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Implementation of an expanding thermal source network as a step towards CO_2-neutral industry

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ABSTRACT

This study analyses a modern thermal source network (TSN) currently implemented in an industrial area. The central issue under examination is how this TSN, incorporating renewable energy sources and multiple storage systems, can facilitate the decarbonisation of industrial energy supply. The TSN's planned operation demonstrates its potential to enhance the sustainability of industrial energy systems by reducing primary thermal energy consumption from 32.5 GWh/a to 19.3 GWh/a through demand balancing within the TSN, whereby the remaining demand can be met by renewable sources. Measurements indicate that during the initial operational phase, the system's behaviour differs from the originally planned full-load operation. This is due to an excess of waste heat and cold supply: Utilizing excess heat in winter maintains elevated network temperatures and enhances heat pump efficiency (seasonal performance factor up to 6), but results in network heat losses of up to 32 %. These are regarded as non-critical given the prevailing low load conditions, where not all buildings are yet connected to the TSN. The adaptive, expanding design of the portrayed TSN reveals key advantages for similar applications in industrial energy networks. It also demonstrates the potential for energetic retrofitting of large-scale industrial areas and can serve as a blueprint.

Abbreviations

5GDHC	5th generation district heating and cooling	SOC	State of charge
CH	Chiller	SPF	Seasonal performance factor
CP	Construction phase	sTES	Seasonal thermal energy storage
DOC	Demand overlap coefficient	TSN	Thermal source network
HX	Heat exchanger		

1. Introduction

A substantial share of global energy consumption is attributable to the heating and cooling of buildings: In 2022, heating accounted for approximately 50 % of global final energy consumption and 38 % of global CO_2 emissions. Approximately half of this energy consumption is dedicated to space heating or domestic hot water, while the remaining half is employed in industrial processes. Globally, only 13 % of this heating demand is met by renewable energy sources [1]. In the European Union the proportion of final energy consumption for heating and cooling is 50 % as well [2], with a share of renewable energy sources of approximately 25 % [3]. Consequently, a considerable reliance on fossil fuels remains at the global and EU levels.

Two strategies for reducing this dependency are the reduction of consumption, for instance through the enhancement of heat supply efficiency, and the integration of renewable energy sources into the heating sector. Both solutions can be implemented in heating and cooling networks [4,5]. Accordingly, the role of such networks in the future provision of heating and cooling is considered to be of great importance for a successful energy transition [2,6]. The evolution of

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heating networks over four generations, from steam-based systems to hot water systems at 60 °C, has been described by Lund et al. [5]. Østergaard et al. [7] describe the recent advances in the development of cooling networks. The integration of thermal networks with decentralised heat pumps enables a simultaneous fulfilment of heating and cooling demands through a shared infrastructure. This technical concept is frequently designated as the fifth generation of heating and cooling networks (5GDHC) [8]. Additionally, the terms “district system with simultaneous heating and cooling demand” [9], “district heating and cooling networks with decentralised substation” [10], and “bidirectional low-temperature network” [11] are encountered. The most recent addition to the terminology employed in this field is a recommendation by the IEA DHC: thermal networks which are primarily utilised as a source for heating and cooling should be labelled as thermal source networks (TSNs) [12]. The term TSN highlights the key characteristic of these systems — serving as a thermal source — while not conflicting with the generation logic.

TSNs represent a novel and emerging field of innovation, with growing significance in the context of modern energy infrastructure. In light of the mounting demand for sustainable and flexible energy systems, TSNs present a promising avenue of inquiry, offering the potential to simultaneously address heating and cooling demands. The characteristics and advantages of TSNs are described for example by Boesten et al. [13], Lindhe et al. [14], and Gjoka et al. [15]. The growing body of research in this area aims to optimize TSNs in terms of their efficiency, adaptability, and feasibility. The subject can be divided into the categories: “system design and optimisation” [16–24], “modelling and simulation” [9,25–31], and “control” [32–37].

Research on system design and optimisation explores ways to improve the hydraulic and thermal performance of TSNs. Sommer et al. [18] compare traditional TSNs with reservoir TSNs, demonstrating that optimized flow control in reservoir-based networks can enhance heat pump efficiency and reduce hydraulic losses, provided that dynamic mass flow regulation is implemented. Revesz et al. [20] expand this perspective by integrating power and mobility energy systems within TSNs, showing that such integration could lead to substantial cost and carbon savings (up to 80 %). Advancements in modelling and simulation play a crucial role in assessing and refining TSN performance. Abugabbara et al. [9] develop a Modelica-based simulation model to analyse a real-world TSN in Sweden, finding that 40 % of the network’s heat is balanced internally and total purchased energy is reduced by 69 %. Blacha et al. [25] demonstrate through dynamic Modelica simulations that a TSN at Medicon Village, a city district in Lund (Sweden), can balance 50 % of its heating and 78 % of its cooling demand internally, improving overall system efficiency. In the area of control, studies emphasize the need for intelligent energy management strategies to maximize efficiency and flexibility. Buffa et al. [32] apply model predictive control to shift up to 14 % of electricity demand for heat pumps within the TSN from peak to off-peak hours, enhancing energy efficiency and sector coupling. Taylor et al. [33] further advance economic model predictive control frameworks for TSNs, incorporating hydraulic pumps, reversible heat pumps, and multi-energy systems to optimize system-wide operation, achieving a 10.4 % reduction in energy costs compared to rule-based control. Together, these studies highlight advancements in TSN research, from system design to modelling and control. While reduction potentials vary by case, the reported values demonstrate TSNs’ impact on efficiency, cost reduction, and sustainability in heating and cooling.

This paper focuses on the application of TSNs in an industrial energy system. Industry and commerce are among the largest consumers of thermal energy [38–40]. The integration of TSNs into these systems presents an opportunity to reduce energy consumption through increased efficiency. In conventional systems, cooling demands are often met using recooling plants that consume electricity and discard the extracted heat as waste, while heating demands are fulfilled separately, often using fossil fuels. By contrast, TSNs enable the reuse of waste heat from cooling processes to meet simultaneous heating demands in other buildings. This minimizes the need for separate energy inputs and avoids the waste of valuable thermal energy. TSNs also facilitate the integration of renewable energy sources by utilizing low-temperature heat sources and high-temperature heat sinks. In the area of TSN implementation and real-world application, some related studies are available. Buffa et al. [41] conducted a statistical survey of 40 TSNs in Europe. The authors’ analysis classifies and compares the systems in terms of, e.g., their thermal sources, installed capacity or temperature level. Gabrielli et al. [42] developed an optimisation model based on the “anergy network”, which was implemented on the ETH Zurich campus. This consists of a network of interconnected buildings on the campus, with a borehole field serving as both a heat source and thermal storage. Wirtz et al. [43] conducted an analysis of 53 TSNs in Germany, demonstrating the success of implemented projects and supporting future planning processes by identifying best practice examples. In a case study of the first TSN implemented in the UK, Gillich et al. [44] describe the retrofitting of existing buildings with heat pumps, thereby enabling their connection to the TSN infrastructure without the necessity for additional remediation measures. Based on workshops with industry partners from the TSN sector, Abugabbara et al. [45] inspected best practice examples and necessary further developments, referring to four systems that have been successfully implemented in Sweden.

To date, related studies rarely refer to industrial energy systems, or only in the context of the integration of industrial waste heat sources [41–45]. Notably, none of the reported studies deal exclusively with industrial consumers, consequently lacking operational experience from this sector. Still, this is of significant consequence, as industrial systems are distinguished by elevated performance expectations, more complex demand profiles, and particular energy efficiency prerequisites in comparison to other (thermal) energy systems. Moreover, there is a shortage of attention devoted to planning aspects in conjunction with the implemented systems [43]. This study addresses these gaps by presenting the first implementation and analysis of an uninsulated TSN in an industrial context, offering significant novelty. By combining insights from the planning phase with monitoring data from the first year of operation, it provides a rare opportunity to compare planning assumptions with full-scale real-world performance.

Consequently, this paper addresses the pivotal question of how a TSN can facilitate the decarbonisation of the industrial energy supply.

To answer this question, we analyse a currently implemented modern TSN. Chapter 3 outlines the project methodology of the incampus, an industrial site in Ingolstadt where the TSN is implemented, from inception to its completion, and discusses selected planning aspects related to the system’s design. It thus represents a role model for analogous projects and offers insights into network planning. Chapter 3 also provides a technical description of the TSN in its industrial context, along with an account of the planned operational procedures. Thereby, it is demonstrated how the TSN at incampus can contribute to the sustainability of energy consumption in an industrial context. Chapter 4 presents an analysis of the initial operational experience and measurement data, illustrating the behaviour of the implemented system in real-world conditions over the first year. Although, at this point, not all planned buildings, sources, or sinks are connected to the TSN, the presented data provides preliminary insights into the validity of the planning premises and potential areas for optimisation.

2. Methodology and modelling framework

This study adopts a case study approach to investigate the technical opportunities and performance of a TSN implemented at the incampus site in Ingolstadt, Germany. The methodology is structured into the following components.

2.1. Analysis of planning documentation

The foundation of the case study is an extensive analysis of planning documentation, which informed the chapters on the general system description, pipe system comparisons, technical system description, and envisaged operation. Contextual information was derived from over 100 individual planning documents and supplemented by stakeholder interviews and discussions with the planners.

2.2. Energy balance simulation model

For specific results, such as those presented in Figs. 7 and 11, a deliberately lean energy balance model was implemented using MATLAB/Simulink with a fixed simulation step size of 1 h. The demand-side input was based on hourly demand profiles obtained from the planning documentation. These archetype-based profiles provide 8760 hourly values per building and were judged sufficiently accurate at the concept-design stage, i.e., no ex-post calibration to measured data was performed. The archetype-based approached for deriving these profiles is described in Ref. [49]. For the overall network, no detailed physical modelling was conducted. In particular, the model disregarded temperature levels and rather focused on energy flows. Similarly, distribution losses were neglected for simplification, resulting in outcomes linked to the ideal operation of the system, effectively representing a best-case scenario. The model has three hierarchical steps. First, at the building level, for every building i and hour t the net thermal demand $Q_{i,t}^{remaining}$ is obtained by a simple subtraction of the hourly cooling load from the heating load taken from the planning profiles (Eq. (1)):

$$Q_{i,t}^{remaining} = Q_{i,t}^{heating} - Q_{i,t}^{cooling} \tag{1}$$

Thus, a positive value denotes an unmet heating demand, while a negative value denotes an unmet cooling demand within the building.

