different agents are independent of each other or, in other words, the agents are hydraulically decoupled. Hydraulic decoupling was one of the key thoughts when developing the reservoir network concept [31].

4. Controlling flow variations for robust and efficient operation of low-temperature networks

We previously showed that flow variations through agents equipped with heat pumps may cause heat pump shut-down or immediate heat pump damage in the case of freezing. Additionally, abrupt flow changes may cause pressure surges (Appendix A3) that can damage pipes and other network components. Flow variations should thus be avoided or at least kept within an acceptable range. Here, we introduce measures for robust operation and discuss their advantages and disadvantages.

4.1. Measures for controlling volume flow variations

Methods M1 to M5 are specific suggestions for robust DHCS operation

Method 1 (M1), Increasing flow rate: Increasing the flow rate through the heat pump by either opening control valves at the prosumers or by increasing the speed of their circulation pumps does not decrease the flow variations by themselves. However, larger flow rates may avoid reaching the critical minimum flow rate when flow variations occur. We consider this method a "brute force" method because the electricity consumption of the circulation pumps is extremely sensitive to the flow rate in the network as the hydraulic power is proportional to the flow rate to the power of three. Doubling the flow rate will increase the circulation pumps' electricity consumption by a factor of approximately eight. Moreover, increasing the flow rate augments the risk of pressure surges causing damage to pipes and network components.

M2, Increasing the agent authority: A large agent authority reduces flow variations caused by agent/agent interactions (Section

3.1). The agent authority is increased by either adding hydraulic resistance to the agent or by reducing the hydraulic resistance of the remaining section, e.g., using larger pipe diameters. In general, adding resistance to the agents is preferable over increasing the flow rate (M1), because hydraulic power (and thus the circulation pumps' electricity consumption) is proportional (and not over-proportional) to the pressure drop of the hydraulic circuit. Increasing the pipe diameter of the remaining section reduces the electricity consumption of circulation pumps but increases investment costs. In existing networks, increasing the pipe diameter is typically not practicable.

M3, Bypass: The Bypass method is only possible in the classical network type (Fig. 2a). The speed of the circulation pump is increased, and excess flow is bypassed at, e.g., the end of the network. This method ensures larger flow rates through the transmission pipes. Prosumer activities then affect the flow rates in the transmission pipes to a smaller extent and consequently, the flow variations in the prosumers are reduced. However, accepting flow through the bypass affects the return-flow temperature and decreases network efficiency. Moreover, large flow rates increase the circulation pumps' electricity consumption.

M4, Intermediate circuits: Agent interactions are avoided by hydraulically decoupling the network agents. Decoupling can be realised by creating additional intermediate circuits (Fig. 3a). The network and the intermediate circuit are either connected directly or by a heat exchanger (in Fig. 3a, the heat exchanger option is shown). Intermediate circuits increase the costs, add complexity to control and decrease the network efficiency by requiring a temperature gradient across the heat exchanger.

M5, Control: Flow variations are reduced by carefully controlling the valves and circulation pumps of the agents. If flow variations in the agent occur slowly, e.g. at time scales of minutes, the agent's control is able to react to flow changes before the maximum flow variation has occurred. In classical networks, opening and closing control valves slowly may be used to dampen the network dynamics. The control of bidirectional networks is more challenging because circulation pumps have a minimum speed, e.g. 30% of the maximum speed, even when equipped with variable speed drives. However, a starter circuit in combination with two control valves (Fig. 3b) may guarantee agents to switch onto and off the network slowly. In the switch-off state, valve V1 (Fig. 3b) is open, valve V2 closed and the circulation pump, as well as the heat pump, are inactive. To initiate the connection to the network, the circulation pump starts at its minimum speed. At this point, the agent is hydraulically still disconnected from the network and the fluid circulates within the starter circuit. Thereafter, V2 gradually opens while V1 closes. The gradual opening guarantees a smooth switch-on to the network, to which the other agents have time to react. Finally, V1 closes and the heat pump is fully switchedon to the network. From this moment onward, the flow rate is controlled by the speed of the agent's circulation pump. To switch off the network, the process repeats in reverse order.

In summary, various methods were presented to ensure robust heat pump operation in low-temperature networks. Methods M1 to M4 are considered workarounds because they sacrifice energy efficiency and/or result in larger investments. Method M5 is preferred because it is inexpensive and still ensures maximum energy efficiency, particularly for the classical network without the starter circuit. Because M5 always requires control valves, even for the bidirectional network, it is beneficial to select valves that include all-in-one solutions for monitoring flow rate and temperatures and which, ideally, can communicate with the circulation pumps in the system and are certified for energy billing.

4.2. Advantages of combined valve-sensor solutions

Robust operation: As outlined above, valve-controlled agents (M5) with slow-moving valves reduce flow variations and pressure surges without decreasing energy efficiency or increasing investments (M1 to M4), except for bidirectional networks that may require a starter circuit.

Monitoring critical parameters: Low-temperature networks must satisfy specific flow and temperature regimes for robust heat pump operation (Section 2.2). Those regimes are automatically monitored when the control valves are combined with flow rate and temperature sensors. A control algorithm may control the flow rate through the heat pump based on the temperature difference across the heat pump's evaporator (e.g. 4 K). Boundary conditions may be set that overwrite this criterion whenever the minimum flow rate of the heat pump is reached or whenever the outflow-temperature at the evaporator approaches freezing temperature.

Flow rate optimisation: Network efficiency for an existing network depends on the circulation and heat pumps' electricity consumption. These are influenced by the flow rate and inlet temperature to the evaporator of the heat pump. With flow rates and temperature sensors in each agent, the overall network flow rates and temperatures are known. This provides the chance to optimise energy efficiency. In the case study of Section 5, we demonstrate a specific methodology on how to improve energy efficiency for a classical network.

Pressure optimisation: Circulation pumps in classical networks are often controlled by keeping a certain differential pressure across all prosumers. This differential pressure is typically based on design conditions and usually only measured across the most

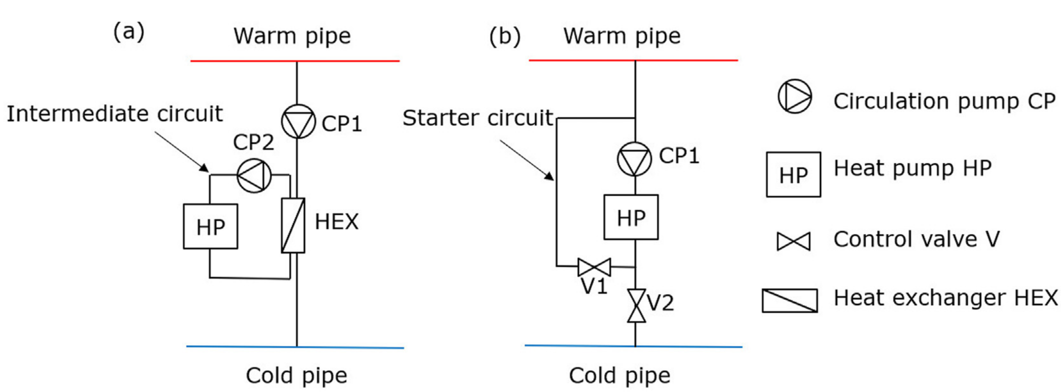

Fig. 3. Schematics of agent connections to the network. a, Intermediate circuit to achieve hydraulic decoupling. In the classical network, the circulation pump CP1 is replaced by a control valve. **b,** Starter circuit for slowly connecting to and disconnecting from the network.

critical prosumer, typically located furthest away from the circulation pump. Using this control strategy, the circulation pump generally creates excess differential pressure at partial load state. Having information on the opening degree of all control valves in the agents, the pump speed can be reduced until the first control valve of an agent is fully open. Controlling the valve opening degree reduces the electricity consumption of the circulation pumps [32].

