ISEC 2024 – 3rd International Sustainable Energy Conference
Future District Heating and Cooling
https://doi.org/10.52825/isec.v1i.1152

Published: 18 Apr. 2024

Analysis of Industrial 5GDHC System in Ingolstadt

A Step Towards CO_2-Neutral Industry

Simon Nikolaus Müller[1,*], Rainer Strobel[2], Markus Faigl[3], and Tobias Schrag[1]

[1] University of Applied Sciences Ingolstadt, Institute for new Energy Systems (InES), Germany
[2] Planungsgruppe M+M AG, Technical consulting, Germany
[3] AUDI AG, Factory planning, Germany

*Correspondence: Simon Müller, simon.mueller@thi.de

Abstract. This study comprehensively examines the technical manifestation and planning process for a shared thermal energy network at a 75-hectare industrial area in Ingolstadt. Unlike traditional systems, this (5GDHC) network showcases a smart integration of energy flows across 70 buildings with a yearly heating demand of around 17 GWh and a yearly cooling demand of around 35 GWh. The network spans over 9,100 meters of piping with diameters up to 800 mm. With thermal power from various sources including 1.8 MW waste heat from a data centre and potential for 10 MW from the Danube River, the system epitomizes a dynamic balance of heating and cooling demands. The paper itself examines the planning process of the system and encompasses topics such as defining energy requirements and load profiles, assessing potential energy sources and sinks for enhanced system efficiency, and analysing pipe and network design. Through this investigation, the study provides valuable insights towards a methodology to facilitate the successful implementation of future industrial 5GDHC systems, furthering the cause of sustainable energy.

Keywords: 5GDHC Network, Industrial Energy Planning, Sustainable Energy System, Industrial District Heating and Cooling

1 Introduction

The IN-Campus in Ingolstadt, Germany, demonstrates a new era in energy supply with its fifth-generation district heating and cooling (5GDHC) network. This system distinguishes itself from traditional district heating by enabling energy sharing among connected entities and balancing heating and cooling demands dynamically within the same network (see Figure 1). Lower operating temperatures of the network (5-30°C) and the use of decentralized heat pumps to tailor supply temperature to specific building needs are main characteristics. This approach is pivotal for achieving the campus's goals of maximal efficiency and carbon neutrality.

Despite the promise of 5GDHC technology, the current research landscape reveals a notable scarcity of planning guidelines and operational data, reflecting a nascent field grappling with standardization [1, 2]. Prior research has often bypassed the critical early planning stages, focusing predominantly on residential settings and leaving a gap in guidelines applicable to industrial contexts [3, 4].

This study embarks on exploring previously uncharted territories by providing a comprehensive description and analysis of the IN-Campus energy system, alongside an examination of its planning stages. While this work primarily lays the foundation with a systematic assessment, it sets the stage for future efforts in developing guidelines and more generalized approaches for 5GDHC systems.

Addressing Environmental Impact and Technical Challenges

The environmental merits of 5GDHC systems are substantial, particularly in their capacity to harness renewable energy sources and waste heat more efficiently than conventional district heating systems that typically rely on fossil fuels (see Figure 1). This inherent efficiency stems from their ability to operate at lower temperature levels, thus paving the way for a more sustainable energy future by significantly reducing carbon emissions and enhancing energy conservation.
The application of a 5GDHC system on the scale of an industrial area like IN-Campus is pioneering, introducing a degree of uncertainty due to the lack of precedents. Additionally, industrial settings often demand high-temperature levels for specific processes, contrasting with the lower temperature regime of 5GDHC systems. Despite these challenges, the versatility of 5GDHC systems to meet varied demands – including traditional space heating and cooling for offices, laboratories, and test benches – underscores their potential to revolutionize energy solutions in non-residential as well as in residential areas.

Description of the IN-Campus Energy System

Strategically engineered to serve a 75-hectare industrial park for research and development, the IN-Campus 5GDHC network is planned to span over 9,100 meters of piping. Gradually expanding over four construction phases it will connect up to 70 non-residential buildings like offices, laboratories or test benches when reaching its final dimensions. The network itself combines properties of a heat source and sink, and a thermal energy storage. In terms of additional heat sources, the system capitalizes on the thermal output of a data center, effectively converting its waste heat of 1.8 MW in the initial phase and up to 4 MW when reaching the final expansion into a valuable energy source. Groundwater wells, serving dual roles as thermal sources and sinks, complement the system with a thermal capacity of around 1 MW. The thermal exploitation of the nearby Danube River for cooling as well as heating purposes is also possible.