Second, at the network level, all buildings' residual loads are aggregated according to Eq. (2):

$$Q_t^{network} = \sum_{i=1}^{N_{bldg}} Q_{i,t}^{remaining} \tag{2}$$

While a positive $Q_t^{network}$ represents the hourly heating deficit that must be covered by central sources or storage discharge, negative values represent cooling deficits, which need to be covered by cold sources or transferring heat into the storage.

Finally, when a storage is included in the simulation (e.g., Fig. 11), the network load charges or discharges an ideal-mix storage tank of capacity C_{max}. For each hour the tentative new state of charge (SOC) is calculated via Eq. (3):

$$\widetilde{SOC}_{t+1} = SOC_t - Q_t^{network} \tag{3}$$

and then clipped to physical limits via Eq. (4):

$$SOC_{t+1} = \min(max(0, \widetilde{SOC}_{t+1}), C_{max}) \tag{4}$$

and finally subjected to a standing-loss factor of 0.01 % h^{-1} (≈1 % per 100 h). No power-rate limits were imposed, reflecting the "best-case/concept" scope of this work.

Key numerical settings used for simulation are listed in Table 1, while the MATLAB function used to model the behaviour of the energy storage is provided in Appendix A.

2.3. Analysis of operational data

Operational data from the TSN was collected during its first year of operation (July 1, 2023 to June 30, 2024) to analyse system performance during the ramp-up phase. Data was obtained through a network of sensors, including energy meters and temperature sensors, installed at key points such as building substations, the energy hub, and along the TSN distribution pipes. Ground temperatures were also monitored at selected locations.

Table 1
Key parameters used in the simulation.

Parameter	Value	Rationale
Simulation horizon (no-storage cases)	8,760 h (1 full year)	Matches planning profiles and reporting period.
Simulation horizon (storage cases)	26,280 h (3 years)	Three-year spin-up prevents the arbitrary initial SOC from biasing storage charge/discharge behaviour.
Simulation step size	1 h, discrete	Aligns with demand-profile resolution and hourly loss factor.
Storage capacity C_{max}	0–128 GWh (scenario range)	Related to Fig. 7.
Standing loss	0.01 % h^{-1} (η = 0.9999)	Representative for seasonal thermal energy storage.
Max charge/ discharge power	∞ (not limited)	"Best-case/concept" assumption; isolates capacity effect.

The available data included heating energy demand, supply and return temperatures, flow rates, and ground temperature profiles. Most measurements were recorded at a minute resolution, and the data was processed and aggregated to generate daily, monthly, and yearly summaries. Key outputs from the analysis included a Sankey diagram illustrating heating and cooling flows, thermal demand and supply trends, and temperature profiles of the TSN and surrounding ground.

While the system is in its ramp-up phase and long-term trends may differ, the data provides valuable insights into the TSN's initial performance and highlights its operational dynamics.

3. Case study

3.1. General system description

The incampus is a 75-ha industrial estate situated in Ingolstadt, Germany. The site is located on the former premises of a refinery near the Danube River and is currently being developed by AUDI AG and the city of Ingolstadt into an innovative business park and technology centre (Fig. 1).

The history and development of the incampus site have been shaped by significant milestones, including the remediation of the former refinery and the construction of new infrastructure, as summarized in Table 2. A more detailed description of the project's history and structure can be found in Appendix B.

The ongoing transformation of the incampus is guided by sustainability criteria and resource efficiency. For instance, existing basin structures are repurposed and transformed into seasonal thermal energy storage (sTES) facilities. In the envisioned energy system, these storage facilities are to facilitate increased flexibility and utilisation of renewable energies. To minimise the primary energy demand in the system, the heating and cooling supply concept was aligned with different locally available energy sources and sinks (groundwater, river water, geothermal energy, waste heat). Further, a core component is the TSN, enabling the flow of energy between consumers and the aforementioned (low-temperature) sources, while electricity-driven heat pumps facilitate sector coupling. The more detailed rationale to invest in a TSN can be found in Appendix C.

A significant challenge for the proposed energy system is its gradual development over four major construction phases (CPs) (Fig. 2). The incampus setting represents a pioneering endeavour, as its energy system must operate effectively from the outset, when only a limited number of consumers are connected, as well as in its eventual final expansion stage (CP4), which is planned to be decades away. In this context, for example Angelidis et al. (2023) highlight that 5GDHC systems are particularly well suited to a phased network expansion [10]. Meanwhile, in 2023, the first buildings on the incampus were connected

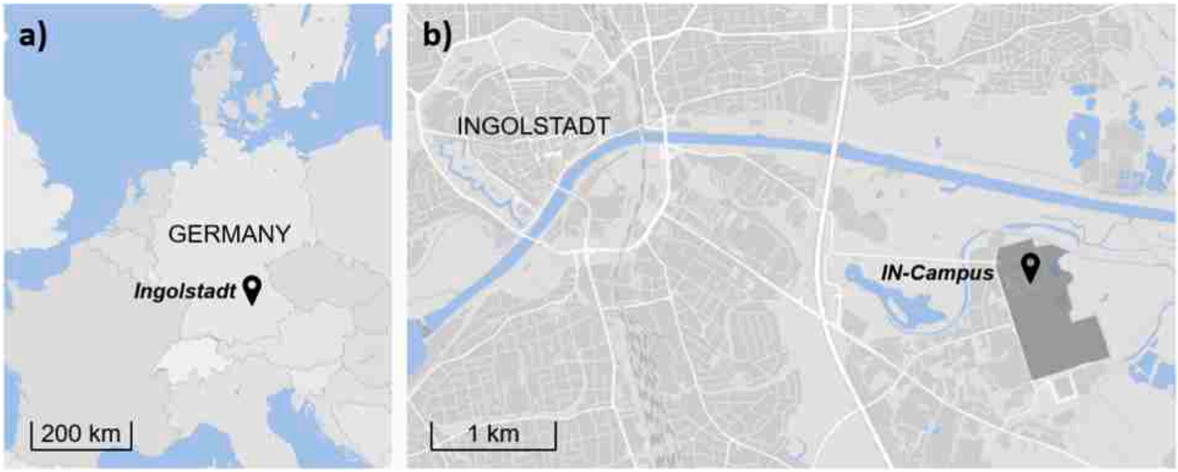

Fig. 1. a) Location of the city of Ingolstadt in Germany, and b) of the incampus in Ingolstadt (base map taken from Ref. [46]).

Table 2
Project history of incampus site.

1965–2008	Refinery operations
2010–2013	(Remaining) dismantling
2015	Foundation of IN-Campus GmbH, Acquisition of the property
2016	Adoption of redevelopment contract
2016–2018	Remediation work
2017	Approval of the development plan
2018	Start of earthworks and pipeline construction
2019–2021	Construction of energy hub
2022	Launch of data centre
2023	Start of use of security centre

to the TSN. This coincided with the commencement of waste heat utilisation from a data centre and the thermal utilisation of groundwater wells.

3.2. Comparison of different pipe systems

The technical planning process at the incampus is part of the project structure described before. It was primarily analysed by the authors based on the existing documentation for over 100 individual planning aspects. The overall logic was further refined in discussions with the planners of the energy concept to obtain a planning manual for the technical development of the site. This manual is divided into five main chapters (Fig. 3), covering fundamentals such as energy requirements, infrastructure implementation, innovative technologies, commissioning management, and monitoring strategies.

As part of phase two, technical planning and implementation, a comparative analysis was conducted between a 1-, 2-, and 3-pipe TSN, evaluating the advantages and disadvantages of each solution. The key factors taken into consideration were energy efficiency, technical feasibility, and economic aspects. Technical feasibility, in this context, primarily refers to the complexity of construction and the complexity of the control system required for each configuration. The final analysis resulted in the recommendation of a traditional two-pipe system. This decision was driven by the system's efficiency and ease of control, as well as the complexity of installation and operational reliability, which were given high priority during the assessment. A single-pipe system may offer a more straightforward installation and lower costs, but this is offset by a reduction in efficiency and a more complex control system. A three-pipe network was also evaluated, but its potential efficiency benefits were contingent upon the necessity for a third temperature level with a higher output. As this was not a requisite for the incampus, this option was rejected due to the elevated installation complexity, higher costs, and more intricate control mechanisms.

The planning process at incampus is consistent with the findings of Sommer et al. [47,48], who conducted a comparative analysis of a single-pipe reservoir network, a classical two-pipe network, and a bidirectional two-pipe network across 13 criteria related to cost, control, flexibility, and more. The analysis yielded a similar conclusion, namely that the classic network represented the optimal solution overall. The bidirectional network was identified as a slightly more efficient but

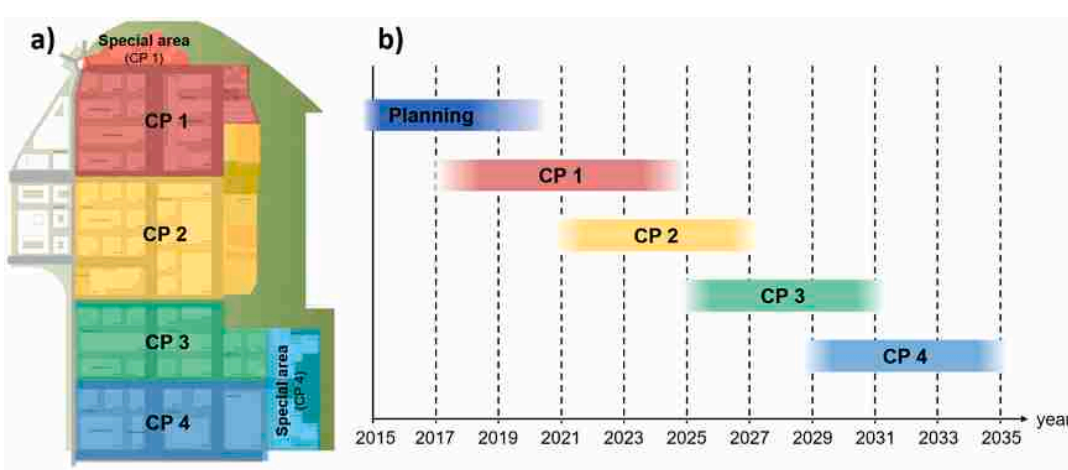

Fig. 2. a) Development plan of the incampus, indicating the construction phases (CP), and b) the timeline of the planning and construction phases.