Thermal energy billing: The simultaneous monitoring of flow rate and temperature difference provides a direct measure of thermal power that can be used for billing thermal energy if the sensors are certified accordingly.

Control valves that monitor the valve's opening degree and measure flow rate and temperatures already exist. Cloud solutions for the measured data provide information for optimisation, billing and failure analysis.

The findings of the previous chapters will be applied to two case studies. The two case studies are motivated by different aspects of this paper. The first case study applies the findings of sections 2 and 3, i.e. the dependency of the heat pump efficiency on the flow rate across the evaporator and the corresponding control strategy to a classical groundwater-supplied low-temperature network. The second case summarises various findings of this paper and additional findings of existing literature on low-temperature networks for decision making. The findings are arranged in a decision matrix. Apart from quantifiable aspects, the decision matrix also includes qualitative criteria which are often neglected in decision-making, such as control strategies and resilience. The weighting of the different criteria is motivated by a proposed network on a greenfield in Melbourne. We assume that a decision between the three, most common low-temperature network types must be made for the new campus: the classical, bidirectional and reservoir network.

5. Case study 1: The low-temperature network of Krommen-Kelchbach, Valais, Switzerland

This case study aims to reduce the electricity consumption of a low-temperature network with distributed heat pumps. The electricity consumption is the sum of the electric energy of circulation pumps and heat pumps. In section 2, we have demonstrated that increasing flow rates through heat pumps improves the COP and therefore decreases the electricity consumption of heat pumps. However, increased network flow rates increase the electricity consumption of the circulation pumps. Starting from measurements of the current situation, we investigate whether a change in flow rate in the low-temperature network of Krommen-Kelchbach reduces the total electricity consumption.

5.1. Network description

The low-temperature network of Krommen-Kelchbach is situated in Naters, Valais, Switzerland (Fig. 4). At the moment, it is only used for heating (no cooling). Groundwater is used as heat source. The heat of the groundwater is transferred to the network fluid across a heat exchanger that is located in the plant. A central circulation pump located in the plant transports the network fluid to the 13 connected prosumers (in this case, consumers of heat) and back to the plant. The circulation pump ensures a constant differential pressure of 1.4 bar across the last prosumer. Heat pumps located in the prosumer buildings extract heat from the network to cover their heat demand. The flow rates through the heat pumps are controlled using pressure-independent control valves, ensuring either constant or zero flow depending on whether the heat pump is active or inactive. In the "optimised control" (OC) building (Fig. 4), we replaced the pressure-independent control valve by an EnergyValve provided by the company Belimo. The EnergyValve measures and controls the flow rate through the evaporator and measures the temperatures before and after the heat pump. The goal is to estimate the potential for minimising the total electricity demand of the system by adjusting flow rates. Therefore, we first investigate the electricity consumption of the circulation pump as function of the network's flow rate. Then we study the electricity consumption of the heat pump as a function of the flow rate. Finally, the findings are combined and generalised to minimise the overall electricity demand. The method outlined can be applied to any low-temperature network to optimise the overall system efficiency.

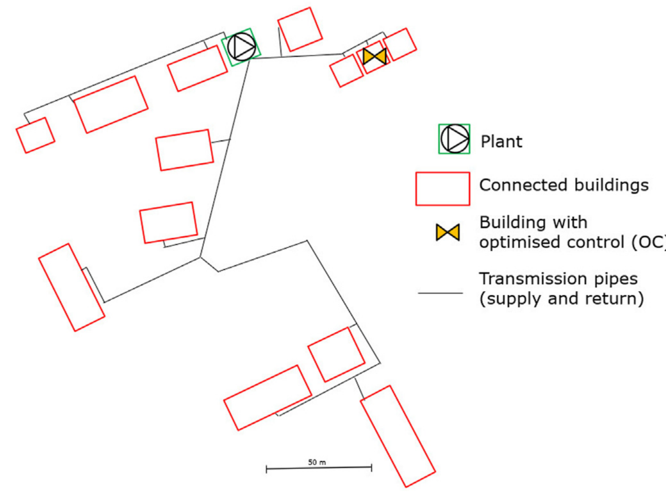

Fig. 4. Schematic of the thermal network of Krommen-Kelchbach, Valais, Switzerland.

5.2. Electricity consumption of the circulation pump

The electric power $P_{el,CP}$ (W) of the circulation pump in the plant is

$$P_{el,CP} = \eta_{CP}^{-1} C_{tot} V'^{3}_{CP} \tag{14}$$

Here, $\eta_{CP} = 0.5$ (−) is the overall efficiency of the circulation pump, C_{tot} (Pa s^2 m^{-6}) is the hydraulic resistance of the network and V'_{CP} (m^3 s^{-1}) is the flow rate through the circulation pump. For the analysis, we consider design conditions. The maximum observed flow rate is approximately 100 m^3 h^{-1}. Five more buildings are expected to be connected to the network in the future, increasing the demand by approximately 30%. The design flow rate is thus expected to be approximately 130 m^3 h^{-1}. Pipe diameters are designed for a specific pressure drop of 125 Pa m^{-1} [16]. The transmission pipes of the network are approximately 1200 m long. The expected pressure loss is 1.9 bar along the transmission lines. The circulation pump therefore generates a differential pressure of $\Delta p_{CP} = 1.5$ bar + 1.4 bar = 2.9 bar. This setup corresponds to an agent authority of 1.4/1.5 = 0.93 for the last prosumer and expected flow variations of 3.5% (Section 3). The hydraulic resistance of the network is $C_{tot} = \Delta p_{CP}/V'^{2}_{CP} = 2.2 \times 10^8$ Pa s^2 m^{-6}. Using (14), the electric power of the circulation pump is now determined as a function of the flow rate. In Fig. 5 (dotted line at the bottom), we show the electric energy consumption $E_{el,CP}$ (MWh) of the circulation pump as a function of the flow rate. To transfer electric power to electric energy, $P_{el,CP}$ is multiplied by the time interval during which the heat pumps are active to supply the annual heat demand Q_{con} to the buildings. We estimated Q_{con} = 1.64 GWh from

