Interreg
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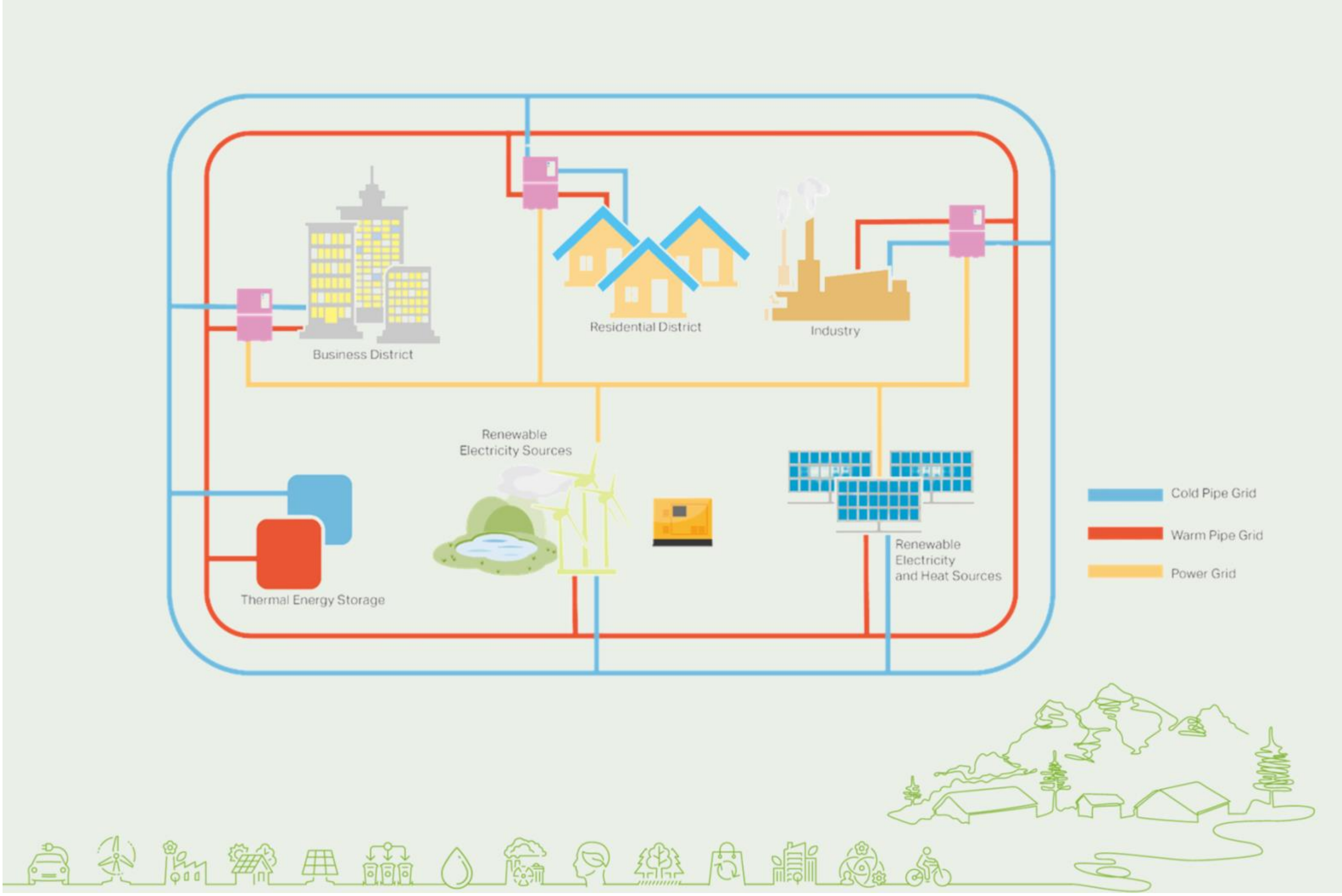
ALPHA

D1.5.3

Decision-making support methodology for developing up-to-date H&D/5GDHC networks



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Introduction

The ALPHA project brings together nine partners from five EU Alpine countries; namely, Austria, France, Germany, Italy, and Slovenia. Its overarching objective is to accelerate the decarbonisation of heating and cooling (H&C) systems by promoting the development and implementation of modern district heating and cooling (DHC) networks. As a model of transnational cooperation, ALPHA aims to address key territorial disparities and fragmentation across the Alpine region, fostering a unified and adaptable approach to modern H&C planning.