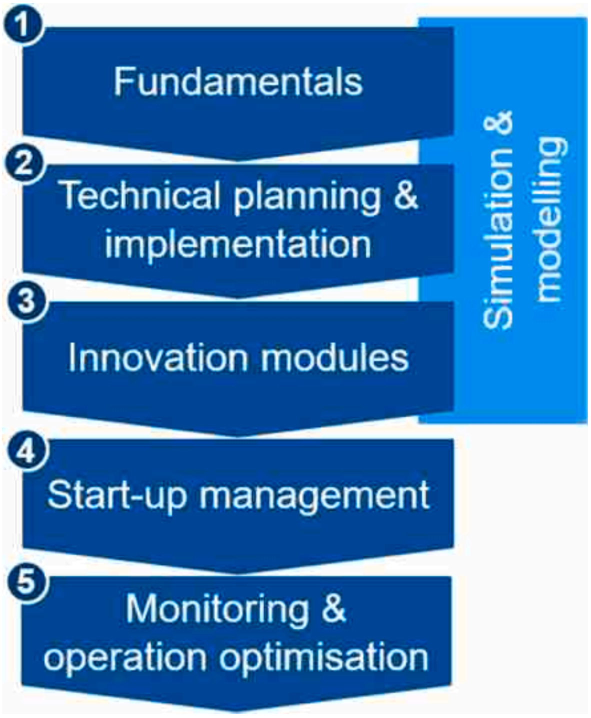

Fig. 3. Phases of technical project development at the site.

more challenging control option, while the single-pipe reservoir network demonstrated a ranking between the two in terms of efficiency.

3.3. Technical system description

3.3.1. Buildings

In the final phase of its expansion, at the end of CP4, the TSN is foreseen to connect up to 70 buildings, with a total network length of approximately 9 km and pipe diameters reaching 710 mm. Each of the buildings will be connected to the TSN via a decentralised heat pump. Fig. 4 illustrates the hydraulic connection between the heat pump, the building's heating and cooling circuits, and the TSN. The system is capable of operating in four modes.

1) Heating mode, with heat extraction from the TSN via a heat pump.
2) Free cooling mode, with heat dissipation to the TSN via a heat exchanger.
3) Mechanical cooling mode, with heat dissipation to the TSN via a heat pump.
4) Dual mode (illustrated for the predominant heating demand), where both heating and cooling are provided simultaneously. In this mode, heat is shifted within the building and additionally transferred to or from the TSN as needed.

Depending on the building demands (cooling or heating), heat can be extracted from or supplied to the TSN regardless of the temperature level. In a favourable scenario, individual building demands within the TSN are in equilibrium, thereby necessitating only a minimum amount of primary energy for heating and cooling.

To determine the required capacity of the centralised network infrastructure across all four construction phases (CP1–4, Fig. 2), the incampus development team employed "archetype-based planning profiles" (described in Ref. [49]) —simplified, bottom-up load profiles generated prior to this study. These profiles drew on generic building archetypes, standard usage patterns, and representative weather data rather than detailed dynamic simulations. Although inherently approximate, they were deemed sufficiently robust for preliminary design decisions in a greenfield project, where exact usage conditions had yet to be finalized.

As part of our analysis, we present these existing planning data for the 70 buildings, which encompass a diverse range of functions including offices, laboratories, test benches, workshops, canteens, and cafés. The resulting hourly heating and cooling demand profiles yielded a cumulative annual heating demand of 17 GWh/a and a cooling demand of 35 GWh/a across all four phases. A more detailed account of these energy demands for the buildings in the first construction phase (CP1) is presented in Fig. 5 and Table 3.

The temporal overlap of the cooling and heating demands of the buildings and in the TSN can be expressed by the demand overlap coefficient (DOC, Φ), as introduced by Wirtz et al. [50]. The proportion of simultaneous heating and cooling demands ($\dot{Q}_{simultaneous}$) is obtained by calculating the minimum between heating and cooling demands ($\dot{Q}_{heating\ demand,t}, \dot{Q}_{cooling\ demand,t}$) at each time step (Eq. (5)):

$$\Phi = \frac{\dot{Q}_{\text{simultaneous}}}{\dot{Q}_{\text{total}}} = \frac{2 \times \sum_{t \in T} \min\left\{\dot{Q}_{\text{heating demand},t}, \dot{Q}_{\text{cooling demand},t}\right\}}{\sum_{t \in T}\left(\dot{Q}_{\text{heating demand},t}, \dot{Q}_{\text{cooling demand},t}\right)} \tag{5}$$

The equation computes the ratio of simultaneous heating and cooling demands to the total energy demand ($\dot{Q}_{total}$) over a period T. For the

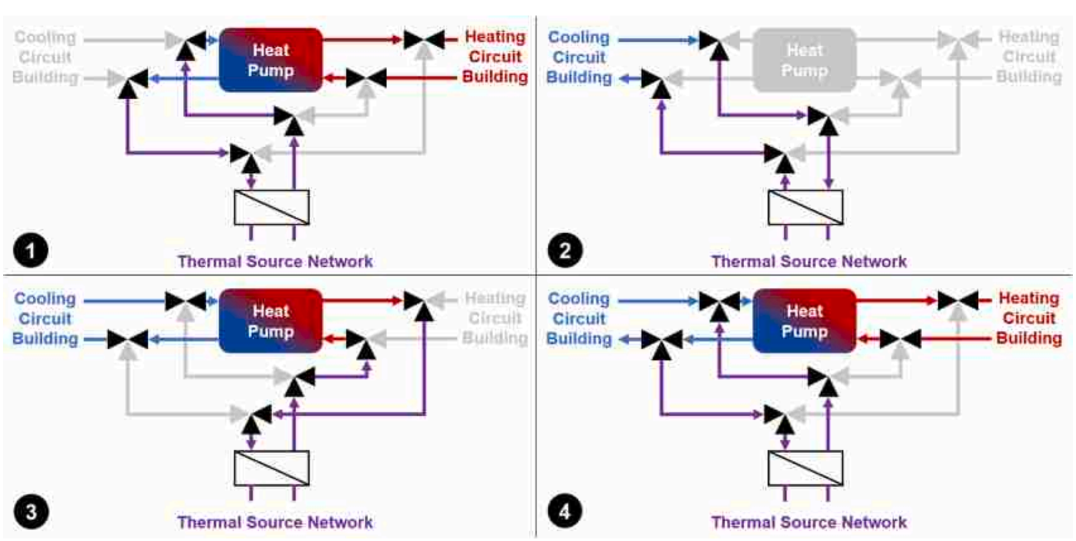

Fig. 4. Hydraulic coupling of decentralised heat pumps to the TSN and various operating states.

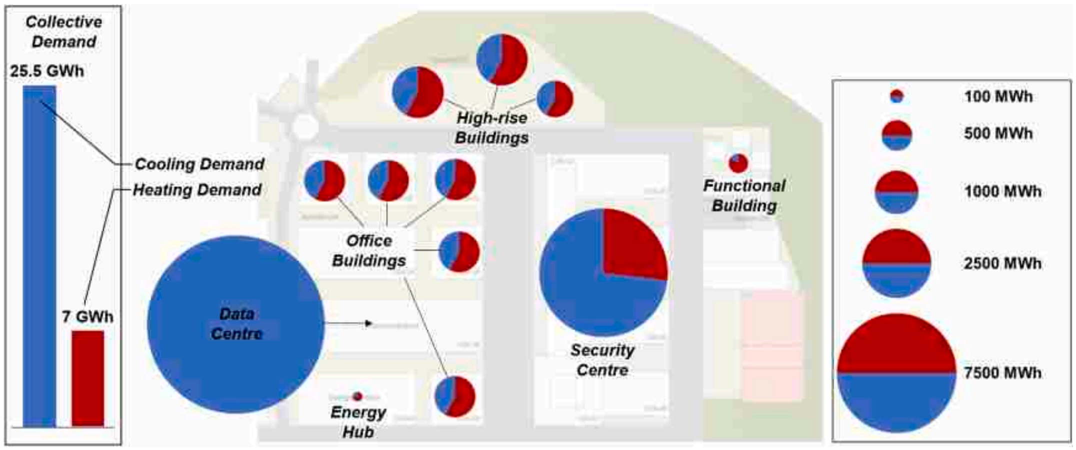

Fig. 5. Overview of the projected heating and cooling demands of the buildings foreseen in the initial construction phase (CP1) of the incampus.

Table 3
Projected heating and cooling demands, their ratio, and demand overlap coefficient (DOC) of the buildings foreseen in the initial construction phase (CP1) of the incampus.

Building	1	2	3	4	5	6	7	8	9	10	11	12
Index	C04-01	C04-02	C04-03	C04-05	C04-06	C04-07	C04-08	C06	C07-01	C07-02	C07-03	C08-01
Name/type	Office	Office	Office	Office	Data Centre	Energy Hub	Office	Security Centre	High-rise	High-rise	High-rise	Functional Building
Gross floor area (m^2)	15,000	15,000	15,000	15,000	–	310	15,000	79,368	22,320	23,970	12,150	2,400
Heating (MWh)	509	509	509	509	0	11	509	2263	781	781	413	163
Cooling (MWh)	374	374	374	374	16,000	4	374	6153	573	573	303	30
Ratio H/C (%)	58/42	58/42	58/42	58/42	0/100	73/27	58/42	27/73	58/42	58/42	58/42	84/16
Building DOC Φ	0.03	0.03	0.03	0.03	0	0.03	0.03	0.37	0.03	0.03	0.03	0.03

building level time intervals t are typically hourly, and the summation period T is usually one year. Overall, a higher DOC indicates a more equalised distribution of cooling and heating demands, in turn reducing the primary energy demand. As listed in Table 3, a low DOC of $\Phi = 3\,\%$ is projected for most of the planned buildings. This indicates that only approximately 3 % of the heating and cooling energy demand will occur simultaneously within the building and can be balanced there.

An exception in the initial CP1 concerns the Security Centre (C06), which serves multiple functions (incl. offices and laboratory/test facilities), resulting in a projected overlap of 37 % in cooling and heating demands. The general objective of internal demand balancing is to reduce the demand to be covered by the TSN.

For the unbalanced thermal demands, especially in the buildings with a low DOC, balancing via the TSN is of great interest to increase energy efficiency. Based on the planning data, the network DOC, containing all buildings of CP1, is projected to be 21.5 %. This corresponds to a heating and cooling demand of approximately 6.3 GWh/a, which is balanced via the TSN. Further, it is indicated that the winter months account for a significant proportion of the balancing (Fig. 6).