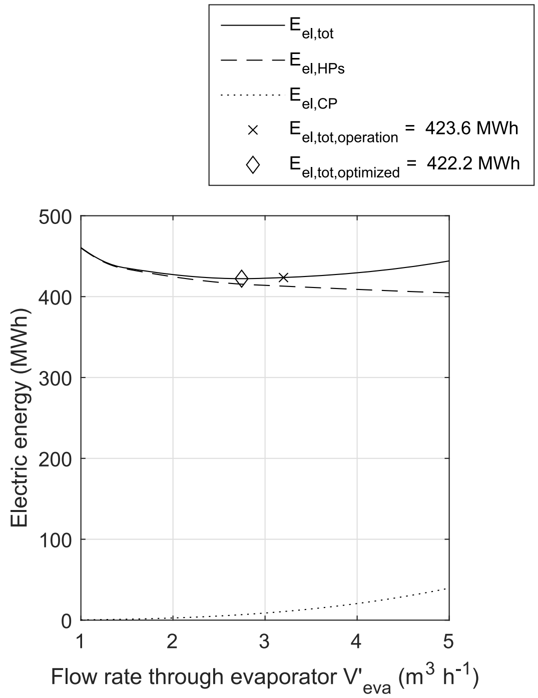

Fig. 5. Annual total electricity consumption as a function of the flow rate through the heat pump in the OC building. The total flow rate in the network is obtained by multiplying the shown flow rate by the number of buildings, here 41.

measurements, in approximate agreement with the 1.8 GWh mentioned in Ref. [33].

5.3. Electricity consumption of the heat pumps

For calculating the annual electricity consumption $E_{el,HPs}$ (MWh) of the heat pumps, we assume that all buildings connected to the network are identical to the OC building, therefore

$$E_{el,HPs} = nE_{el,HP,OC} \quad (15)$$

Here, $E_{el,HP,OC}$ is the annual electricity consumption of the heat pump in the OC building and n is the number of buildings connected to the network, defined by $n = V'_{CP}/V'_{eva,OC} = 41$, where $V'_{CP} = 130$ m^3 h^{-1} and $V'_{eva,OC} = 3.2$ m^3 h^{-1} is the average flow rate measured through the evaporator of the heat pump of the OC building. Because the OC building is one of the smaller buildings within the network, n is larger than the number of buildings that will eventually be connected to the network. The electricity consumption $E_{el,HP,OC}$ is calculated by multiplying the electric power $P_{el,HP,OC}$ with the time interval in which the heat pumps are active to deliver Q_{con} to the buildings. This time interval depends on the COP of the heat pump and thus on the flow rate. To evaluate the flow rate dependence of the COP of the OC building, we scaled the heat pump experiment of Section 2.3 to the flow rates measured in the OC building (Appendix A4). The electricity consumption of the heat pumps as a function of the flow rate through the heat pumps is shown in Fig. 5 (dashed line).

5.4. Total electricity consumption

The total annual electricity consumption $E_{el,tot}$ (MWh) of the network is

$$E_{el,tot} = E_{el,CP} + E_{el,HPs} \quad (16)$$

The flow rate dependences of $E_{el,tot}$, $E_{el,CP}$ and $E_{el,HPs}$ are shown in Fig. 5 expressed by the flow rate through the evaporator of one heat pump. As expected, $E_{el,HPs}$ decreases with increasing V'_{eva} (dashed line in Fig. 5) because of the increased COP at a larger flow rate through the evaporator (Section 2.3). In contrast, $E_{el,CP}$ increases with increasing V'_{eva} ($P_{el,CP} \sim V'^3_{eva}$). The heat pump currently operates at a flow rate of 3.2 m^3 h^{-1} (cross in Fig. 5), corresponding to $E_{el,tot} = 423.6$ MWh. Only 10.6 MWh (2.5%) of the 423.6 MWh are attributed to $E_{el,CP}$. The optimum flow rate is achieved by reducing the current flow rate from 3.2 m^3 h^{-1} to 2.7 m^3 h^{-1}, i.e. by 14%. Reducing the flow rate decreases $E_{el,CP}$ by 36% to 6.8 MWh. However, because $E_{el,CP}$ only contributes by a small fraction to $E_{el,tot}$, the decrease of $E_{el,tot}$ is only by 0.3%, now 422.4 MWh. We note that $E_{el,CP}$ is only 0.4%–0.6% of the supplied heat Q_{con} to the buildings, whereas 1.5%–2.0% are generally assumed as a rule of thumb [16] in low-temperature networks driven by heat pumps.

The evaluation of the low-temperature network Krommen-Kelchbach in Valais, Switzerland, shows that the annual electricity consumption is dominated by the heat pumps and the circulation pumps' share is small. The main challenge in this network is to ensure efficient and robust heat pump operation. Flow optimisation, under current operation, has a negligible effect (0.3%) on the total electricity consumption. In networks where the share of circulation pumps' electricity consumption on the total electricity consumption is larger, the optimisation potential will be more considerable.

For the second case study, we consider a proposed network on a “greenfield” in Melbourne and use the findings of this paper to generate a decision matrix that summarises the advantages and disadvantages of three network types.

6. Case study 2: The proposed low-temperature network in Melbourne, Australia

In case study 2, we incorporate the findings of this paper into decision making using the TOPSIS approach. The criteria and weights are motivated by a planned low-temperature network in Australia. Decision making is often based on quantifiable criteria such as energy consumption, costs, or emissions. Low-temperature networks are less frequent and more challenging to operate than high-temperature networks. Therefore, criteria such as control strategies and robust operation gain importance but they are difficult to quantify. Here, we provide a comprehensive list of criteria including a suggestion for weighting to facilitate decision making.

The University of Melbourne is planning Australia's premiere innovation hub for engineering and design for its new campus at Fishermans Bend, the country's largest urban renewal project. The University aims to provide an example sustainable development by implementing innovative solutions for energy, water, waste, and transportation, among others. In this context, a low-temperature network has been proposed as a sustainable alternative for the campus's heating and cooling needs. In this section, three possible network configurations are analysed and compared using the

Fig. 6. Artist's view of the proposed campus for the University of Melbourne (from Ref. [34]).

TOPSIS method regarding specific criteria to determine the optimal configuration for the proposed network.

The proposed low-temperature network for the University of Melbourne will supply buildings of a new campus with heat and cold using (reversible) heat pumps (Fig. 6). In contrast with the northern European systems, in Melbourne, the cooling demand exceeds heating demand. The peak loads for cooling and heating are expected to be around 3.4 MW and 1.2 MW, respectively. The annual cooling and heating demands are expected to be roughly 1′400 MWh and 260 MWh, respectively. The gross floor area is approximately 37′700 m^2, resulting in heating and cooling demands of 40 kWh m^{-2} a^{-1} and 7 kWh m^{-2} a^{-1}, respectively. The seasonal storages considered for the project are geothermal heat exchangers (known as “energy piles”) located within the structural piles underneath the buildings. The energy piles are approximately 30–35 m deep. The undisturbed ground temperature below the depth of 20 m is approximately 18 °C throughout the year. Cooling towers are proposed to eject waste heat into the air to balance the annual energy flows. In summary, the relevant agents of the proposed network are:

(i) prosumers: university buildings with cooling and/or heating demand.
(ii) plants: cooling towers to eject residual heat to the ambient air
(iii) storages: various sets of energy piles underneath the buildings.