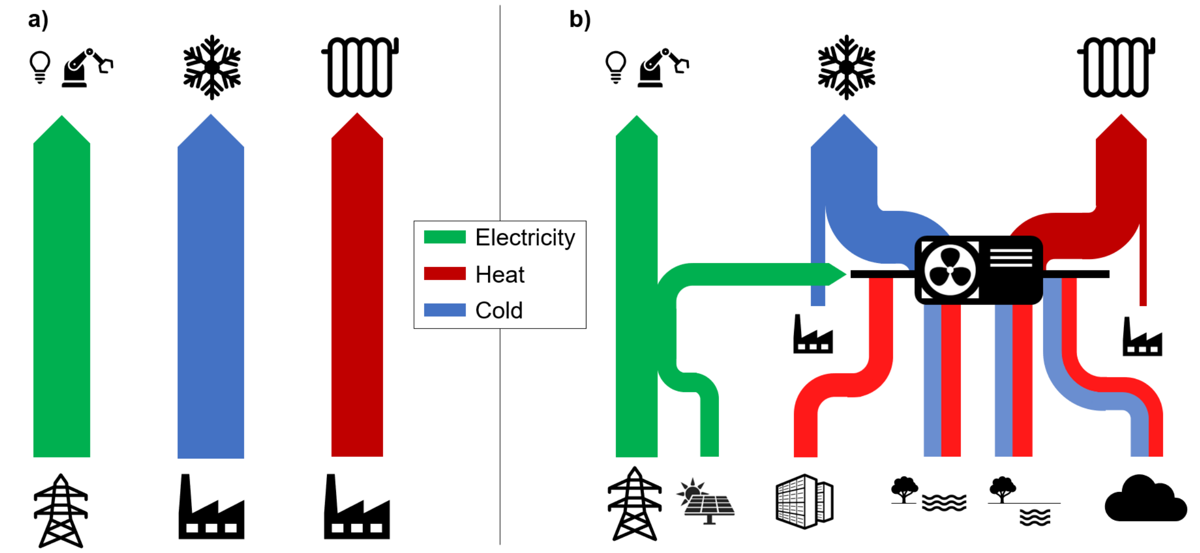

Figure 1. *Comparison of Conventional Linear and IN-Campus Smart Energy Systems (following [5]). Panel (a) illustrates the conventional linear energy system characterized by unidirectional flow and isolated energy pathways (for electricity, heat and cold), lacking integration between different energy types. Panel (b) showcases the IN-Campus smart energy system, highlighting the central role of the 5GDHC network and distributed heat pumps in facilitating dynamic, interactive energy exchanges. The figure also hints at the system's enhanced flexibility through the integration of diverse heat sources and sinks (like waste heat from a data center, river water, ground water or ambient air).*

Besides that, firefighting water tanks equipped with plate heat exchangers are utilized as thermal energy storage. With a combined volume of 3,150 m³, they possess a substantial energy storage capacity of 130 MWh. Additionally, the construction of a seasonal thermal energy storage (sTES) utilizing available basin infrastructure from the former refinery site is planned.

The 5GDHC network's design underscores its ambition for thermal autonomy, complemented by links to existing local heating and cooling networks for enhanced resilience and adaptability.

2 Research Question and Methodology

Central to the inquiry is understanding the intricate process behind the planning and deployment of such advanced energy systems. Specifically, the aim is to uncover:

> *What are the key process steps involved in planning of a shared thermal energy system (5GDHC) in an industrial area considering the IN-Campus as a case-study?*

This question not only navigates through the technical and operational facets of 5GDHC systems but also aligns with broader objectives of energy sustainability, efficiency, and adaptability in industrial applications.

To dissect this complex question, the methodological framework is divided into three distinct yet interconnected segments (see Figure 2):

1. System Description and Preliminary Analysis:

The introduction presented a conceptual description of the IN-Campus's 5GDHC network. This exploration is anchored in a qualitative assessment of the available planning documentation and three on-site inspections. It ensures a holistic grasp of the system's design, functionality, and potential, setting a solid foundation for subsequent analysis.

2. In-depth Planning Process Examination:

The planning process underwent a thorough examination, informed by a wide array of planning documents, including research reports, decision-making documents, general planning documentation, informational presentations, documentation on variant comparison, summary documents, functional descriptions, requirement specification documents, and simulation data from the planning phase. Additionally, insightful exchanges with key figures such as the technical project manager for the IN-Campus planning, the project manager for the IN-Campus control system, and the Head of Technical Consulting of the planning office were instrumental in mapping out the sequential steps to realize the 5GDHC concept. This in-depth scrutiny was crucial for uncovering the unique challenges and opportunities presented by implementing such systems in an industrial context.

3. Summarizing Key Planning Steps:

Following the comprehensive analysis, a significant effort was dedicated to summarizing the planning process and identifying crucial process steps. These steps, now presented in this conference contribution, encapsulate the core elements of planning and deploying a 5GDHC system within an industrial setting like the IN-Campus.

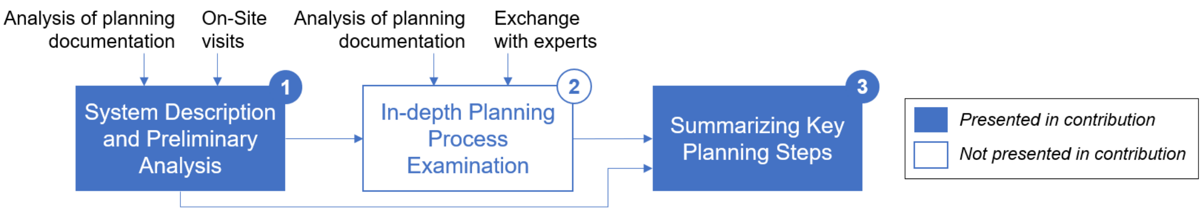

Figure 2. *Methodology of the study.*

3 Planning Process of 5GDHC Networks

This chapter investigates the planning process essential for deploying 5GDHC networks in the context of industrial areas. It outlines the sequential planning steps, initiating with the formulation of energy requirements and load profiles from the demand side.

The essence of any planning process, particularly evident in the planning of the IN-Campus, underscores the imperative for swift action. At the project's inception, the focus is on identifying overarching solutions rather than delving into detailed intricacies. Quick, broad-stroke strategies are preferred, recognizing that they offer more value than lengthy, detailed, and expensive efforts aimed at perfecting every aspect.

Furthermore, the planning approach is characterized by a minimal need for detailed input information. Acknowledging the challenges in obtaining comprehensive data – whether due to financial constraints or the practical infeasibility at the early stages – this method leans towards a pragmatic and flexible strategy.

Importantly, each step in the planning process (especially for the IN-Campus) is tailored to meet specific needs of industrial environments. While some tools may find application across various sectors, a nuanced approach is indispensable for addressing the unique challenges and requirements of industrial settings, distinguishing them from other applications.

In essence, the planning steps outlined in the following share a common ground based on the three aspects mentioned above. These principles collectively form the backbone of a pragmatic and effective planning process for 5GDHC networks in industrial applications.