In Fig. 6b, "balanced demand" refers to the portion of heating and cooling demands that occur simultaneously, calculated as the minimum of the two at each time step. This balancing is largely influenced by the nearly constant 2 MW cooling demand from the data centre, which is matched by available heating loads during colder periods. In summer,

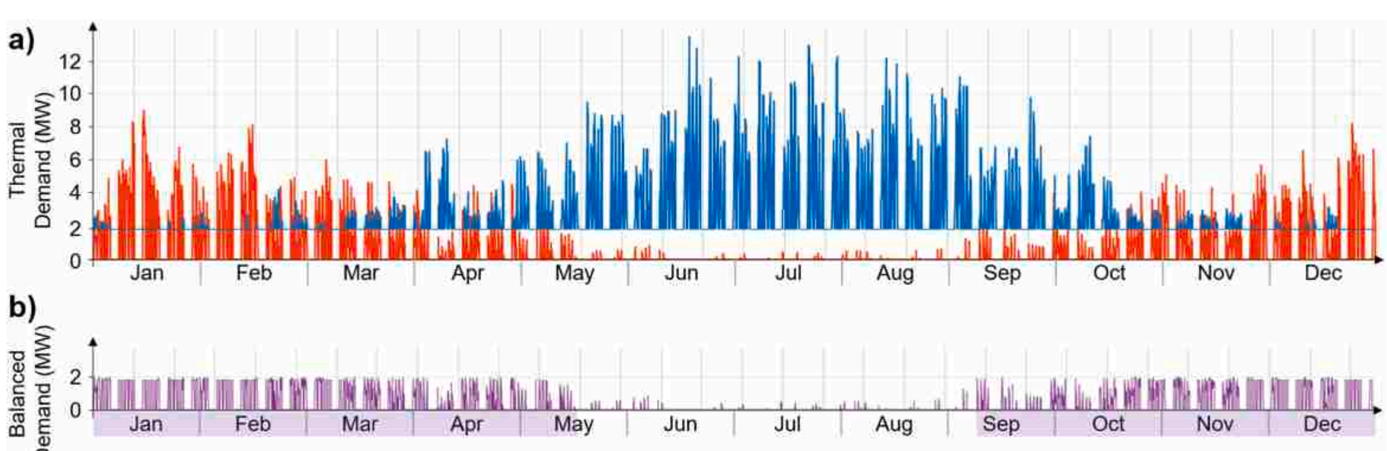

Fig. 6. a) Projected cumulative heating (red) and cooling demand profiles (blue) of the buildings in the first construction phase (CP1) at the TSN level; b) projected resulting balanced demand (purple).

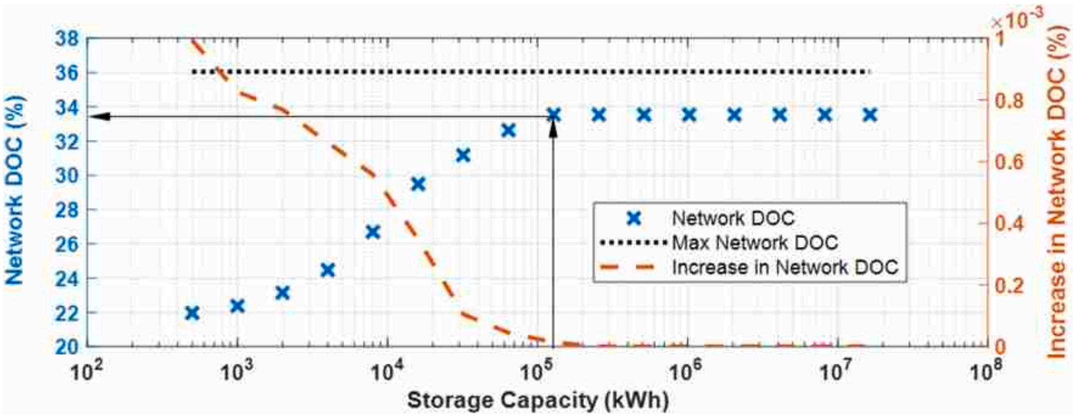

Fig. 7. Projected impact of thermal energy storage capacity on the incampus network DOC for CP1.

heating demand drops to nearly zero, leading to minimal simultaneous occurrences, as reflected by the drop in balanced demand to zero during those months.

The utilisation of thermal energy storage can typically result in an increased network DOC [50], which is beneficial for overall system efficiency. However, the inclusion of long-term thermal energy storage in the calculation of the DOC is not defined. Eq. (6) proposes a methodology for incorporating thermal energy balanced through central long-term storage ($\dot{Q}_{storage}$) into the DOC calculation:

$$\Phi = \frac{\dot{Q}_{simultaneous} + \dot{\boldsymbol{Q}}_{\boldsymbol{storage}}}{\dot{Q}_{total}} = \frac{\dot{Q}_{simultaneous} + \boldsymbol{min}\left\{\sum_{t\in T}\dot{\boldsymbol{Q}}_{\boldsymbol{storage\ charged},t}, \sum_{t\in T}\dot{\boldsymbol{Q}}_{\boldsymbol{storage\ discharged},t}\right\}}{\dot{Q}_{total}} \tag{6}$$

For a given period T, the minimum between the energy charged ($\dot{Q}_{storage\ charged}$) and discharged ($\dot{Q}_{storage\ discharged}$) from storage is identified as the amount of energy that has been effectively balanced through the storage system. Subsequently, the balanced energy is added to the simultaneously occurring heating and cooling demands to calculate the overall DOC. For CP1 the storage related variables $\dot{Q}_{storage\ charged}$ and $\dot{Q}_{storage\ discharged}$ were calculated over the entire year based on simplified energy flows, including storage losses. This approach indicates that the network DOC in the CP1 could be further increased (Fig. 7).

As anticipated, larger thermal energy storage capacities facilitate more comprehensive thermal load balancing, thereby enhancing the network DOC. However, the data also demonstrates diminishing returns in the increase of network DOC with the addition of each subsequent storage unit (Fig. 7, orange line). This is because, in order to maximize the DOC, thermal loads separated by longer time periods must be matched, requiring the energy to be stored for extended durations, which in turn increases the necessary storage capacity disproportionately.

The maximum calculated network DOC is achieved with a hypothetical thermal storage size of 128 MWh, resulting in a 12 % increase, bringing the DOC to 33.5 %. Due to storage losses in the model, this is slightly below the theoretical maximum DOC (Fig. 7, black line), which assumes perfect load balancing without losses. The maximum DOC for CP1 is just above 36 %, constrained by the limited overlap between heating and cooling demands. With cooling loads roughly four times larger than heating, even perfect balancing leaves a significant portion of unbalanced cooling demand, setting this upper limit.

3.3.2. *Thermal sources and sinks*

One objective of the energy system of the incampus is to provide the highest possible share of local, renewable energy sources to ensure low-carbon emissions and high autarky during operation. For this, the TSN enables access to low-temperature heat sources and high-temperature heat sinks (Fig. 8). A summary of these sources is provided in Table 4. Notably, the TSN at the incampus site was designed without insulation, enabling thermal interactions with the surrounding soil. This design choice plays a role in both heat and cold losses, as well as potential geothermal interactions.

Detailed descriptions of these sources and their integration into the TSN are provided in Appendix D. While the aforementioned sources (Table 4) feed the TSN centrally, the existing buildings constructed during the initial phase are equipped with additional, decentralised connections to the district heating network operated by Stadtwerke Ingolstadt, the utility company of the city of Ingolstadt. They can provide auxiliary heating power at peak demand times in winter, providing enhanced redundancy and maximised security of supply. Additionally, this allows for the decentralised heat pumps to be designed with lower nominal power, making them more efficient both economically and energetically. The connections are designed to cover 50 % of the projected maximum heating power by the heat pump and 50 % by the district heating connection, with at least 80 % of the thermal energy being provided by the heat pump during operation (and a maximum of 20 % by the district heating network). However, the overall goal for the operation of CP1, and for future CPs, is to omit the use of these district heating connections as much as possible, relying primarily on the TSN.

3.3.3. *Thermal energy storage*

As an additional component of the energy system of the incampus, several thermal energy storage units are available. They are included to compensate for mismatches between heating and cooling demands, allowing for greater system flexibility. Guelpa et al. [51] present a comprehensive analysis of the use of thermal energy storage in heating networks and show that it can contribute to lower operating costs, reduced CO_2 emissions and increased energy efficiency. Besides, Zhang et al. [52] specifically analyse the impact of short-term thermal energy storage in low-temperature heating networks, concluding that centralised units are optimal for renewable energy integration. They also

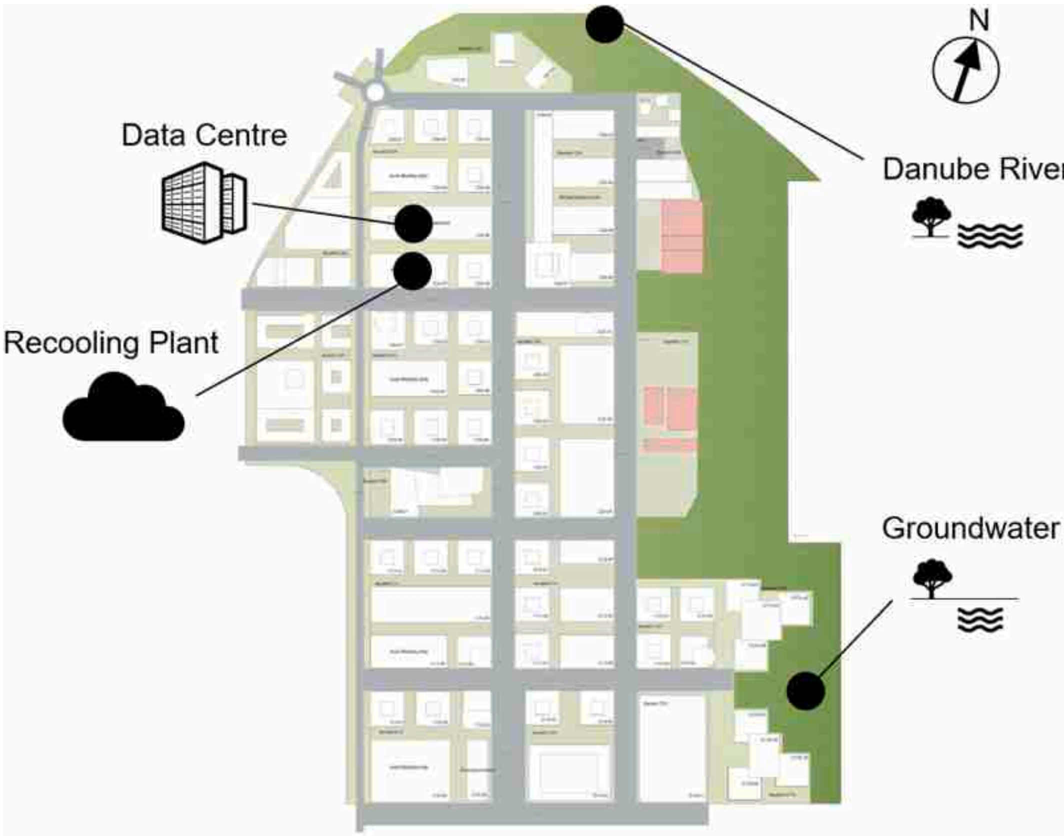

Fig. 8. Location of local, renewable thermal sources and sinks at the incampus [49].