The proposed network shall be in line with the United Nations Sustainable Development Goals (https://sdgs.un.org/goals), such as affordable and clean energy (Goal 7); industry, innovation and infrastructure (Goal 9); sustainable cities and communities (Goal 11) and climate action (Goal 13).

6.1. Basic design configurations of low-temperature networks

We present three basic design configurations for low-temperature networks. The number and type of network agents are motivated by this case study but simplified for comprehensiveness. The network agents for all configurations are three prosumers, one plant and two storages. The analysed operation state considers one prosumer with heating demand (red in Fig. 7), and two other prosumers with cooling demand (blue in Fig. 7). For all three network configurations, a circular arrangement was chosen to allow for better visual comparison to the reservoir network (Fig. 7c). In the classical network (CN) configuration (Fig. 7a), the prosumers are connected parallel to the transmission pipes and equipped with control valves to adjust flow rates. The main circulation pump is typically installed at the plant and transports the fluid through the supply and return transmission pipes to the prosumers and back to the plant. This network configuration is often used in district heating systems with a single large plant, e.g., a lake, to supply all prosumers with heating or cooling. In such a configuration, no additional storage is needed. Storages can, however, be connected to the network in parallel in the same way as the prosumers.

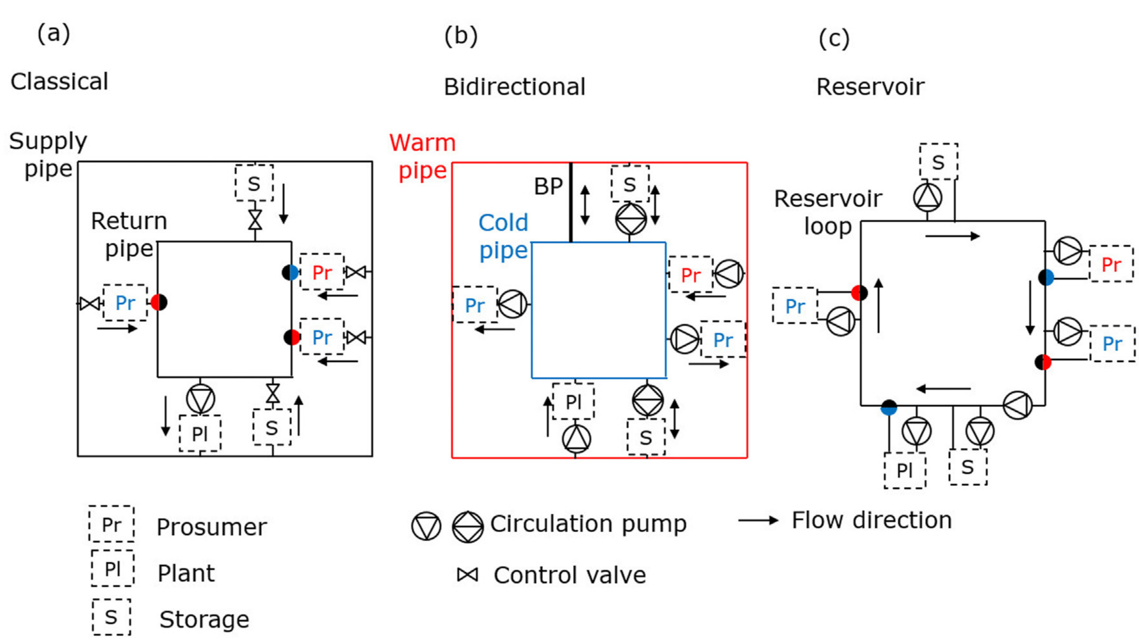

Fig. 7. Schematics of three different low-temperature network types. a, Classical network, CN. **b,** Bidirectional network, BN. **c,** Reservoir network, RN. The colour of the prosumers indicates cooling (blue) and heating (red) demand of the prosumer. The coloured dots in (a, c) indicate mixing of different temperatures.

The second design principle is the bidirectional network (BN) configuration (Fig. 7b) [3,10,26–30]. In such a network, prosumers are connected parallel to the transmission pipes identical to the classical network configuration. However, in contrast to the classical configuration, all agents adjust their flow rates using their own circulation pumps. Prosumers with heating demand take fluid from the warm pipe, extract thermal energy, and inject the cooled fluid into the cold pipe. Vice versa, prosumers with cooling demand take fluid from the cold pipe, supply thermal energy to the building, and inject the heated fluid into the warm pipe. The residual fluid is transported across the storage to balance mass flow between warm and cold pipes. The circulation pumps of the storages are controlled to ensure zero flow through the bypass (BP), thus avoiding mixing between warm and cold fluid. The flow direction through the storage can change during operation, depending on whether heating or cooling demand of the prosumers dominates. The pump symbol at the storage indicates the alternating flow direction through the storage in Fig. 7b. In general, the flow direction through the individual prosumers may also change when their heating and cooling demand alternates. However, the effect on the network is identically represented by different prosumers with either heating or cooling demand that are active at different times. Varying fluid and energy flows within the network pipes motivate the term "bidirectional".

In the third network configuration, the reservoir network (RN) [31], all agents are connected in series (Fig. 7c) to a reservoir loop. As in the bidirectional network, each agent operates its own circulation pump. The fluid in the reservoir loop is circulated by the main circulation pump, the reservoir pump. The name "reservoir" is motivated by the notion that the agents do not "impact" each other hydraulically and act as if they were connected to a large fluid volume, a reservoir.

6.2. Comparison of network types using TOPSIS

Three network types have been described in the previous Section, the classical network (CN), the bidirectional network (BN) and the reservoir network (RN) (Fig. 7). Here, we qualitatively compare these three types. The comparison involves, beyond technical and economic aspects, also environmental and social dimensions of decision making. For the comparison, we use the TOPSIS (Technique for order preference by similarity to ideal solutions) method, developed by Ref. [35], which is one of the most common methods for evaluating alternatives in energy planning [36]. TOPSIS evaluates a certain number of alternatives (CN, BN and RN) with respect to specific criteria. Weights are assigned to each criterion depending on its importance. Each alternative is scored with respect to the criteria, resulting in a decision matrix (Table 1). The weights and the decision matrix are the input for the TOPSIS algorithm. The final output is a closeness coefficient, which allows ranking of the alternatives. A closeness coefficient of 1 is the best possible result for an alternative, meaning that the alternative is identical to the ideal solution. A closeness coefficient of 0 is the worst result for an alternative, meaning that the alternative is identical to the anti-ideal (or worst) solution. The computational steps of TOPSIS are (i) normalisation of the scores in the decision matrix to map each score into the range between 0 and 1, (ii) normalisation of the weights into a range between 0 and 1, (iii) computation of the ideal and the anti-ideal solution, (iv) computation of the weighted distance of each alternative from the ideal and the anti-ideal solution and (v), computation of the closeness coefficient from those two distances. Different methods have been applied to normalise the weights and the decision matrix [37–40]. We use the original algorithm of TOPSIS [40,41]. For both, weights and scores, we chose a range from 1 to 9. A weight of 9 means greatest importance and a score of 9 means best performance, 1 reflecting least importance and worst performance, respectively. We chose to attribute a score of 9 to the best alternative for each criterion. This does not bias the evaluation, because the closeness coefficient is invariant with respect to multiplication by a constant. A score of (3, 9, 6), e.g, will produce the same closeness coefficient as a score of (300, 900, 600) or (1, 3, 2). Table 1 shows the 13 criteria including weights, the three alternatives, the resulting decision matrix, the computed closeness coefficient and the resulting ranking. The criteria are sorted into three different groups "costs", "control and flexibility" and "other". The sums of the weights of the criteria within each group are 26, 26 and 13, respectively. This means the "cost" criteria and "control and flexibility" criteria contribute equally to the final ranking. "Other" criteria have half the importance of "cost" and "control and flexibility". The comparison is based on topics discussed in the previous sections, but also refers to literature findings and, in particular with respect to the weight of the different aspects, is subjective. The reasoning for the choice of weights and scores is found in the Appendix A5. The goal of this

Table 1
Ranking of network types. See Appendix A5 for the reasoning of weights and scores.