3.1 Identification of Energy Demand and Development of Load Profiles

The planning of the IN-Campus 5GDHC system started with a critical initial step which is the development of load profiles. From the beginning, detailed information about demand was scarce, largely because the project was a greenfield initiative, starting from scratch with no existing infrastructures to guide demand assumptions. This scarcity of information, reflective of the evolving characteristics of industrial environments, necessitated initial designs to be inherently flexible. They were crafted to accommodate the changes inherent in the various construction phases, which can span years, highlighting the importance of a planning phase that is adaptable to future demand uncertainties and physical developments with minimal initial information available.

In contrast to traditional fourth-generation district heating (4GDH) systems, the IN-Campus 5GDHC network is characterized by entities assuming dual roles as both producers and consumers of heat, so-called prosumers. This dynamic required a meticulous approach in constructing load profiles tailored specifically to the needs and capabilities of the IN-Campus.

Systematic Approach to Developing Prosumer Profiles

This section outlines the systematic method employed for developing prosumer profiles within the IN-Campus setting, delineated into four integral steps:

1. Definition of Archetypes (Energetic Blueprinting):

The process initiated with "Energetic Blueprinting," where distinct energetic archetypes for buildings within the IN-Campus were identified. These archetypes integrated key characteristics such as normalized heating profiles and specific cooling demands. For the IN-Campus project, two primary archetypes were established: one for a workshop/test bench facility and another for an office building. These archetypes, designed to reflect the range of building types within the industrial area, provide generalized but detailed values for heating/cooling demands and maximum heating/cooling powers, alongside a normalized demand profile based on hourly consumption.

2. Profile per Building (Archetype Fusion):

Subsequently, the “Archetype Fusion” phase utilized the IN-Campus development plan to create nuanced profiles for individual buildings, merging archetypes to reflect the complex structures found in an industrial setting like the IN-Campus (see Table 1). While simple structures might align with a single archetype, more complex facilities, such as laboratories with office spaces, merge archetypes to form a comprehensive profile.

When additional information (e.g., density of people, room height, ventilation, or internal heat gains) is available these profiles can be further refined to better match specific thermal demands, as illustrated in adaptations for the powerhouse’s demands or the multipurpose hall (see Table 1). What is kept then from the archetypes is the relative temporal distribution of demands.

Ultimately, by scaling these profiles to the total area of each building, the aggregated heating and cooling demands are calculated.

Table 1. *Overview of building types, their respective shares of archetypes and resulting thermal energy demands. [5]*

Construction Phase	**Building Type**	**Office Archetype**	**Workshop Archetype**	**Specific heating demand** [kWh/m²a]	**Specific cooling demand** [kWh/m²a]
1	Office	100 %	0 %	34	25
1	Security centre	44 %	56 %	29	78
1	Powerhouse	17 %	83 %	**34**	**12**
1	High-rise building	100 %	0 %	34	25
…	…				
4	Multipurpose hall	100 %	0 %	**48**	**7**

In addition to the energy demands, the temperature level at which heat or cold is provided is a crucial consideration in this planning step. Although not listed among the initial planning steps, temperature level considerations were integral to the overall design of the IN-Campus energy system. From the outset, a key decision was made to ensure that all heating and cooling requirements were met efficiently at low temperature levels. This decision was for example manifested in the design choice to outfit all buildings with thermally activated building structures. Moreover, the planning for the IN-Campus implicitly excluded production processes that typically demand high-temperature heating. This strategic exclusion allowed the energy system to focus on meeting non-process-related heating demands.

3. Combination with Heat Pump Model (Energetic Transformation):

The “Energetic Transformation” phase integrated the developed heating demands with a heat pump model, translating the diverse heating and cooling demands into electricity demand. At the same time, this step considered the potential impacts on the district heating network, which serves as the primary side of the heat pump, thereby transforming building-specific needs into values that can easily be formed into a cohesive system model for the IN-Campus.

4. Combination to Network (Holistic Synergy):

Finally, the “Holistic Synergy” phase saw the amalgamation of individual building profiles into a comprehensive network (see Figure 3). This step enabled a holistic assessment of the IN-Campus energy scenario, facilitating a thorough evaluation of system performance and efficiency.