Table 4
Overview of thermal sources and sinks at the incampus.

Source	Function	Key features	Thermal power
Danube River	Heat source/ sink	Heat source in winter and heat sink in summer; thermal potential: 10 MW; regulated to protect the ecosystem.	Up to 10 MW
Waste heat	Heat source	Waste heat from data centre; initial: 1.83 MW (14.6 GWh/a), future: 3 MW (24 GWh/a); exceeds total heating demand.	1.83 MW → 3 MW
Recooling plants	Heat sink	Located at the Energy Hub; two closed (1.6 MW) and three open units (4.4 MW) for summer cooling.	6 MW total
Groundwater	Heat source/ sink	Thermal potential of 1 MW; stable temperature year-round; paused in April for ecological reasons.	1 MW

Table 5
Summary of thermal energy storages at the incampus.

Storage	Key features	Thermal capacity
Sprinkler tanks	Primarily for fire extinguishing but also used for thermal storage; allows heating/ cooling between 10 and 25 °C; located in the Energy Hub; total volume: 3150 m^3	55 MWh
Network and soil	Pipe water volume: 1220 m^3 (CP1); 2200 m^3 (final stage); the soil around the pipes acts as a natural thermal buffer.	CP1: 14.2–42.6 MWh (10–30 K) Final: 25.6–76.8 MWh (10–30 K)
sTES	Reuses existing refinery infrastructure; water-gravel mixture (porosity: 0.4); designed for a 30 K differential.	Max. 383 MWh

highlight the increasing importance of (water-based) decentralised thermal storage as the potential to use the storage capacity of the building envelope decreases. Table 5 summarizes the centralised storage units at the incampus, including sprinkler tanks in the Energy Hub, the TSN itself and a water-gravel-based sTES. Detailed descriptions of these storages are provided in Appendix E.

3.4. Envisaged operation

The planned operation and interaction of the buildings (Section3.3.1), the thermal sources and sinks (Section 3.3.2), and the thermal energy storages (Section 3.3.3) at the incampus can be divided into two main phases. The first of these is a heating-dominated phase, with its peak demand in winter. The second is a cooling-dominated phase, with its peak demand in summer. Fig. 9 illustrates the energy flows between the buildings, sources, sinks and storage for both phases.

As illustrated in Fig. 6, the projected heating demands of the buildings are dominating from mid-October onwards. To cover these, the waste heat generated by the Data Centre can be fully transferred into the TSN, to be utilised by the decentralised buildings' heat pumps. Furthermore, thermal energy from the water-gravel sTES, which can be charged during the summer, is available for discharge into the TSN. The sprinkler tanks serve as buffers, accommodating short-term fluctuations. In addition to these primary heat sources, both groundwater and water of the river Danube are employed as supplementary heat sources.

From mid-April onwards, cooling demands predominate in the network, largely related to the Data Centre. As all other buildings have minimal or no heating demands during summer (Fig. 6), a significant portion of the waste heat from the Data Centre is foreseen to be dissipated via the groundwater. Furthermore, excess heat can be stored in the sTES or the TSN, increasing the temperature level in the pipework. Once the sTES is fully charged, additional cooling capacity can be provided via the recooling plants or as planned for the future, via the Danube.

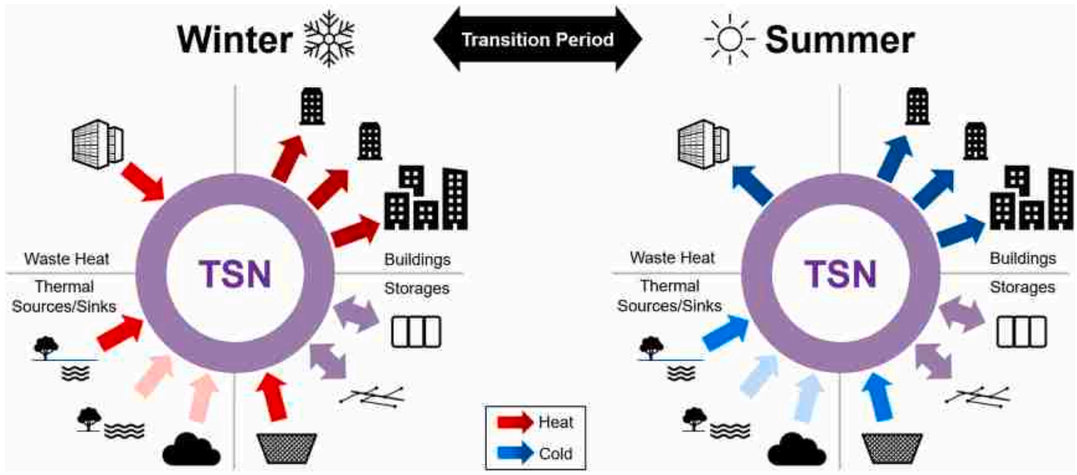

Fig. 9. Planned operating scenarios of the incampus for winter and summer, divided into buildings, waste heat and other thermal sources, and storage.

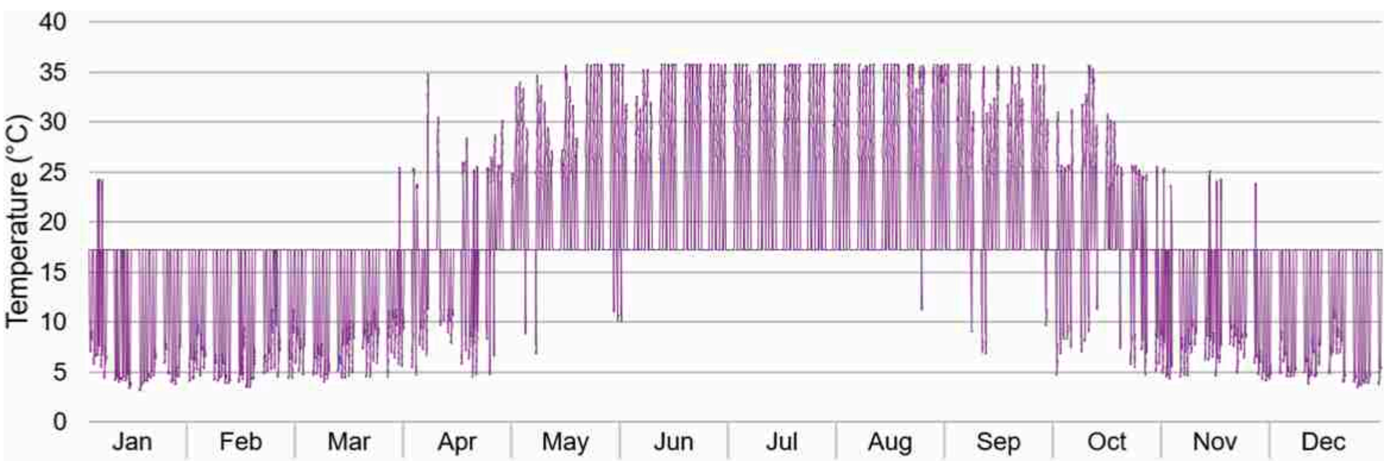

Fig. 10. Simulated annual temperature profile of the incampus TSN for the first construction phase (CP1).

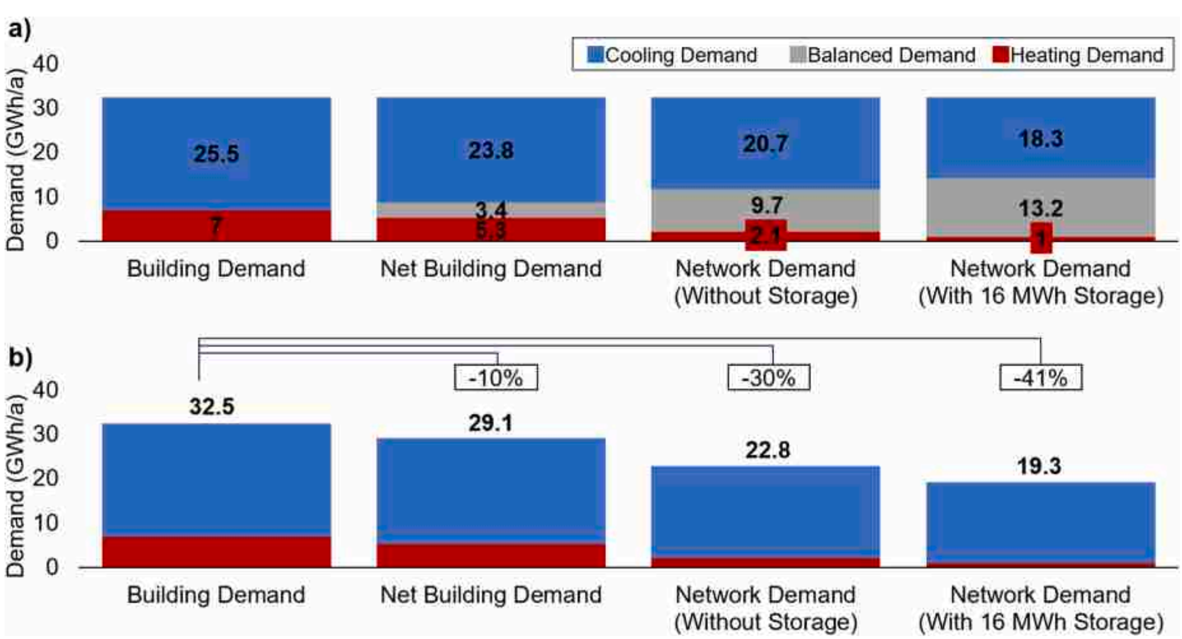

Fig. 11. Projected thermal demands of the buildings, with a) the thermal demand transferred from the TSN to the buildings, and b) the residual demand covered by the Energy Hub.