	Weight	Classical CN	Bidirectional BN	Reservoir RN
Costs (sum of weights = 26)				
Low electricity consumption of heat pumps/chillers	9	7	9	8
Low electricity consumption of circulation pumps	3	5	9	7
Low installation costs	9	6	5	9
Low maintenance costs	5	9	6	5
Control and flexibility (sum of weights = 26)				
Simple control	8	9	5	8
Identical and constant supply temperatures	5	9	7	3
Flexible injection temperatures	5	9	7	3
Flexible network expansion	4	8	7	9
Enabling direct cooling	4	7	9	8
Other (sum of weights = 13)				
Resilience	7	9	7	6
Low resources use	4	6	7	9
Monitoring	2	9	8	7
Results				
Closeness coefficient		0.63	0.40	0.46
Ranking		1	3	2

comparison is therefore not to provide a definite answer on network choice, but rather collect relevant technological and non-technological aspects and to show an example on how to include them in decision making.

Using TOPSIS for evaluating the three different network types, the preferred choice is the classical network (Rank 1, closeness coefficient = 0.63). The second choice is the reservoir network (Rank 2, closeness coefficient = 0.46), closely followed by the bidirectional network (Rank 3, closeness coefficient = 0.40). All closeness coefficients are between 0.4 and 0.7 and thus distant from 0 to 1. This signifies that each alternative is a compromise. For example, the bidirectional network is the best in terms of electricity consumption [27], but the worst for the criterion “simple control”. Some phenomena of one network can result in a high score for one criterion but a low score for another criterion. For example, mixing of warm and cold fluid in the return pipe of the CN allows for flexible injection temperatures (positive, thus high score criterion “Flexible injection temperatures”), but, on the other hand, results in a greater electricity demand of heat pumps and chillers (negative, thus low score for criterion “Low electricity consumption of heat pumps/chillers”). Because criteria like “simple control”, “resilience” or “flexible injection temperatures” are difficult to measure quantitatively and are additionally subjective to the evaluator, these criteria are often neglected in practical planning and only the measurable, mainly cost-related parameters are considered. This may introduce a bias in decision making. The decision matrix used here is motivated by the situation in Melbourne. However, we do not expect large changes in the scores for other low-temperature networks that integrate geothermal storages and provide cooling using chillers. When cooling is meant to be provided directly using heat exchangers instead of chillers, the criterion “Enabling direct cooling” will gain weight and the closeness coefficients of the three network types will be more similar to each other, however, without changing the ranking.

7. Conclusion

In this work, we discussed hydrothermal requirements for low-temperature networks focusing on heat pump performance. Heat pumps require specific flow rate and temperature regimes for robust and efficient performance. Agent/agent interactions in thermal networks cause flow variations that can push flow rates and temperature levels outside the allowed operation boundaries. This can cause heat pump failure or even damage. To quantify flow variations, the concept of the agent authority was introduced. The agent authority allows for estimating expected flow variations in a network when network agents switch on to or switch off from the network.

Various methods to ensure robust heat pump operation were presented. The most favourable method in terms of energy efficiency and investment is based on control valves combined with flow rate and temperature sensors. For an existing low-temperature network in Valais, Switzerland, a method for reducing the total electricity consumption by adjusting network flow rates was presented. This network currently operates close to its optimum. Flow optimisation reduces the total electricity consumption of circulation pumps and heat pumps by 0.3% only.

In another case, for a proposed low-temperature network in Melbourne, Australia, we ranked three basic network types according to 13 selected criteria using the TOPSIS approach. In the evaluation analysis, all three network types are ranked close to each other, with closeness coefficients between 0.40 and 0.63. Within this range, the classical network was found the most suitable, followed by the reservoir network and the bidirectional network. Low-temperature networks with geothermal storages have been built as bidirectional networks in Switzerland, likely because of the energy efficiency criterion, and because the reservoir network was not yet developed. When non-measurable parameters regarding control and resilience are included in decision making, the superiority of the bidirectional network decreases. However, low-temperature networks that integrate a significant fraction of renewables must be built, and in the end, practical experience with real networks will show which network type will satisfy future expectations.

This paper presented relevant hydrothermal challenges and concepts for designing and operating low-temperature networks with distributed heat pumps. The phenomena discussed in this paper are not new in general but novel within the context of low-temperature networks. Low-temperature networks have been evolving from high-temperature networks but are facing challenges that are different from high-temperature networks. Using heat pumps instead of heat exchangers in the energy transfer stations, flow rates, hydraulics, and control gain importance. The new insights must be considered during design and operation. This paper discusses the most critical challenges for a reliable operation of low-temperature networks. In that sense, low-temperature networks question established concepts and require out-of-the-box thinking and careful monitoring of flow rates and temperatures. Not much information is documented in the literature at the moment. This paper contributes to developing robust and efficient design as well as operation of low-temperature networks.

Author contributions

Tobias Sommer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Roles/Writing - original draft, Writing – review & editing.**Artem Sotnikov**: Software, Formal analysis, Writing – review & editing **Matthias Sulzer**: Conceptualization, Methodology, Funding acquisition, Investigation, Writing – review & editing **Volkher Scholz**: Conceptualization, Formal analysis, Roles/Writing - original draft, Writing – review & editing **Stefan Mischler**: Conceptualization, Funding acquisition, Formal analysis, Writing – review & editing **Behzad Rismanchi**: Formal analysis, Writing – review & editing **Kristian Gjoka**: Formal analysis, Writing – review & editing **Stefan Mennel**: Conceptualization, Methodology, Funding acquisition, Project administration, Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A1. Heat pump specifications and experimental specifications

The heat pump used in the experiment in Section 2.3 is shown in Fig. A1, the heat pump specifications and experimental conditions are summarized in Table A1. The design heating power of the heat pump is 10 kW. The heat pump was operated using brine on the evaporator side and water on the condenser side. The brine is an ethylen-glycol mixture with a freezing temperature of − 23 °C, determined by a refractometer. The working fluid is R410A. The compressor is a scroll-compressor by Emerson. Plate heat exchangers from the manufacturers SWEP and Emerson are used for the evaporator and condenser, respectively.