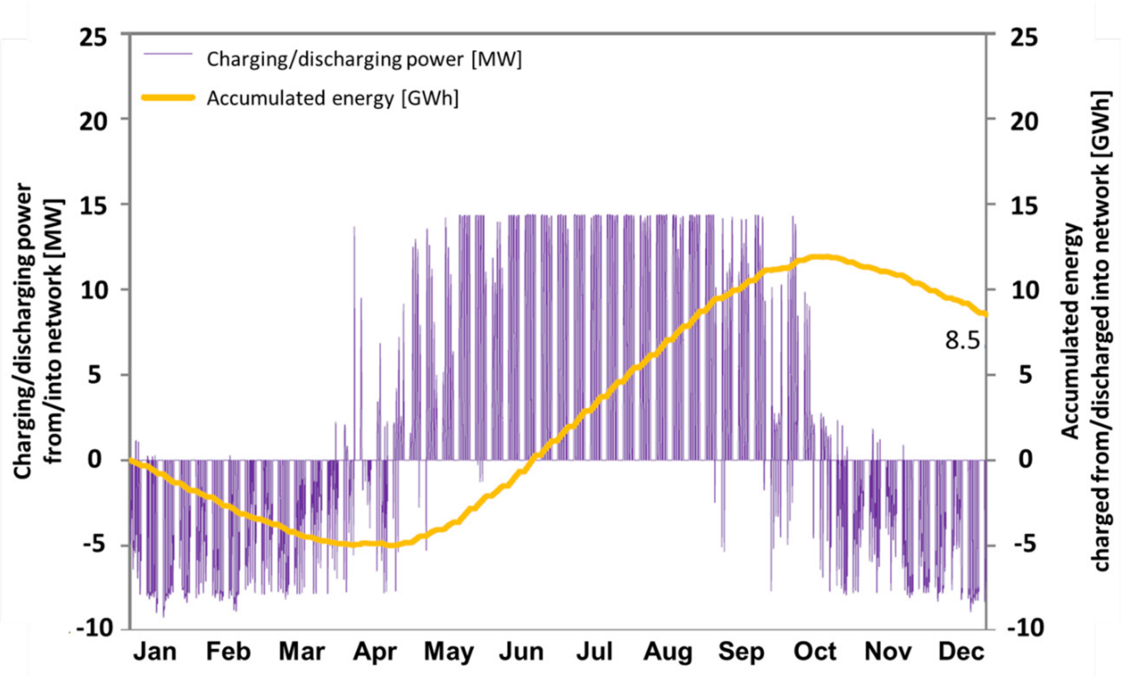

Figure 3. *Resulting charging and discharging power for the network and accumulated energy within the network as the result of the holistic thermal energy demand of distributed heat pumps of the IN-Campus [5].*

Figure 3 shows that throughout the year the combined energy demand of the IN-Campus undergoes significant fluctuations. The winter months see a net energy deficit due to heating needs, while from mid-April, as cooling demands rise, the network experiences a net energy gain. This cyclical pattern highlights a predominant cooling demand, necessitating the integration of external sources and sinks to balance the system, a strategy further explored in Chapter 3.2.

In addition to the holistic assessment depicted in Figure 3, it’s important to note that the figure primarily displays the net thermal charging or discharging of the network. It filters out thermal loads that are internally balanced within the network, such as simultaneous cooling and heating demands in different buildings. This internal energy sharing, particularly pronounced during transition periods, contributes significantly to the network’s efficiency and economic benefits. (Work is underway to develop a detailed overview of these internally balanced energy flows, further highlighting the IN-Campus network’s operational efficiency.)

Legal Obligations and Energetic Development of New Buildings

In the intricate process of 5GDHC system planning for industrial areas, accommodating evolving legal standards is paramount, especially when considering the energy requirements of new buildings. This necessity becomes evident during the archetype fusion phase, where specific adjustments to key energetic properties, such as cooling demand, are made based on available information and anticipated legal developments.

Anticipating future regulatory changes is crucial for orchestrating an energy system designed to evolve over years, if not decades. In the initial planning stages of the IN-Campus around 2016, the framework for non-residential buildings was heavily influenced by several critical documents: the Energy Saving Ordinance (EnEV), Renewable Energies Heat Act (EEWärmeG), and the Energy Performance of Buildings Directive (EPBD). These regulations set the course for energy-efficient construction, with the EPBD mandating the shift towards Nearly Zero Energy Buildings (NZEB) from 2021 onwards. [6]

To align with the EPBD's stipulations for primary energy demand, which advocate for the integration of renewable energy sources and efficiency improvements [5], various calculations were undertaken. Utilizing the DIN V 18599 standards, these assessments explored potential consumption reductions in office spaces under different construction and system technology scenarios. Each construction phase was evaluated with specific assumptions, guided by the EnEV, insights from ongoing projects, and the ambition to reach or even exceed the Passive House standards [5]. (The Passive House standard is a rigorous, performance-based energy standard aimed at achieving high-efficiency buildings with minimal heating and cooling demands, through optimizing insulation, air tightness, and solar gains, adaptable across all climate zones [7].) The planning embraced a holistic vision towards achieving a "zero-energy campus", characterized by minimal to negative primary energy consumption and CO_2 emissions, reflecting a dedication to advanced technological innovation.

The outcomes, depicted in Figure 4, illustrate a nearly constant assumption for specific cooling demands across future construction phases. In contrast, specific heating demands are projected to decrease significantly, a trend driven by impending legal requirements. This projection underscores the importance of incorporating such legal and technological considerations into the planning stages to ensure not only compliance but also efficiency.

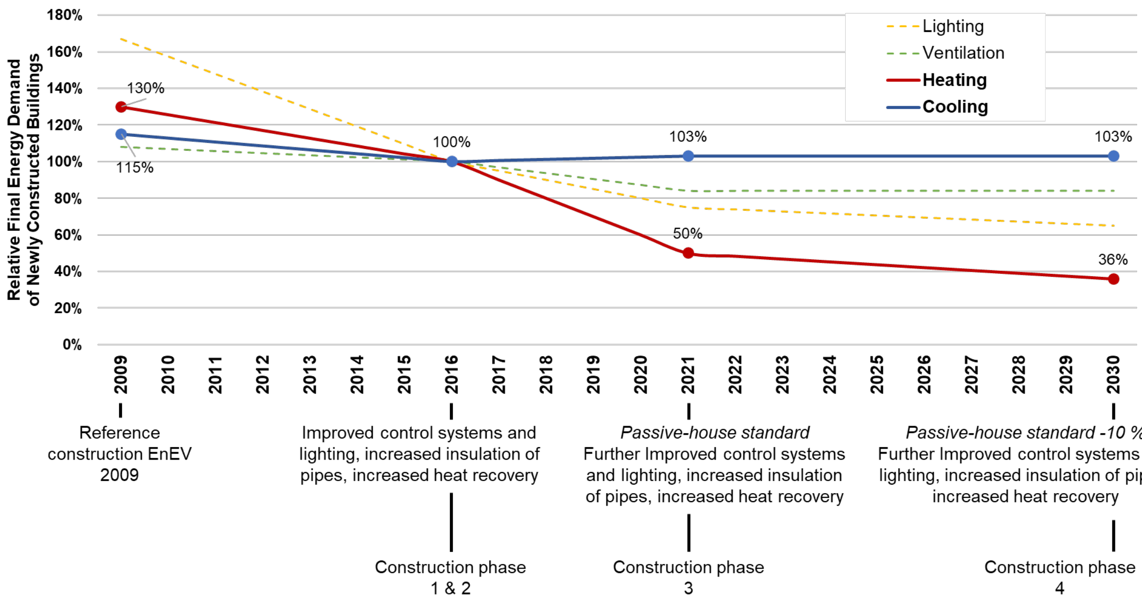

Figure 4. *Assumptions about development of final energy demand of non-residential buildings until the year 2030 (following [5]).*

This proactive approach to planning, which intertwines legal foresight with technological progression, offers a holistic view of the energetic development of new buildings. Such an approach is vital for establishing a sustainable and efficient energy system, ready to meet the demands of the future.