To analyse the system's behaviour under these boundary conditions, an annual temperature profile of the TSN was generated during the planning phase as part of the hypothetical operation scenario for the incampus energy system. This simulation, conducted prior to implementation, assessed the TSN's temperature distribution and aimed to evaluate the system's ability to maintain a temperature range of 5–17 °C during winter and 17–36 °C during summer. The resulting temperature profile, presented in Fig. 10, reflects planning documentation insights rather than real-world operational data.

Results show that the thermal sources and sinks identified during the planning phase are sufficient to meet the temperature demands of the TSN, despite significant daily fluctuations. Furthermore, the projected energy demands of the incampus TSN, illustrated in Fig. 11a, were derived using a simplified simulation model developed for this study, based on inputs from the planning documentation. The cumulative heating demands of all buildings in CP1 are estimated to be 7 GWh/a, while the gross cooling demands (incl. the Data Centre) may reach 25.5 GWh/a. The net heating and cooling demands correspond to the demands that cannot be balanced within the building and must therefore be covered by the TSN.

Fig. 11a illustrates that 3.4 GWh/a of thermal demands are expected to be balanced at the building level. Further, it is possible to cover further demands at the TSN level. Thereby, if no thermal storage capacities are considered, the balanced demand would rise to max. 9.7 GWh/a (i.e., 30 % of the gross demand). The incorporation of a thermal storage capacity of 16 MWh (which is approximately equivalent to the calculated storage capacity of the grid with a temperature spread of 10 K, Section 3.3.3) results in an increase in the amount of balanced demand to max. 13.2 GWh/a. This corresponds to 41 % of the gross demand, while the remaining heating (1 GWh/a) and cooling demands (18.3 GWh/a) must be covered by the thermal sources/sinks. Besides, Fig. 11b illustrates the maximum possible reduction in total heating and cooling demand, from 32.5 GWh/a to 29.1 GWh/a through balancing on the building level, and subsequently to 22.8 and 19.3 GWh/a through TSN-level balancing.

4. First monitoring results

The results of the first monitoring data of the incampus' energy system cover one year from July 1, 2023 to June 30, 2024.

The data includes the energy demand of four primary consumers (Functional Building (C08-01), Security Centre (C06), Data Centre (C04-06), and Energy Hub (C04-07)). Further, due to incomplete connections to the TSN and the ramp-up phase of several buildings, such as the Security Centre, which was not yet operating at full capacity, the overall energy demand was lower than anticipated in the planning phase. Consequently, the energy transmitted through the TSN was also lower than expected.

Additionally, the TSN connection to the Danube River and the sTES had not yet been established. Although the recooling plants were installed and ready for use, they had not been employed. Therefore, only the Data Centre represented a source of waste heat, while groundwater served as the primary source for cooling.

4.1. System energy balance

The Sankey diagram presented in Fig. 12 provides a visual representation of all energy flows, where buildings connected to the TSN are located as conventional consumers on the right-hand side. These are subdivided into the Security Centre as the main consumer and the remaining group of buildings.

Over that specific year, the consumer side (excl. Data Centre) accounted for 831 MWh of heating and 570 MWh of cooling demands. The TSN was employed to meet all cooling demands. In contrast, for heat supply, the TSN was responsible for meeting 82 % (680 MWh) of the demand. The remaining 18 % (151 MWh), occurring at peak demand, were covered via decentralised building connections to the conventional district heating network of the city of Ingolstadt (Section 3.2.5). Notably, 76 % of these peak demands occurred in December and January.

680 MWh of the heating demand was covered by the TSN on the consumption side, whereby 611 MWh (ca. 90 %) was used by the Security Centre. The heat demands at the TSN level were largely met by waste heat from the Data Centre, with a total of 868 MWh of heat fed into the TSN. In the same period, the TSN covered a total of 570 MWh of cooling demands on the consumer side, whereby 89 % were used by the Security Centre. For this, 628 MWh of cold was provided via groundwater.

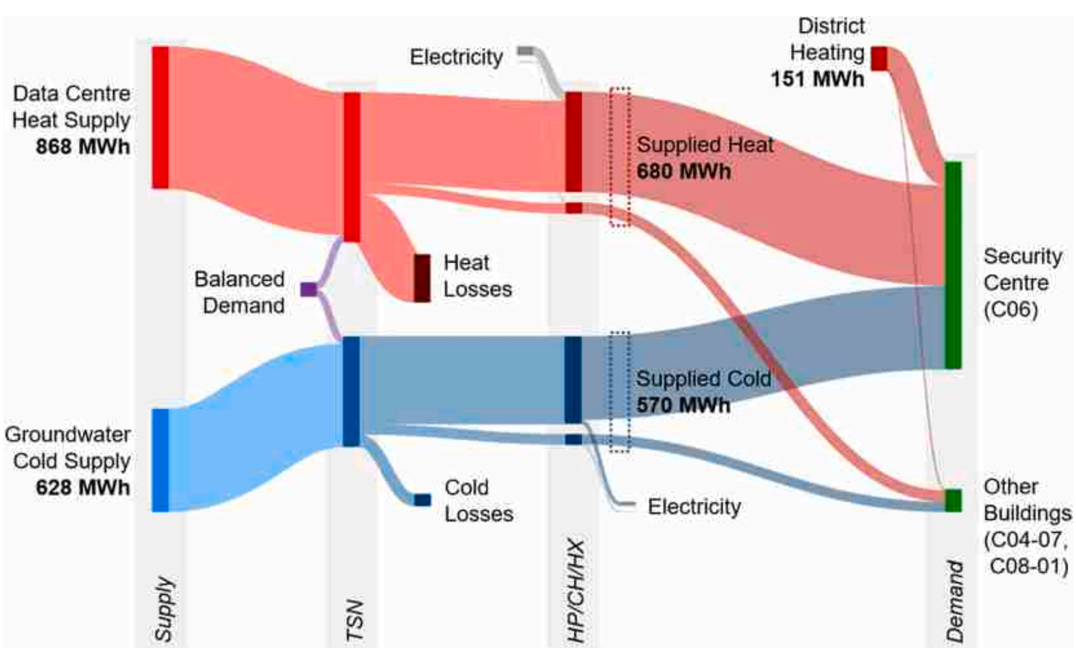

Fig. 12. Sankey diagram of the incampus TSN, illustrating the supply and demand for heating and cooling of the incampus in the first construction phase, referring to different levels (TSN: Thermal source network, HP: Heat pumps, CH: Chillers, HX: Heat exchangers).

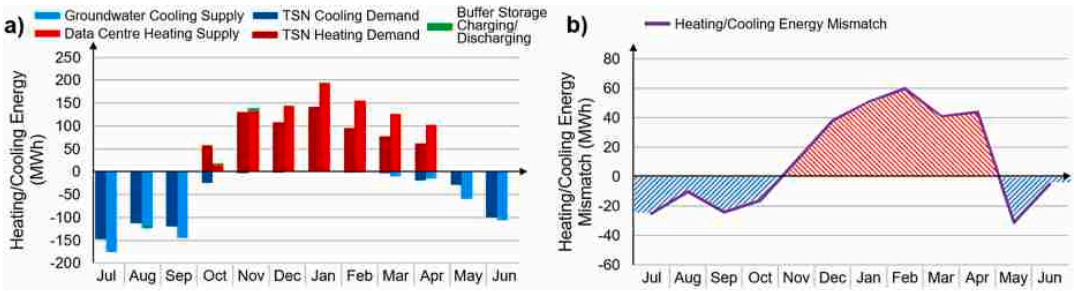

Fig. 13. a) Thermal supply and demand, and b) heating/cooling mismatch of the incampus TSN.

The losses of the TSN to the ground are classified as "heat losses" and "cold losses". The losses are expressed as a percentage of the energy supplied. In general, the heat transfer losses are in the range of 25–32 %, while the cold transfer losses are in the range of 10–15 % (this range accounts for uncertainty related to the "balanced demand" and uncertainty in the measured data related to "electricity").

4.2. Breakdown of system supply and demand structure

Fig. 13a illustrates the monthly thermal demands in the TSN and the associated thermal supplies (via groundwater and the Data Centre). Thereby, the apparent mismatch is largely due to thermal losses, but it is also influenced by changes of the TSN temperature and thus the storage or release of energy. Further, Fig. 13b illustrates that the energy mismatch during predominant heating (i.e., from November to March) exhibits a range of 11–60 MWh per month. In general, the discrepancy between cooling supply and demand is less pronounced: in cooling-dominated months (i.e., from May to September) the difference ranges from 5 to 31 MWh per month.

5. Discussion

This study provides the first documented evaluation of an uninsulated TSN in an industrial setting. By integrating planning-phase considerations with real-world operational data from the first year, it enables a direct comparison between initial assumptions and actual system performance, offering valuable insights into the practical feasibility and efficiency of such networks.

The monitoring data, as exemplified in Figs. 12 and 13, demonstrates that the TSN is fully capable of supplying the thermal energy required by the connected buildings during the initial operational phase. During the first year of this ramp-up process, 868 MWh of heat from the Data Centre, and 628 MWh of cold from the groundwater wells were provided to the TSN. This energy was then used to meet demands of the Functional Building, Security Centre, and Energy Hub, supplying 680 MWh of heat and 570 MWh of cold. However, the data also highlights that the proportion of balanced demands remains minimal. This is largely due to the limited number of connected buildings and the low degree of heterogeneity in the energy demands of the current consumers. These findings underscore the importance of continued system expansion to fully realize the potential of demand balancing within the TSN.

These findings are complemented by additional insights into the system's heat and cold losses. Measurements revealed losses in the range of 25–32 % for heat and 10–15 % for cold. These values are considerably higher than simulation-based heat loss predictions of 10 %, that have been reported for comparable systems [9]. This is because the system is not operating at full capacity. The Data Centre and groundwater currently provide an excess of low-cost waste heat and cooling, which is employed to maintain the TSN temperatures within a favourable range for the heat pumps (see Fig. 14a). In other words, the temperature difference between the source and sink sides is kept relatively low, thereby improving the heat pumps' coefficient of performance. Consequently, the minimization of thermal losses driven by these TSN temperature levels is assigned a lower priority. This results in an overall seasonal performance factor (SPF) of 6 in heating mode and 8 in cooling mode, both of which can be considered good for heat pumps and chillers. Unlike a momentary coefficient of performance (COP)—which refers to the instantaneous ratio of heat output to electrical power—the SPF aggregates performance over an extended period, accounting for variations in load, runtime, and operational conditions.