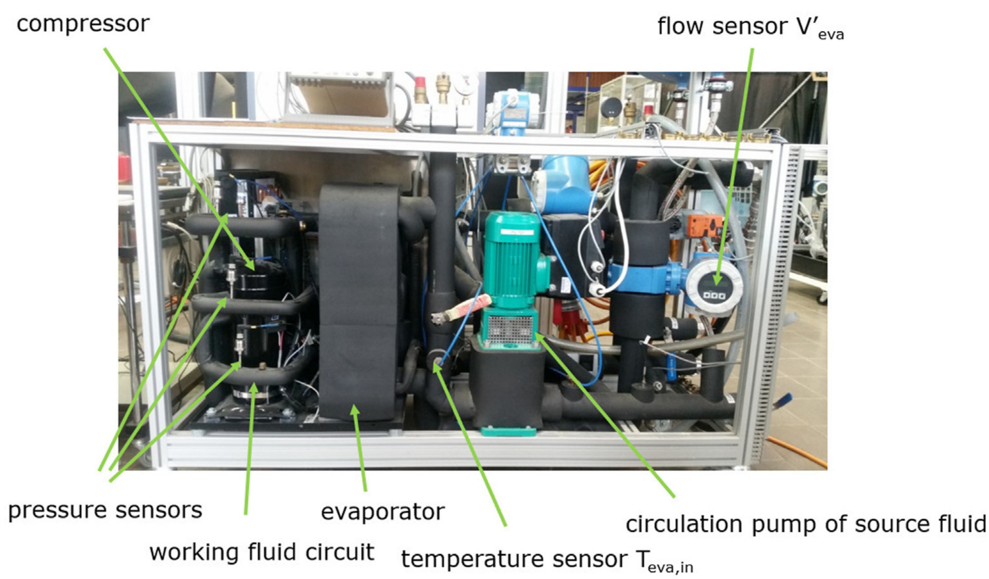

Fig. A1. Heat pump used in the heat pump experiment in Section 2.3.

Table A1
Heat pump specifications and experimental conditions.

Parameter	Unit	Value
Heat pump		
Design heating power	kW	10
Working fluid	–	R410A
Liquid on evaporator side		Brine: Ethylen-glycol mixture
Experimental conditions		
Inflow temperature into evaporator $T_{eva,in}$	°C	15 ± 0.1
Inflow temperature into condenser $T_{con,in}$	°C	35 ± 1
Flow rate across the condenser V'_{con}	$l\ h^{-1}$	3′500 ± 200
Flow rate across the evaporator V'_{eva}	$l\ h^{-1}$	Variable

Appendix A2. Numerical example for estimating flow variations using the concept of agent authority

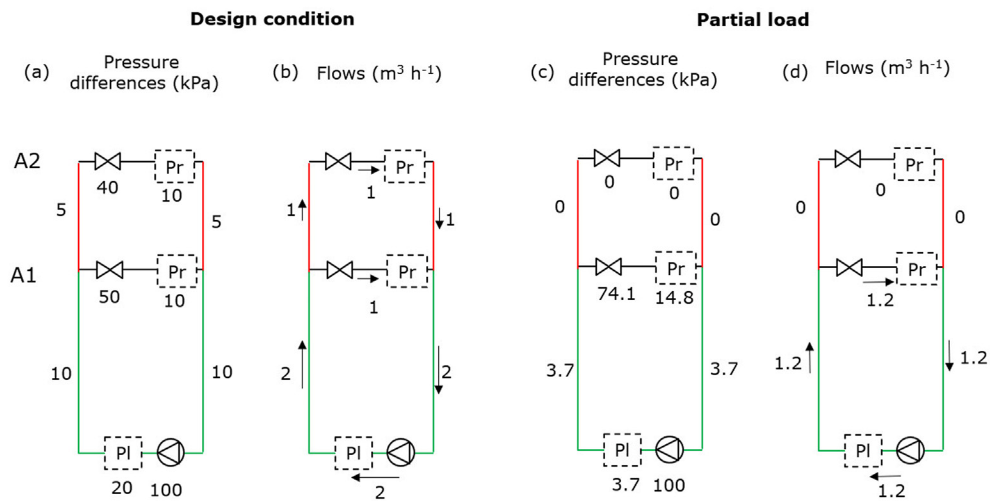

Fig. A2. Numerical example for calculating flow variations based on agent authority. **a,**Pressure differences (kPa) for each network section at design condition. **b,** Flow rates (m^3 h^{-1}) for each network section at design condition. The arrows indicate the flow direction. **c, d,** Calculated pressure differences and flow rates for partial load, when agent A2 (at the top) is inactive. See text for details.

In Section 3.1, a method for estimating flow variations based on agent authority was presented. In Fig. A2, we show a simple numerical example to illustrate the calculation. For this example, we use the classical network design shown in Fig. 2a. The expected pressure differences and flow rates for design conditions are indicated in Fig. A2a, b. In this example, the circulation pump creates a differential pressure of 100 kPa. The sum of the pressure drops in each of the hydraulic circuits of agent A1 and A2 thus also equals 100 kPa. From these pressure differences the agent authorities, valve authorities and flow variations for A1 and A2 are calculated from (6), (7), (12)

$$VA1 = \frac{50}{100} = 0.5 \tag{A1}$$

$$AA1 = \frac{50 + 10}{100} = 0.6 \tag{A2}$$

$$\frac{V'_{A1,PL}}{V'_{A1,D}} = \sqrt{\frac{1}{AA1}} = \sqrt{\frac{1}{0.6}} \approx 1.3 \tag{A3}$$

$$VA2 = \frac{40}{100} = 0.4 \tag{A4}$$

$$AA2 = \frac{40 + 10}{100} = 0.5 \tag{A5}$$

$$\frac{V'_{A2,PL}}{V'_{A2,D}} = \sqrt{\frac{1}{AA2}} = \sqrt{\frac{1}{0.5}} \approx 1.4 \tag{A6}$$

For both agents, VA ≤ AA as argued in Section 3.1. Flow variations are expected to be in the range of 30% for A1 and 40% for A2. In order to calculate flow rates at partial load, the required flow rates at design condition are defined. We assume that A1 and A2 require the same flow rate of 1 m^3 h^{-1}. Consequently, the flow rate through the circulation pump is 2 m^3 h^{-1}. From the pressure differences and flow rates, the hydraulic resistances $C = \Delta p_D/V'^2_D$ are calculated for each network section. Here, Δp_D (Pa) is the pressure drop across the network section and V'_D is the flow rate across the same network section. Using those resistances, pressure differences and flow rates are the calculated for partial load, when A2 is inactive (Fig. A2c,d). When A2 is inactive, the flow rate through A1 increases from 1 m^3 h^{-1} at design conditions to 1.2 m^3 h^{-1} at partial load, by 20%. Using the concept of agent authority, we estimated flow variations of 30% for A1. The reason for the discrepancy is that the assumption of zero pressure drop in the remaining section is not exactly fulfilled. It is still 3 times 3.7 kPa = 11.1 kPa (Fig. A2c). The concept of agent authority does not provide exact values for volume flow variations but rather order of magnitude estimates. It has the useful property that only pressure differences (no flow rates) and these only for design conditions are required to provide an idea of expected flow variations.