3.2 Evaluation of Local and Sustainable Energy Sources and Sinks

The planning of the IN-Campus's 5GDHC network has involved a thorough examination of various local and sustainable sources and sinks, assessing their potential to supplement the network's heating and cooling demands. This evaluation is pivotal in harnessing environmental resources efficiently, aligning with the network's temperature limits to not exceed 30°C in summer and maintain at least 5°C in winter.

Figure 5 illustrates the location of these thermal sources and sinks, providing a visual guide to their integration within the campus area.

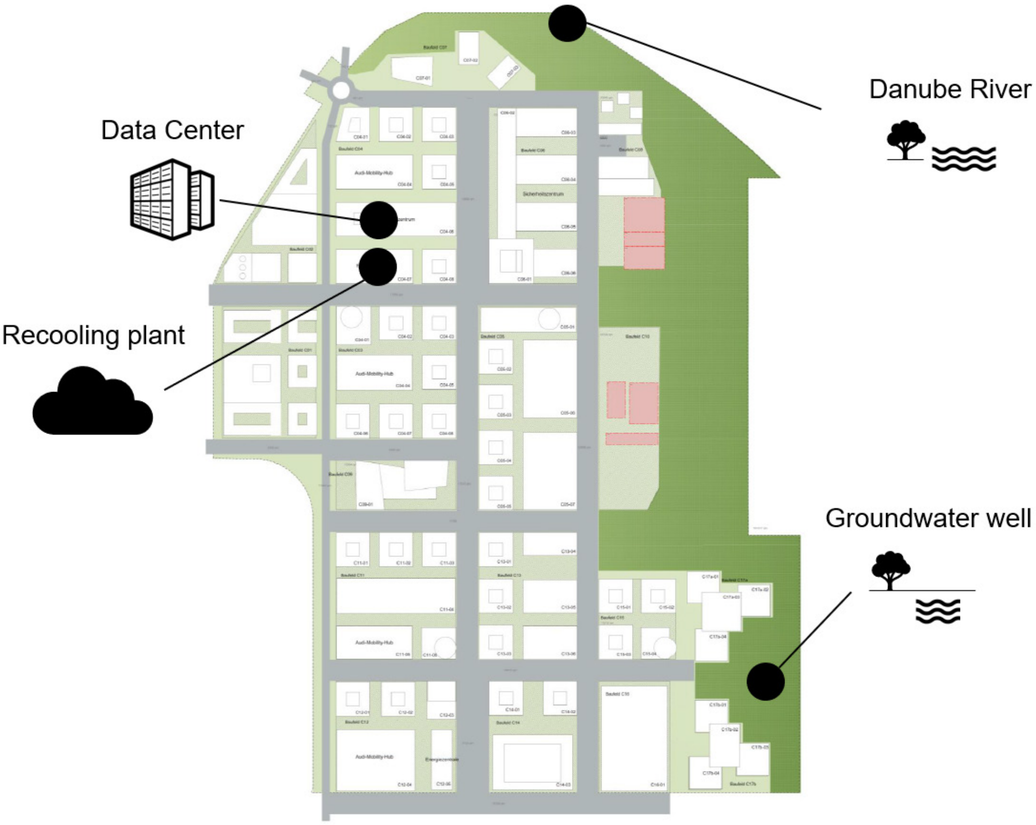

Figure 5. *Location of thermal sources and sinks on the IN-Campus area (following [5]).*

Danube River:

The Danube River emerges as a significant thermal source and sink, with a regulatory maximum temperature cap of 30°C for discharge. Operational constraints allow for cooling purposes only when the river's temperature remains below 25°C [8]. Leveraging a temperature differential of 9.5K and a volume flow of 900 m³/h, the river offers a substantial thermal potential of 10 MW under optimal conditions. [5, 9]

Groundwater Wells:

Groundwater wells present another crucial source, with a usable temperature difference of 5K and an initial volume flow rate of 170 m³/h, translating to a thermal power of 1,000 kW. This source/sink is particularly notable for its consistent temperature profile, providing a reliable baseline for heating and cooling applications. [5, 9]

Data Center Waste Heat:

The data center's waste heat is identified as a key contributor, offering an initial thermal power of 1,830 kW for heating. This reuse of waste heat not only exemplifies the

5GDHC network's sustainability ethos but also enhances the overall energy efficiency of the IN-Campus. [5, 9]

Recooling Plant:

The air-based recooling plant, primarily intended for emergency or redundancy purposes, plays a crucial role in the IN-Campus's cooling strategy, especially during the summer months. With a cooling capacity of 2.25 MW, this facility is designed to mitigate heat accumulation within the network, ensuring balanced thermal conditions throughout the year. [5]

Table 2. *Overview of thermal sources and sinks connected to the IN-Campus energy system with information about volume flow, available thermal power, and limitations.*

Source / Sink	Limitations	Volume flow	Available Thermal Power
Danube River	Maximum feed-in temperature of 30 °C, limited by a river temperature below 25 °C. Allowed temperature difference of 9.5 K.	900 m^3/h	10 MW
Ground-water Well	Allowed temperature difference of 5 K between extraction and discharge.	170 m^3/h.	1 MW
Data Centre	Availability of waste heat is secondary to operational security of data centre.	Flexible (depends on sizing)	(Initial Phase): 1.83 MW
Recooling Plant	Limited by outdoor air temperature	Flexible (depends on sizing)	(Summer): 2.25 MW.