The heat and cold losses contributing to the energy mismatch are further illustrated in Fig. 14, which highlights the role of the temperature difference between the uninsulated TSN pipes and the surrounding ground. This temperature difference drives thermal interactions and significantly influences the energy mismatch. As part of the energy system monitoring, this mean temperature difference is illustrated in Fig. 14b, derived from absolute measurement data (Fig. 14a).

As expected, the results reveal that the dynamics of the energy mismatch (Fig. 13b) exhibit a strong correlation with the temperature difference (Fig. 14b). Additionally, the variation of the TSN temperature exerts an influence on the energy balance of the system, which is particularly present in October (Fig. 14a), when the system transitions from a cooling-dominated operation during summer to a heating-dominated operation. There, over a period of only four days, the temperature drops from 21 to 14 °C. This reduction is equivalent to 10 MWh of heat, which otherwise would have had to be covered by the Data

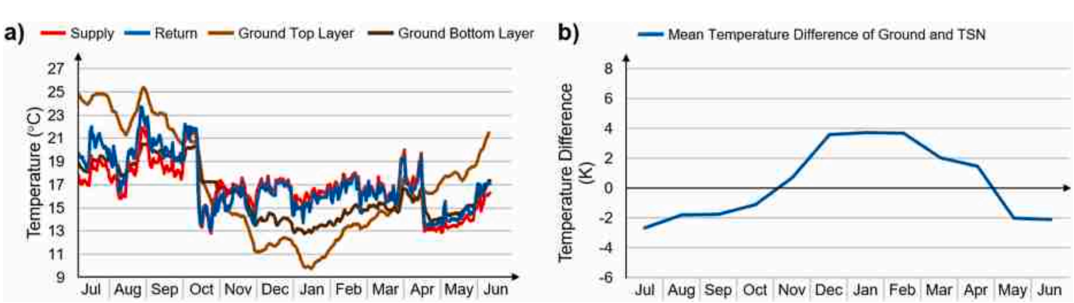

Fig. 14. a) Temperature profiles of TSN supply and return pipes, and ground top and bottom layer, and b) mean temperature difference between TSN pipes and the ground.

Centre's waste heat. Further, this corresponded to 17 % of the heating demand for this month. During more stable temperature periods (e.g., from December to March), the primary cause of the energy mismatch must be attributed to thermal losses.

As illustrated in Fig. 13b, the heating energy mismatch (represented by the red-striped area) exceeds the cooling energy mismatch (blue-striped areas) throughout the year. Combined with Fig. 14, which shows that the mean network and ground temperatures at the end of the year return to levels similar to those at the beginning, this suggests that the greater heating mismatch reflects overall heating losses in the system.

As observed, the surplus of waste heat generated by the Data Centre is employed to maintain elevated temperatures within the TSN during winter. This is also demonstrated by a comparison of the projected temperature profile of the TSN in CP1 at full load (Fig. 10) with the measured TSN temperatures in the selected monitoring timeframe, as illustrated in Fig. 15.

In comparison to the projected temperature profile in winter, which fluctuates between the pre-defined, upper and lower limits of 5 and 17 °C, the measured temperature profile demonstrates a consistently elevated average of 16 °C (see Fig. 15). This increases the efficiency of the heat pumps yet results in considerable thermal losses. Nevertheless, these losses are inconsequential, as surplus heat would otherwise require energy-intensive dissipation through recooling systems. The current approach is more efficient and, under low load conditions, represents an appropriate strategy. Besides, if heating and cooling demands grow, the TSN temperatures could be lowered in winter and raised in summer to reduce losses and potentially convert them into geothermal gains. A reduction in TSN temperature during winter could result in the TSN being cooler than the surrounding ground, leading to a heat transfer from the ground into the TSN — essentially a heat gain for the system. Conversely, an increase in the TSN temperature in summer could raise it above the ground temperature, allowing for heat transfer from the TSN into the ground, thereby generating cooling gains for the system.

Overall, the monitoring data confirms the TSN's effectiveness while highlighting differences compared to the planning assumptions. These findings must be considered within the context of the system's ramp-up phase, as discussed in the following limitations.

It is important to note that, during the measurement period from July 1, 2023 to June 30, 2024, neither all buildings planned for CP1, nor all of the thermal sources and sinks were connected to the TSN. This limitation also applies to the available storage units. Given the phased expansion of the incampus TSN, more time will be needed to fully evaluate and validate certain planning assumptions against measurement data. As the system approaches full operational capacity, future studies will be better positioned to assess long-term performance and potential deviations from planning expectations.

Some assumptions made during the planning phase were highly simplified, as were the simulations conducted for this study, which focused on energy flows while disregarding detailed physical interactions, such as temperature dynamics and distribution losses. While these simplified approaches provided valuable insights, more detailed physical models could yield deeper understanding and more precise results for the TSN's behaviour under varying conditions.

6. Conclusion and outlook

This study presents an analysis of the energy system of the incampus site, focusing on its modern, expanding TSN in an industrial environment. Based on a technical description of the site and an assessment of the planning and initial operational experience, the system demonstrates the potential to establish new standards in several key areas:

One key aspect is the transformation of the incampus site, which was previously a refinery, into a modern, sustainably operated industrial park. This illustrates the viability of innovative solutions in the conversion of industrial areas, thereby providing a model for future retrofitting projects.

In terms of planning, one of the main insights is a projected reduction of primary thermal energy demands from 32.5 GWh/a to 19.3 GWh/a that can be achieved through effective demand balancing within the TSN, and the utilisation of local, renewable energy sources, such as waste heat from a data centre, and groundwater-based cooling. This illustrates the potential of TSNs to enhance the sustainability of industrial energy systems.

Initial operational monitoring results substantiate the efficacy of the planning logic underlying the TSN: in particular, its enhanced flexibility is enabled by the TSN design, and its capacity to ensure efficient operation during a gradual operational ramp-up. Although the system exhibits disparate behaviour during low load operation compared to its anticipated full-load performance, the pivotal advantages of the TSN can be already identified. The system can utilise renewable energy sources to meet its energy demands and demonstrates high flexibility and robustness. While the surplus of waste heat and cold during this phase results in higher heat losses, they are not to be seen as critical under low load conditions. Instead, they contribute to raise the TSN temperatures to levels that allow the decentralised heat pumps to operate more efficiently. The TSN's operational flexibility, in conjunction with the integration of renewable energy sources, validates its core design principles, offering a scalable approach for retrofitted and/or modernised industrial sites.

However, achieving benchmark status will require further validation, particularly as the system approaches full-load operation. Future

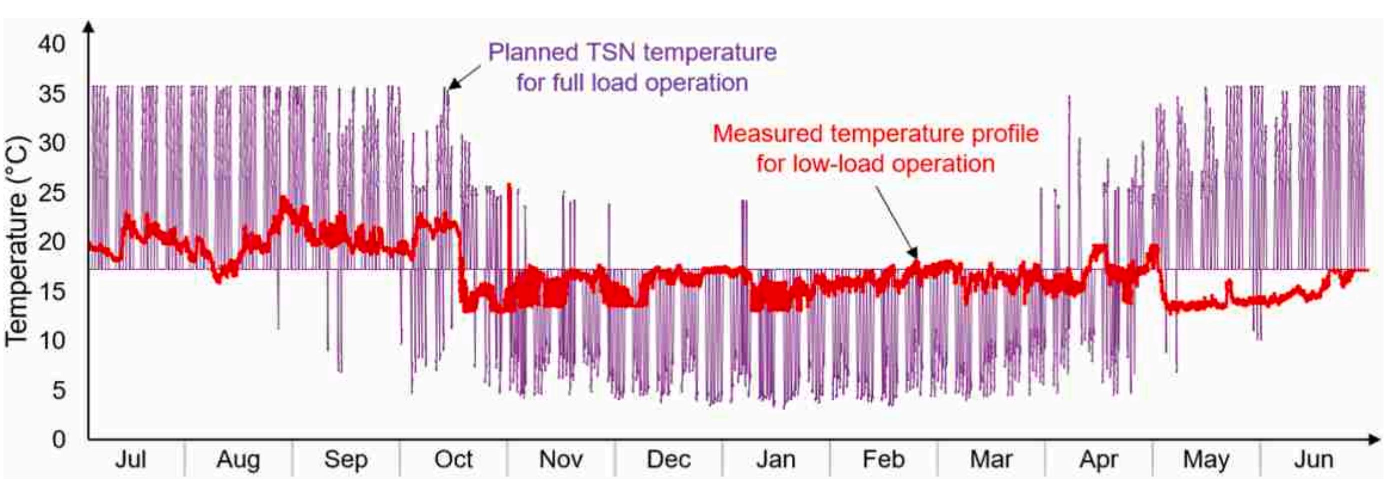

Fig. 15. Comparison of planned temperature profiles of TSN in full-load operation and measured temperature profile of TSN.

research should focus on analysing the TSN's role as thermal storage, the impact of temperature variations on thermal losses or gains, and the overall system efficiency, including the performance of decentralised heat pumps. Additionally, improving control algorithms for complex energy systems and conducting an economic analysis — potentially including a cost-benefit or lifecycle analysis — will be essential to ensure the long-term viability and competitiveness of TSNs. Finally, the scalability of the incampus energy system and its application to other industrial sites should be further assessed, ensuring TSNs contribute meaningfully to industrial decarbonisation.

CRediT authorship contribution statement

Simon Müller: Writing – original draft, Visualization, Conceptualization. **Christoph Bott:** Writing – review & editing. **David Schmitt:** Writing – review & editing, Supervision. **Markus Faigl:** Writing – review & editing. **Klaus Göttl:** Writing – review & editing. **Rainer Strobel:** Writing – review & editing. **Peter Bayer:** Writing – review & editing, Supervision. **Tobias Schrag:** Writing – review & editing, Supervision, Project administration.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used *ChatGPT* by OpenAI and *DeepL* Translator by DeepL SE in order to improve language and readability. After using these tools/services, the author(s) reviewed and edited the content as necessary and take(s) full responsibility for the content of the publication.

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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.136766.