The project advances this goal by establishing an Alpine-wide coordination and planning framework that supports stakeholders in rolling out integrated H&C decarbonisation pathways. Through collaborative research, capacity-building activities, and methodological innovation, the project develops strategic resources and planning tools to assist local authorities, SMEs, and infrastructure developers in aligning with both EU policy priorities and the unique geographical, administrative, and socioeconomic conditions of Alpine territories.

This deliverable, **D.1.5.3 – Decision-Making Support Methodology for developing up-to-date H&C/5GDHC networks**, forms part of Activity 1.5. The latter is designed to synthesise the knowledge accumulated throughout the project's initial phase and to integrate it into a comprehensive planning framework. Specifically, this activity seeks to produce a robust and adaptable decision-making methodology that can guide the planning, design, and implementation of up-to-date H&C networks, particularly those aligned with 5th-generation standards.

The present deliverable thus serves the following purposes:

- To identify and analyse key parameters –technical, regulatory, economic, environmental, and social– that influence the planning of decarbonised H&C systems in the Alpine Space.
- To outline the steps and stages involved in the development of such systems, from the initial needs assessment to full operational deployment.

- To provide a structured, customisable decision-making methodology that integrates these parameters and guides stakeholders through each planning phase.

- To build on the outputs of Activity 1.4, which provides territorialised and customisable tools to support H&C planning. The methodology proposed here is designed to integrate seamlessly with these tools, offering a coherent and adaptable planning framework that responds to local needs while supporting Alpine-wide harmonisation.

The insights and outputs developed will not only serve as a reference for ALPHA's partners and pilot actions in the course of the project but will also contribute to the broader roll-out of efficient and climate-resilient heating and cooling solutions across the Alpine region and beyond.

Parameters and requirements for designing up-to-date H&C networks

Designing modern H&C networks requires a holistic understanding and fulfilment of various parameters and requirements. These range from technical design considerations to regulatory frameworks at different levels, as well as an array of economic, environmental, and social factors. To ensure the design and implementation of a successful and sustainable H&C network, these aspects must be addressed in a balanced way. This section presents and elaborates on these diverse parameters and considerations, starting with key technical aspects of modern H&C systems, and more specifically 5th generation DHC networks.

Key technical aspects in designing modern DHC networks

Modern DHC systems are crucial for decarbonising Europe's thermal energy demand. While, traditional third-generation district heating relied on centralised fossil-fuelled plants supplying water at 90-120 °C,[1] technology innovation, better building insulation, and digitalisation now enable lower-temperature systems that integrate clean energy sources.[2] Fourth-generation district heating (4GDH) networks distribute heat at much lower temperatures (typically 70 °C down to 40-50 °C), sharply cutting losses and allowing use of low-grade renewable and waste heat.

The emerging fifth-generation concept (5GDHC) goes further: these are ambient-temperature, bi-directional thermal loops (circulating water ~5-30 °C) with decentralised heat pumps, enabling simultaneous heating and cooling exchange between buildings.[3] That way, the system effectively becomes a circular heat/cold exchange network, as waste heat from one building's cooling can directly serve another's heating demand, and vice versa.

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[1] Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., & Fedrizzi, R. (2020). Fifth-Generation District Heating and Cooling Substations: Demand Response with Artificial Neural Network-Based Model Predictive Control. *Energies*, *13*(17), 4339. https://doi.org/10.3390/en13174339

[2] Bertelsen, N., Mathiesen, B. V., Djørup, S. R., Schneider, N. C. A., Paardekooper, S., Sánchez García, L., Thellufsen, J. Z., Kapetanakis, J., Angelino, L., & Kiruja, J. (2021). *Integrating low-temperature renewables in district energy systems: Guidelines for policy makers*. International Renewable Energy Agency. https://www.irena.org/publications/2021/March/Integrating-low-temperature-renewables-in-district-energy-systems