While this chapter outlines the foundational planning and potential of incorporating these sources and sinks into the 5GDHC network, further analysis is required to fully quantify their impact on the overall energy balance. It is already evident that the maximum required thermal power, such as the cooling power during summer months of 15 MW (see Figure 3), cannot be solely met by the external thermal sources/sinks. To address this discrepancy, the network itself will operate as a thermal buffer storage, alongside other storage facilities discussed in Chapter 4. Such analyses will shed light on the complex interactions within the network, setting the stage for an in-depth study focused on optimizing the energy flow and sustainability of the IN-Campus's heating and cooling infrastructure.

Influence of Fluctuating Temperature Levels on Source and Sink Efficiency

The operational efficiency of the 5GDHC network, serving as both a source and sink for decentralized heat pumps, is significantly influenced by its inherent temperature fluctuations. These variations, primarily driven by seasonal load profiles, play a pivotal role in determining the effectiveness of each thermal source and sink within the system.

During the winter months, the network faces heat deficits, triggered by increased heating. Conversely, summer brings about heat surpluses which increases the so to say thermal state of charge, potentially resulting in elevating the network's overall temperature. The heat surplus in summer is attributed to buildings with high cooling demands injecting thermal energy into the grid, thereby increasing its temperature level. This phenomenon not only reflects the network's adaptive response to changing demands but also enhances the efficiency of cooling during warmer periods. The temperature profiles of available sinks during this time demonstrate a self-regulating effect; as the network's heat surplus (and temperature) increases, the usable temperature difference to most sinks also rises, enabling more efficient cooling operations (see Figure 6, Marking 2).

Similarly, starting in October, the network experiences an uptick in heating demand, leading to a decrease in the grid's thermal state of charge and temperature level. This reduction benefits the network's efficiency since the temperature delta required to be bridged from heat sources to meet the demand of the grid decreases (see Figure 6, Marking 1).

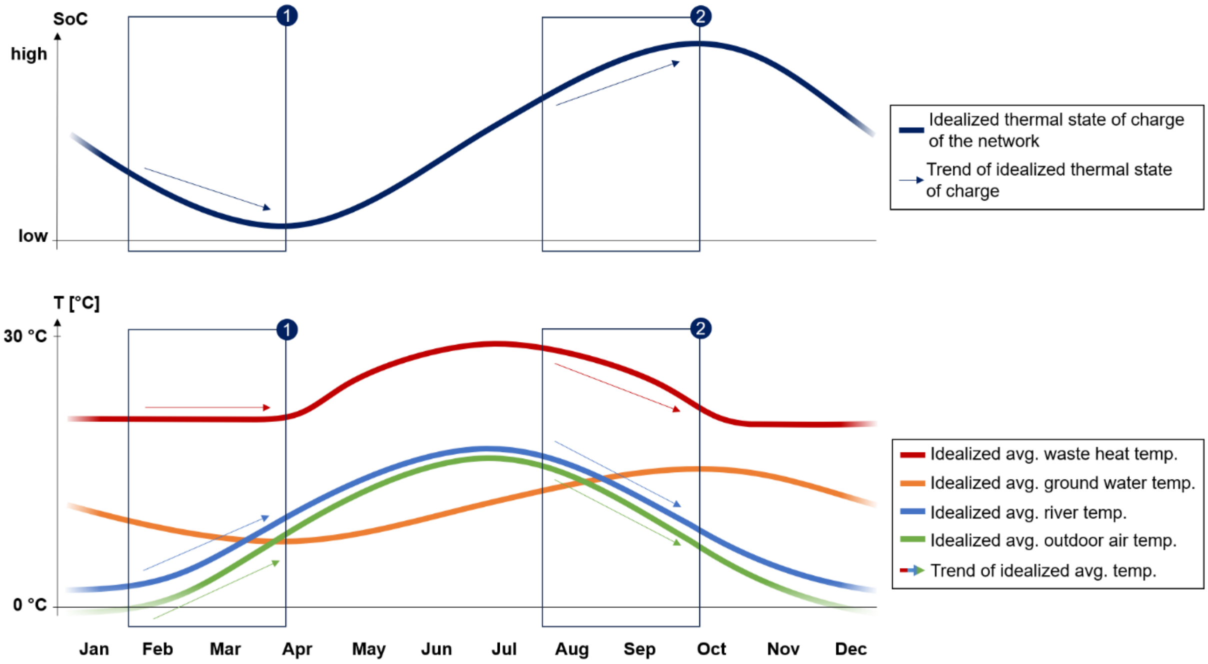

Figure 6. *Development of thermal state of charge of the network (top) and idealized temperature levels of sources and sinks (bottom).*

The qualitative overview (illustrated in Figure 6) indicates the network's capacity for self-regulation, balancing between heating and cooling demands through natural temperature adjustments. However, it's crucial to acknowledge that while the network's ability to modulate its temperature is beneficial with view to external thermal sources and sinks, there are practical limits to these fluctuations as well as effects on the overall energy system efficiency (including decentralized heat pumps and buildings). To prevent undue strain on the infrastructure – such as the risk of freezing – and to optimize the overall system efficiency (including the demand side), additional control strategies are implemented. These strategies are designed to moderate the network's temperature levels, ensuring that the system operates within its optimal range and maintains its structural integrity.

3.3 Analysis of Pipe Design

In the engineering of piping infrastructure, alongside hydraulic considerations, the thermal characteristics, particularly insulation, play a pivotal role. The energy system related to the first phase of construction provided an opportunity for an in-depth examination of this aspect.

Insulation's Impact on Energy Efficiency

Insulation's role in modulating heat losses to the surrounding soil is multi-faceted. In winter, it proves beneficial by reducing heat loss, thus enhancing system efficiency. However, during summer, its ability to impede natural cooling due to soil contact presents challenges, given the increased cooling demands. Additionally, insulation significantly affects the network's general ability to function as a source/sink for low-temperature cooling or heating. This influence extends beyond seasonal efficiency, impacting the network's overall operational flexibility.