Appendix B. Project history and structure

The project development of the incampus started with the refurbishment and re-development of the brownfield that represents a former refinery site. Secondly, a joint venture, IN-Campus GmbH, was established. The third phase focused on extensive construction work, and finally the commissioning of new infrastructure and facilities over more than a decade (Fig. 3a). The former refinery was in operation from 1965 to 2008. The dismantling of the remaining tanks and process plants on the former refinery site commenced in 2010 and was concluded in 2013. IN-Campus GmbH was established in April 2015 and acquired the industrial site in November 2015. The remediation process, which entailed the removal of 900 tonnes of heavy fuel oil and 200 tonnes of light petrol and fluorinated chemicals, commenced in 2016 with the adoption of the remediation contract and concluded in 2018. Specialised remediation techniques, including air sparging — where air is injected into the contaminated ground to strip pollutants from the soil [53] — and soil washing, a water-based process used to scrub contaminants from soils [54], were employed throughout this period. In April 2017, the development plan for incampus was approved, and construction of the site started in 2018. The Energy Hub was constructed between July 2019 and December 2021. The Data Centre commenced operation in July 2022, followed by the vehicle Security Centre and the completion of the infrastructure and outdoor facilities in 2023 [55].

Appendix C. Extended rationale for the Thermal Source Network

Alignment with sustainability goals

From the outset, project stakeholders at the incampus prioritized a low primary energy demand, reduced CO_2 emissions, and a high degree of flexibility for future expansions. Although no direct policy or regulatory incentives were in place, Audi AG's and the city of Ingolstadt's sustainability targets strongly supported the pursuit of an innovative, low-carbon solution.

Effective utilisation of local and renewable resources

The incampus offered access to several low-temperature heat sources—notably waste heat from a data centre, and heat/cold from groundwater wells and the Danube River. These sources align naturally with a low-temperature TSN, enabling efficient waste heat recovery and renewable energy integration. Conventional district heating or separate heating and cooling networks would have operated at higher temperature levels, limiting the efficient reuse of waste heat and requiring greater energy inputs.

Flexibility and modular expansion

A core planning requirement was the ability to scale the network over multiple construction phases. The lower *operating* temperatures and decentralised heat pumps of a TSN make it easier to add new technologies (such as geothermal) or connect additional buildings in the future. This modular approach enables the system to remain operationally efficient even with a small initial load, and then adapt smoothly as more buildings and

energy sources come online.
Risk mitigation and long-term viability

Considering potential future increases in fossil fuel prices and the desire to limit exposure to external market fluctuations, the TSN's low primary energy requirement and reliance on local energy sources reduce long-term cost risks. Although the initial investment may be higher, the system offers improved energy *efficiency* and reduced CO_2 emissions, aligning with corporate and municipal sustainability objectives.

Benchmark for innovative energy infrastructure

Finally, the incampus joint venture—backed equally by Audi AG and the city of Ingolstadt—envisioned the site as a *model* for industrial parks, showcasing advanced energy solutions that can integrate new technologies over time. The TSN's design reflects this ambition, serving as a demonstration of how industrial-scale projects can be both environmentally friendly and economically viable in the long run.

Appendix D. Detailed description of thermal sources and sinks

Danube River

Provided that approval is granted by the Bavarian State Ministry for the Environment and Consumer Protection, the Danube River will be used for both heating and cooling purposes. To do so, water from the river will be extracted, passed through a heat exchanger, and afterwards recirculated into the river. During the winter months, the potential for heat transfer from the river is constrained by a lower temperature limit of the TSN, which is 5 °C. This must be considered by the centralised system control, which then resorts to alternative sources and thermal energy storage facilities. For cooling during summer, the temperature of the water discharged will be restricted to a maximum of 30 °C. Furthermore, any dissipation of heat will only be permitted when the river temperature is below 25 °C [56]. A review of temperature data for the Danube over the past four decades shows that the river temperature during the summer months frequently reached 25 °C, which limits its potential for cooling. However, the maximum temperatures, typically around 26 °C, tend to occur a few days later than peaks in ambient temperatures. These operating specifications are intended to limit the critical discharge of heat into water bodies in summer and the effects on the river's ecosystem, as *discussed* by, e.g., Gaudard et al. [57]. Based on these boundary conditions, a maximum volumetric flow rate for extraction/injection of 900 m^3/h is foreseen. Together with an allowed maximum temperature difference of 9.5 K between the extraction and injection, this offers a thermal potential of up to 10 MW.

Waste heat from the Data Centre

The Data Centre at incampus generates a considerable quantity of waste heat. In its initial phase, it will be capable of generating an average thermal waste heat output of 1.83 MW, which is equivalent to approximately 14.6 GWh/a. It is anticipated that the potential will increase in the future, reaching approximately 3 MW (i.e., 24 GWh/a), due to expansion of computing capacities. It is evident that this heat potential exceeds the total heating demand of the buildings (cf. Chapter 3.1) and cannot entirely be distributed or *stored* in the incampus' energy system. Consequently, a proportion of the surplus waste heat will be dissipated into the ambient environment. Nevertheless, the integration of this waste heat utilisation contributes to the TSN net energy efficiency [49].

Recooling plants

The recooling units on the Energy Hub roof release excess heat into the atmosphere. Two closed cooling units (without water evaporation) can provide a cooling capacity of 1.6 MW, while three open recooling units (with evaporative cooling) can deliver 4.4 MW. These open units are particularly foreseen for summer when external temperatures are elevated, and peak cooling demands are reached. Altogether, the plants can *provide* a cooling power of 6 MW and are designed to compensate for all cooling demands of CP1.

Groundwater

In light of the former refinery operation at the incampus site, ten groundwater wells are deemed necessary to treat potentially contaminated groundwater and prevent its drainage. Thereby extracted groundwater is connected to the incampus network via heat exchangers and can be employed as both a thermal source and sink (Fig. 16). Given an allowed maximum temperature difference of 5 K between extraction and injection, along with a *maximum* volumetric flow rate of 170 m^3/h, the potential thermal power will yield 1 MW [49]. The constant temperature profile of this source/sink allows for a more predictable potential than with other sources (e.g., Danube River). However, the operation of the groundwater extraction wells will be interrupted each April, to prevent effects on the spawning season of local amphibian species. This interruption occurs at a time when alternative cooling sources, such as the Danube River, are available and total cooling demands remain relatively low.

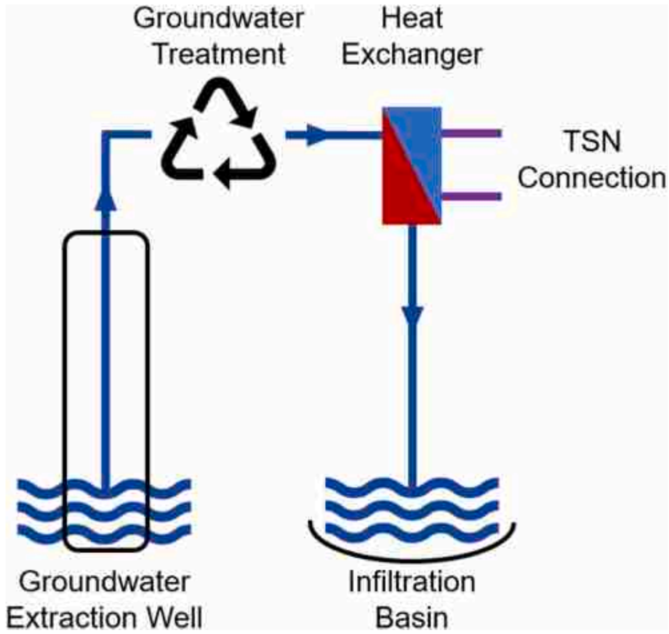

Fig. 16. Connection of the groundwater wells to the Thermal Source Network (TSN).

Appendix E. Detailed description of thermal energy storage

Sprinkler tanks

Sprinkler tanks at the incampus are primarily intended for fire extinguishing purposes but also serve as a secondary benefit for thermal energy storage. Located in the Energy Hub, they comprise a total volume of 3150 m^3, divided into three individual tanks of 750 m^3, 1200 m^3 and 1200 m^3. Heating or cooling the water is foreseen in a temperature range of 15 K (between 10 and 25 °C), providing a thermal capacity of 55 MWh. *The* maximum charging/discharging power is designed to be 1.5 MW, to balance peak demands on a daily scale.

Network and soil

CP1 of the network will result in a total water volume of 1220 m^3 within the TSN pipes. In the final stage (CP1–4), this volume is designed to reach 2200 m^3. Assuming a temperature difference of 10 K [52,58], this results in a capacity of 14.2 MWh for CP1, and 25.6 MWh in the final expansion, respectively. Assuming a seasonal temperature difference of 30 K (35 °C in summer, 5 °C in winter), this results in a capacity of 42.6 MWh for CP1, and 76.8 MWh in the final expansion, respectively. However, it should be noted that the pipes were installed without insulation, to allow for additional thermal interaction with the surrounding soil. In addition to potentially increased heat or cold losses, the surrounding soil is expected to act as a natural buffer, storing and releasing thermal energy, which is intended to provide additional capacity.

Seasonal thermal energy storage

The largest planned storage capacity of the incampus will be provided by a sTES system. The construction of this facility will be based on re-utilisation of the existing infrastructure of the refinery, i.e., its former fire *extinguishing* water basins. In comparison to other sTES, the reuse strategy is employed to result in enhanced sustainability and cost-effectiveness [59–61], and the combined re-use of multiple basin infrastructures as sTES improves operational flexibility [62].

The sTES will be designed as a water-gravel storage with a net volume of $V = 18{,}000$ m^3. Assuming an average density of the water-gravel mixture (with a porosity of 0.4) of $\rho = 1420$ kg/m^3 [63], and a specific heat capacity of $c_p = 1800$ J/kgK, a volumetric specific heat capacity of 2556 kJ/m^{3}K will be obtained. Further, assuming a maximum temperature differential of 30 K (equivalent to the designed TSN temperatures, Section 3.3.2) [64], the thermal capacity of the sTES may comprise max. 383 MWh, whereas avoidance of insulation may again yield increased thermal storage capacity due to interactions of the sTES with its surrounding subsurface [65].

Data availability

Data supporting the findings of this study are derived from internal planning documents and grey literature associated with the incampus TSN system, which are not publicly available due to confidentiality and proprietary considerations. These documents include detailed project plans, technical specifications, and internal analyses, which are property of the respective project stakeholders. Importantly, some of this grey literature was co-authored by authors of this paper, ensuring that the interpretations and conclusions presented herein accurately reflect the original planning intentions and analyses. For further inquiries about the data or to request access to specific information under appropriate confidentiality agreements, please contact the corresponding author.

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