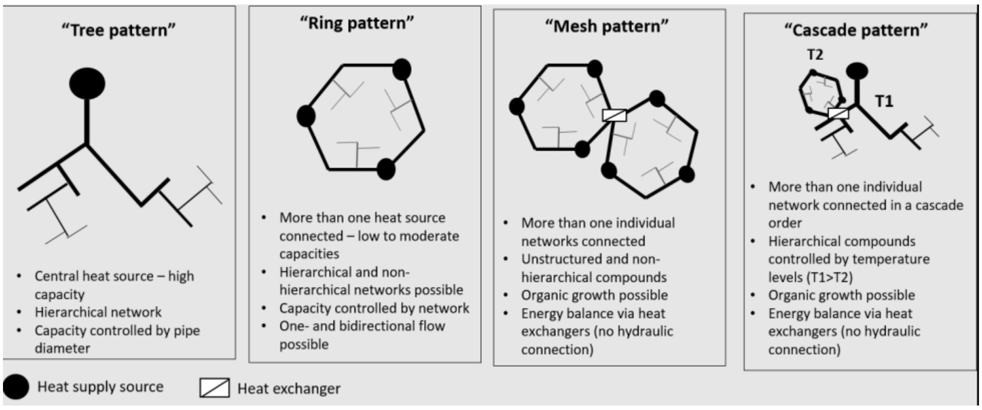
[3] Gong, Y., Ma, G., Jiang, Y., & Wang, L. (2023). Research progress on the fifth-generation district heating system based on heat pump technology. *Journal of Building Engineering*, *71*, 106533. https://doi.org/10.1016/j.jobe.2023.106533

These properties allow 5GDHC systems to neutralise thermal losses, while enabling the network to utilise low-grade heat sources that conventional grids cannot use.

In what follows, the key technical parameters involved in planning such state-of-the-art networks are presented. From layout and components to integration of renewables, storage, smart controls, and system flexibility, these advanced technical configurations seek to maximise efficiency while integrating local energy sources.

Network layout and topology

Early DHC networks were typically laid out as branching radial systems fed from a central plant.[4] By contrast, 4GDH still uses two-pipe supply/return networks but can adopt more looped or meshed topologies to improve reliability and incorporate multiple heat sources at various points. 5GDHC networks are even more novel in terms of topology: they employ decentralised, bi-directional ambient loops rather than strictly radial supply lines.[5] 5GDHC networks typically feature a warm line and a cool line, allowing each connected building to function as both a potential heat source and sink. Buildings can inject heat into the warm side when cooling (rejecting excess heat) or extract heat from the warm side for space and water heating, rejecting the resulting coolth to the cool line as needed.



In practice, these networks often resemble two parallel loops encircling a district or neighborhood, with branch connections to buildings or local sub-loops treated

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[4] Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., & Fedrizzi, R. (2020). Fifth-Generation District Heating and Cooling Substations: Demand Response with Artificial Neural Network-Based Model Predictive Control. *Energies*, *13*(17), 4339. https://doi.org/10.3390/en13174339

[5] Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H. (2019). 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. *Advances in Geosciences, 49*, 129-136. https://doi.org/10.5194/adgeo-49-129-2019

symmetrically. This mesh-like design offers redundancy, as the failure of a single heat pump or local source can be compensated by alternative connections within the loop. Interconnections between multiple loops further enhance resilience by reducing single-point dependencies and facilitating thermal balancing across the network.[6]