Appendix A3. Pressure surges

Flow rates in low-temperature networks are larger than in high-temperature networks because of the smaller temperature differences across the prosumers, while still delivering sufficient heat to the buildings. Most of the existing thermal networks are high-temperature networks with rather small pipe diameters. If the network temperature of such existing networks shall be reduced to incorporate more renewables, the fluid velocity in the pipes must be increased. This increases the risk of pressure surges. Pressure surges occur when the fluid velocity is decreased abruptly, caused for example by the fast closure of a valve or failure of circulation pumps. Within Appendix A3, we only briefly summarise the main aspects of pressure surges. For details we refer to literature [42].

The Joukowsky equation defines the maximum pressure surge occurring for an abrupt fluid stop

$$\Delta p = v \rho c \tag{13}$$

Here, Δp (Pa) is the pressure variation caused by the pressure surge, v (m s^{-1}) is the fluid velocity before the abrupt velocity decrease, ρ (kg m^{-3}) is the density of the fluid and c (m s^{-1}) is the wave speed of the fluid. The direct dependence of Δp on v indicates that large fluid velocities cause large pressure surges. For example, for v = 1 m s^{-1}, ρ = 1000 kg m^{-3} (water) and c = 1450 m s^{-1} (water in a rigid pipe), Δp = 14.5 bar. This example signifies that after sudden valve closure or pump failure, the pipe's pressure may oscillate by ± 14.5 bar around the static pressure. Overpressure may result in pipe damage, underpressure may additionally cause cavitation and consequently damage circulation pumps.

The Joukowski equation is only applicable if the time interval t_S (s) for valve closure is smaller than the time interval t_R (s) between emitting the pressure wave and the reception of the reflected pressure wave at the valve. The pressure wave is emitted at the hydraulic component responsible for stopping the fluid motion and reflection may occur e.g. at the end of a pipe or at the expansion vessel. The time interval t_R is calculated by $t_R = 2L/c$, where L (m) is the length of the pipe section until the reflection point. For L = 2 km and c = 1450 m s^{-1} the time interval t_R is 2.8 s. A valve closure within 2.8 s after a 2 km long pipe section with initial fluid velocity of 1 m s^{-1} thus causes pressure oscillations of amplitude 14.5 bar in the network. For branched network structures, various pressure waves are superimposed. This increases the complexity and reduces predictability. In general, hydraulic simulations are required to accurately identify possible risks.

In summary, long transmission pipe sections without junctions and large fluid velocities, e.g. from a remote plant to the first prosumer, have high risks for pressure surges. Any hydraulic component that may cause abrupt changes of fluid velocity in such a pipe section should be carefully designed. Bypasses with either check valves or pressure relief valves are possible safety measures [42]. During operation, controlled and slow-moving valves reduce the risk of pressure surges.

Appendix A4. Heat pump scaling

The heat pump experiment of Section 2.3 was scaled to the situation measured at the OC building by

$$V'_{eva,S17} = V'_{eva,exp}\frac{V'_{eva,r,S17}}{V'_{eva,r,exp}} \tag{A7}$$

$$Q'_{eva,S17} = Q'_{eva,exp}\frac{Q'_{eva,r,S17}}{Q'_{eva,r,exp}} \tag{A8}$$

$$P_{el,\,S17} = P_{el,exp}\frac{P_{el,r,S17}}{P_{el,r,exp}} \tag{A9}$$

Here, $V'_{eva,exp}$, $Q'_{eva,exp}$ und $P_{el,exp}$ are the measurements from the experiment (index “exp”) and $V'_{eva,OC}$, $Q_{eva,OC}$ und $P_{el,OC}$ the scaled quantities to represent the heat pump at the OC building (index “OC”). For the scaling, a reference state (index “r”) from the heat pump measurements of the experiment and the heat pump measurements at the OC building was chosen according to Table A2.

Table A2
Reference state of the heat pump in the OC building and the experiment

Parameter	Unit	Value	Description
Reference operation state of the heat pump in the OC building for the scaling			
$V'_{eva,r,OC}$	m^3 h^{-1}	3.2	Flow rate through the evaporator of the heat pump
$\Delta T_{r,OC}$	K	4	Temperature difference across the evaporator
$Q'_{eva,r,OC}$	kW	14.9	Transferred thermal power at the evaporator
$P_{el,r,OC}$	kW	5	Electric power of the heat pump
$Q'_{con,r,OC}$	kW	19.9	Transferred thermal power at the condenser
$COP_{r,OC}$	–	4.0	Coefficient of Performance
Reference operation state of the heat pump in the experiment for the scaling			
$V'_{eva,r,exp}$	m^3 h^{-1}	1.9	Flow rate through the evaporator of the heat pump
$\Delta T_{r,exp}$	K	4	Temperature difference across the evaporator
$Q'_{eva,r,exp}$	kW	8.1	Transferred thermal power at the evaporator
$P_{el,r,exp}$	kW	2.1	Electric power of the heat pump
$Q'_{con,r,exp}$	kW	10.3	Transferred thermal power at the condenser
$COP_{r,exp}$	–	4.8	Coefficient of Performance

Appendix A5. Reasoning for the TOPSIS decision matrix

Low electricity consumption of heat pumps and chillers: Energy efficiency in low-temperature networks is equivalent to minimum electricity consumption of heat pumps, chillers and circulation pumps. The electricity consumption of the circulation pumps is typically more than an order of magnitude smaller compared to the electricity consumption of heat pumps (Section 5). Therefore, heat pumps (and chillers for cooling) are the most relevant components regarding total electricity consumption. Providing heat pumps and chillers with favourable temperature levels is thus essential for energy efficiency. The most favourable temperature levels are achieved when mixing of warm and cold fluid within the network is avoided. The BN completely separates the temperature levels of the warm and cold pipe and is thus the most energy efficient network [27]. In the RN, mixing can be avoided, but only for very specific demand situations [31]. In the CN, both warm and cold fluid are mixed in the return loop. Because the annual total electricity saving by separating the temperature levels is typically only 1%–2%, and maximum 5% [27], the scores of the three network types are close to each other. We attribute the maximum weight of 9 to this criterion and scores of (7, 9, 8) for the (CN, BN, RN).

Low electricity consumption of circulation pumps: The prosumers in low-temperature networks exchange thermal energy. In the case of thermal balance between prosumers with heating and cooling demand, flow through plants and storages should be avoided to minimise hydraulic losses. This is achieved in the BN, which obtains the largest score. In the RN, flow through plants and storages can be avoided by turning off the circulation pumps in case of energy balance. However, continuous circulation must be guaranteed in the reservoir loop for network functioning. In the CN (without bypass solutions), there is always flow through the plant. We attribute a relatively low weight of 3 to this criterion because circulation pumps only contribute by a small fraction to the total electricity consumption. The scores are (5, 9, 7) for the (CN, BN, RN).

Low installation costs: Installations costs of low-temperature networks are mainly caused by trenching, piping and seasonal storages. The electric components only form a minor fraction of the cost. For a circular arrangement of agents, the RN only requires one transmission pipe compared to the two transmission pipes in the CN and the BN [31]. Piping is the main lever for possible savings and the RN is thus rated best. Between the CN and the BN, the CN has slightly smaller investment costs because it uses control valves instead of circulation pumps at the prosumers. We attribute a weight of 9 to this criterion and scores of (6, 5, 9) for the (CN, BN, RN).