Figure 7 gives a qualitative overview on the seasonal heat dynamics. Winter's heat pump operation and the resulting network temperature leads to heat transfer from the groundwater towards the thermal network and from the network and pipes towards the ambient air. Summer sees a higher temperature level of the network and therefore increased heat discharge from the thermal network towards both groundwater and air.

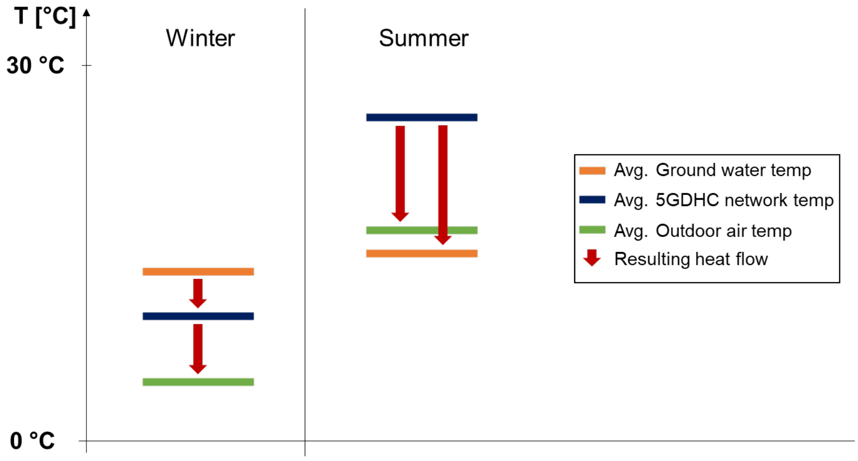

Figure 7. *Qualitative overview of temperature levels of 5GDHC network, groundwater and air, and resulting heat losses (following [5]).*

Simulation studies from [5] quantified the impact of insulation on the mentioned heat flows, demonstrating a reduction in annual energy losses from 245 MWh to 120 MWh with insulation implementation. Yet, only 50 MWh of reduced heat losses are achieved during the winter season as presented in Figure 8. The other 75 MWh of reduced heat losses occur during the summer half-year and are therefore equivalent to increased cooling demands. The diminished heat dissipation capabilities during the summer, highlighting a critical efficiency-cost trade-off.

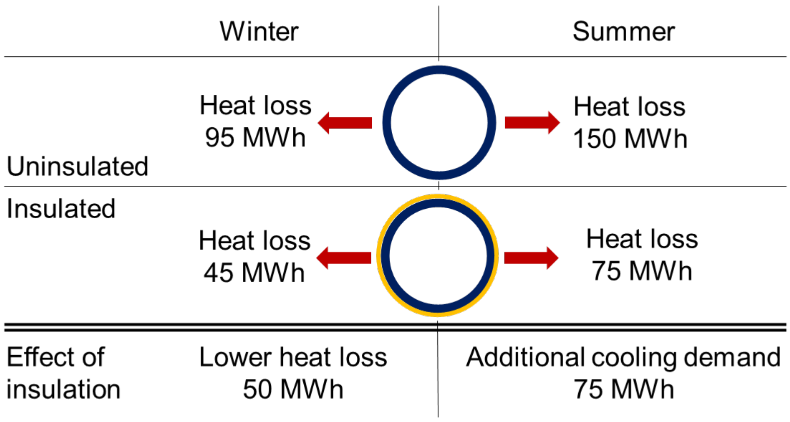

Figure 8. *Energetic effect of insulation of pipes of the IN-Campus network (following [5]).*

Economic Considerations and Recommendations

The economic analysis constitutes a critical phase in evaluating the advisability of implementing insulation within the thermal network. To elucidate, the analysis involved quantifying the financial implications of the (before mentioned) insulation-induced reduction in heat losses and the corresponding increase in cooling demands. These variables were then contextualized within different heating and cooling cost scenarios.

For the IN-Campus thermal network, analysis revealed that the incremental costs incurred from insulating the network tend to outweigh the anticipated benefits. Although operational costs for cooling can decrease with lower electricity prices in the future, the overall economic viability remains doubtful. In a scenario assuming heating costs at 40 €/MWh and cooling, leveraging the low-cost potential of the groundwater wells, at 4.5 €/MWh, the analysis indicated savings under €2,000 per annum for the first construction phase. This outcome, derived from balancing the costs of saved heating energy against additional cooling energy expenses, underscores the conclusion that further insulating the network for energy savings is economically unfeasible [5]. The recommendation against additional insulation is grounded in both its marginal economic benefits and its mixed impact on system performance, particularly during summer months.

This comprehensive evaluation of insulation within the 5GDHC network's pipe design illustrates the necessity of a nuanced approach to infrastructure engineering. It calls for a strategic balance between enhancing energy efficiency and maintaining system adaptability to seasonal demands, all while navigating the constraints of economic viability.

4 Thermal Storage Capacities of the IN-Campus Energy System

The IN-Campus energy system incorporates various storage capacities to balance energy demand effectively. Firstly, the network itself, with a water volume of approximately 2,200 m³, acts as a primary thermal buffer. Secondly, firefighting water (sprinkler) tanks, connected via plate heat exchangers and totalling a volume of 3,150 m³, provide about 130 MWh of energy storage capacity for buffering short-term peak demands. Lastly, the most significant thermal capacity comes from seasonal thermal energy storage, repurposed from existing infrastructure on the site. These storages, part of the advanced fifth-generation of seasonal storage systems [10], hold about 30,000 m³ and can supply up to 428 MWh of thermal energy. This capacity is based on a 30 K temperature difference, matching the network's temperature profile.
The first phase of this innovative use case, starting in 2024, is part of the EU Horizon Europe project INTERSTORES (https://interstores.eu/), exemplifying a sustainable approach by integrating reused infrastructure into modern energy solutions.