Low maintenance costs: Maintenance in mainly needed for electric components, i.e. heat pumps/chillers, circulation pumps and control valves. The number of heat pumps/chillers is equal for each network type. Circulation pumps are more vulnerable to damage compared to control valves. Based on Fig. 7, the number of circulation pumps is 1, 6 and 7 in the CN, BN and RN, respectively. We attribute a weight of 5 to this criterion and scores of (9, 6, 5) for the (CN, BN, RN).

Simple control: Control is simple, when the individual agents can operate independently from each other and when only a small number of conditions and sensors are necessary for robust and efficient network operation. The BN is the most difficult to control because of agent/agent interactions, the strict temperature requirements between the warm and cold pipe and the reversible flow through the storage. For a smooth switch-on/switch-off to or from the network, a starter circuit may be necessary (Fig. 3b). Finally, the control parameters for the circulation pumps at the prosumers are not obvious in the case of simultaneous heating and cooling within the network. In this case, flow through one prosumer with heating demand can be either initiated by the circulation pump of the prosumer itself, or, alternatively, by the circulation pump of another prosumer with cooling demand. The CN is the easiest to control because control algorithms from "classical" high-temperature networks can be adapted. The RN is hydraulically simple to control but requires monitoring of the temperatures along the reservoir loop and continuous adjustment of the speed of the reservoir pump [31]. We attribute a weight of 8 to this criterion and scores of (9, 5, 8) for the (CN, BN, RN).

Identical and constant supply temperatures: Identical supply temperatures are essential in heat-pump driven systems to supply all prosumers with identical and thus fair boundary conditions for operating their heat pumps. This also simplifies the billing of thermal energy. Constant (or slowly varying) supply temperatures are also important for robust heat pump operation. In the RN, the supply temperature varies from agent to agent because of their serial connection. When prosumers switch on to or off from the network, the supply temperatures of the other prosumers change. The RN thus obtains the lowest score. In the BN and the CN, the agents are connected in parallel to the transmission pipes and this should guarantee identical and constant supply temperatures. However, in the BN, stagnant fluid in certain sections of the transmission pipes may occur when heating and cooling demands of neighbouring prosumers approximately balance (forming "hydraulic islands"). The temperature in the stagnant section may then change over time in a different way than in the rest of the network. When fluid in the previously stagnant section starts moving again, a temperature front travels along the transmission pipes and finally reaches the inflow of the heat pumps at the other agents. Also, in the CN, stagnant fluid may occur in the transmission pipes when prosumers are inactive, but this can be avoided by introducing a bypass to ensure a minimum rate of circulation. We attribute a weight of 5 to this criterion and scores of (9, 7, 3) for the (CN, BN, RN).

Flexible injection temperatures: Diverse plants based on renewables supply diverse outflow temperatures. Cooling tower outflow temperatures depend on air temperature. Waste heat temperatures on the process behind. Ideally, a low-temperature network can receive varying temperatures and still provide the prosumers with identical supply temperatures. The mixing of fluid in the return loop of the CN allows the injection of flexible temperatures into the return pipe of the network. In the BN, in contrast, network control is based on a fixed temperature difference between warm and cold pipe. Injection temperatures that do not fit the temperatures of the warm and the cold pipe must be adjusted (typically by mixing inflow water to the outflow water) before injection, meaning additional control effort. The RN, in principle, also allows flexible injection temperatures, but those temperatures affect the following agents along the reservoir loop and varying injection temperatures should therefore be handled with care. We attribute a weight of 5 to this criterion and scores of (9, 7, 3) for the (CN, BN, RN).

Flexible network expansion: Flexibility to network expansion is an important criterion for implementing renewables. Any network type that supports decentralised extraction and supply of thermal energy offers the opportunity for network expansion. The scores for the three alternatives are thus close to each other. Because of its meshed and symmetric structure, we assign a slight advantage to the RN. Because of the numerous control aspects, that must be considered in the BN, we assign a slight disadvantage to the BN. We attribute a weight of 4 to this criterion and scores of (8, 7, 9) for the (CN, BN, RN).

Enabling direct cooling: To enable direct space cooling (without chillers, simply by heat exchangers) the inflow temperature to the prosumers must be $< \approx 20$ °C. Such low inflow temperatures are best achieved, when mixing of warm and cold water is avoided in the network and the "quality" of thermal energy is maintained. Mixing is avoided in the BN and therefore performs best. In the CN and RN, sufficiently low temperatures for direct cooling are more difficult to maintain and may require increasing the size of the geothermal storage to decrease seasonal temperature variations in general. For the RN, increasing the flow rate in the reservoir loop is also an option. In Melbourne, direct cooling is not planned because undisturbed ground temperatures of around 18 °C at 20 m depth will result in network temperatures exceeding 20 °C during summer. We attribute a weight of 4 to this criterion and scores of (7, 9, 8) for the (CN, BN, RN).

Resilience: Systems, in which a service can be provided by different pathways are more resilient. In the three considered networks, pipe and circulation pump damage are the critical resilience aspects. The CN is the most resilient network because it has less circulation pumps than the BN and the RN. Redundant circulation pumps in the plant(s) of the CN should be ensured though. In case of control valve failure in the CN, valves can still be manually opened to prevent shortages of supply. In the RN and the BN, with circulation pumps at all agents, circulation pump failure stops the supply of fluid for heating or cooling. Between the RN and the BN, the RN is considered less resilient than the BN because the RN is additionally vulnerable to failure of the reservoir pump. We attribute a weight of 7 to this criterion and scores of (9, 7, 6) for the (CN, BN, RN).

Low resource use: Resources considered for this criterion are materials, ground and water. If the RN is realised with one transmission pipe instead of two, material for piping is reduced and less ground is moved or modified above and below the surface. This is the main aspect of this criterion. Water use refers specifically to the Melbourne case, where cooling tower ejects waste heat. Cooling towers consume water by evaporation. In Australia, water is a crucial aspect and water consumption should be minimised. Energy efficient networks that provide favourable temperature levels for heat pumps and chillers reduce the heat transfer to the network and therefore also the amount of waste heat to be ejected, which is directly related to water consumption. Between the BN and the CN with equal material and ground use, the cooling towers in the BN will consume slightly less water. We attribute a weight of 4 to this criterion and scores of (6, 7, 9) for the (CN, BN, RN).

Monitoring: Monitoring is possible for all three network types. For the CN with control valves, however, all-in-one solutions exist to monitor flow rate and temperatures simultaneously, providing live data of thermal power consumption (and supply) as well as information on critical heat pump parameters. The existence of all-in-one valve-based solutions are thus considered a slight advantage of the CN compared to the BN and the RN. Because also prosumers in BN may require valves for smooth network switch-on/switch-off (section 4), the BN has a slight advantage compared to the RN. We attribute a weight of 2 to this criterion and scores of (9, 8, 7) for the (CN, BN, RN).

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