5 Conclusion and Outlook

A comprehensive examination of the IN-Campus's 5GDHC network was presented, emphasizing its innovative approach to energy efficiency and decarbonization. It ensured a holistic grasp of the system's design and functionality.
The successive study anchored in a qualitative assessment of the available planning documentation and meticulously outlined the planning process, from defining energy requirements and load profiles to assessing potential energy sources and sinks. Through this analysis, opportunities of integrating renewable and local energy sources and waste heat to enhance system efficiency were addressed, as well as technical challenges inherent in scaling such systems for industrial applications.
The critical role of insulation in influencing the network's energy balance was also analyzed, demonstrating its dual impact on reducing heat loss during winter and posing challenges for natural cooling in summer.

However, this investigation encounters limitations that shape the scope and future direction of the research:

1. Data Accessibility and Project Specificity: The reliance on internal, non-public documents limits the generalizability of findings. Insights are specific to the IN-Campus, potentially requiring adjustments for application in other settings.

2. Insulation Analysis: While insightful, the study's focus on insulation does not encompass all design aspects of the network, such as pipe configuration (two/three pipe system), flow operation modes (active/passive), and pipe dimensioning, which are critical for a comprehensive network design.

3. Energy Source and Sink Integration: While initial planning analyses focused on broad energy flows and balance, detailed simulations are poised to offer granular insights into optimizing energy distribution and managing thermal peak demands. Such simulations are vital for understanding how best to leverage the network as a thermal buffer and for operationalizing thermal energy storages effectively. Coupled with the analysis of operational data, detailed simulations are a crucial next step in refining the system's efficiency and sustainability.

The groundwork laid by this investigation offers a robust foundation and can be enhanced with future research in the following directions:

1. Planning Guidelines and Transferability: An essential future step involves a comparative analysis of the IN-Campus's planning process against traditional approaches. This comparison aims to identify unique planning steps required for industrial 5GDHC systems and formulate comprehensive guidelines for their transferability. Such analysis will be pivotal in developing a methodology that facilitates the adaptation and broader application of 5GDHC systems across diverse settings.

2. Operational Analysis and System Performance: The in-depth examination of the planning process provides a solid basis for assessing the system's operational efficacy. Future studies will delve into comparing simulation predictions with actual operational data from the IN-Campus's initial construction phase. This comparison aims to validate the planning assumptions and explore the causal relationships between planned efficiency and real-world system performance. Enhanced by detailed simulation analyses, this future research will contribute significantly to refining 5GDHC systems' design and implementation strategies, ensuring their alignment with sustainability and efficiency goals.

The exploration undertaken in this study not only enriches the scientific discourse on sustainable industrial energy systems but also charts a course for future investigations to build on these insights. The anticipation of regulatory changes, coupled with the strategic integration of sustainable sources and sinks, exemplifies the proactive planning essential for the successful deployment of 5GDHC networks. As such, this research paves the way for advancing sustainable energy solutions in industrial contexts, contributing to the broader objectives of energy sustainability, efficiency, and adaptability.

Data availability statement

Data supporting the findings of this study are derived from internal planning documents and gray literature associated with the IN-Campus 5GDHC 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 gray 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.

Author contributions

S. N. Müller was in charge of Conceptualization, Visualization and Writing – original draft.

R. Strobel contributed to Validation, and Writing – review & editing.

M. Faigl contributed to Validation, and Writing – review & editing.

T. Schrag contributed in terms of Project administration, Supervision and Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

References

[1] K. Gjoka, B. Rismanchi, and R. H. Crawford, "Fifth-generation district heating and cooling systems: A review of recent advancements and implementation barriers," *Renewable and Sustainable Energy Reviews*, vol. 171, p. 112997, 2023, doi: 10.1016/j.rser.2022.112997.

[2] J. Lindhe, S. Javed, D. Johansson, and H. Bagge, "A review of the current status and development of 5GDHC and characterization of a novel shared energy system," *Science and Technology for the Built Environment*, vol. 28, no. 5, pp. 595–609, 2022, doi: 10.1080/23744731.2022.2057111.

[3] M. Wirtz, T. Schreiber, and D. Müller, "Survey of 53 Fifth-Generation District Heating and Cooling (5GDHC) Networks in Germany," *Energy Tech*, vol. 10, no. 11, 2022, doi: 10.1002/ente.202200749.

[4] S. Buffa, M. Cozzini, M. D'Antoni, M. Baratieri, and R. Fedrizzi, "5th generation district heating and cooling systems: A review of existing cases in Europe," *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 504–522, 2019, doi: 10.1016/j.rser.2018.12.059.

[5] Planungsgruppe M+M AG, Ed., „IN-Campus: Fortschreibung innovatives Energiekonzept Ergebnisse," Stand Vorplanung, 2017.

[6] *Energy performance of buildings directive: EPBD*, 2010. Accessed: Jan. 29 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02010L0031-20210101

[7] J. Schnieders *et al.,* "Design and realisation of the Passive House concept in different climate zones," *Energy Efficiency*, vol. 13, no. 8, pp. 1561–1604, 2020, doi: 10.1007/s12053-019-09819-6.

[8] *Verordnung zum Schutz der Oberflächengewässer: OGewV*, 2016. Accessed: Feb. 26 2024. [Online]. Available: https://www.gesetze-im-internet.de/ogewv_2016/OGewV.pdf

[9] M. Heider, „Entwicklung von Energieversorgungskonzepten mit regenerativen Energien für einen neuen Standort der Audi AG," Bachelorarbeit, Ostbayerische Technische Hochschule Regensburg, Regensburg, 2015.

[10] C. Bott, I. Dressel, and P. Bayer, "State-of-technology review of water-based closed seasonal thermal energy storage systems," *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109241, 2019, doi: 10.1016/j.rser.2019.06.048.