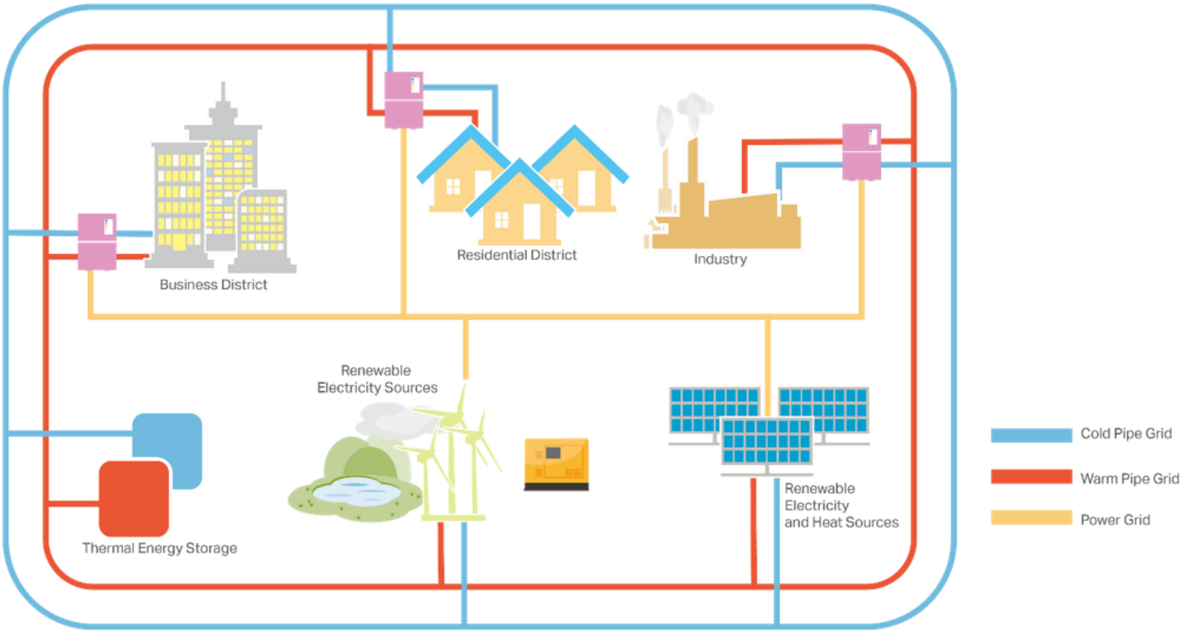

Figure 1*: Schematic representation of a 5GDHC network, illustrating the integration of business districts, residential areas, and industrial facilities into a bidirectional, low-temperature thermal grid. The system connects multiple thermal energy sources, including renewable electricity, thermal energy storage, and industrial waste heat, via separate warm (red) and cold (blue) pipe grids, supported by a power grid (yellow) for electrical components like heat pumps.*[7]

Such ambient loops can be structured in clusters and backbones. For example, the city-scale 5GDHC system in Heerlen (Netherlands) is arranged with several local cluster loops linked by a regional backbone.[8] Each cluster loop operates at ground temperature, exchanging heat with a central backbone via heat exchangers in a “cluster basement” plant. This modular topology allows scaling up from district-level loops to a city-wide network by interconnecting clusters, thereby facilitating expansion and resilience. Notably, 5GDHC can

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[6] Ibid.
[7] Source: https://www.kaori.com.tw/en/modules/news/article.php?storyid=81.
[8] Ibid.

operate with the usual two-pipe layout (warm and cold pipes) or even a single-pipe configuration in some designs. In a single-pipe 5GDHC system, warm and cool flows are managed temporally or via mixing. Such setups, however, are still uncommon and experimental.

Figure 2: *Schematic representation of the Mijnwater 5GDHC network in Heerlen, Netherlands, depicting the cluster and backbone design. The system integrates multiple local thermal loops, each operating at ground temperature, connected via a central backbone.*[9]

From a thermal planning perspective, designing a 5GDHC network involves careful mapping of building clusters with complementary heating and cooling loads. Mixed-use clusters, combining residential, commercial, and industrial buildings, are ideal for maximising internal energy exchange. Advanced guidelines recommend sizing warm and cool lines based on peak expected net flows, with smart valves, flow sensors, and predictive control systems facilitating dynamic thermal balancing and demand response. In summary, district heating and cooling network topology has shifted toward more flexible, meshed configurations.

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[9] Source: Vandermeulen, A., Bronder, P., Vanhoudt, D., Georges, E., & Verbrugge, S. (2020). Testing and performance evaluation of the STORM controller in two demonstration sites. *Energy*, 197, 117177. https://doi.org/10.1016/j.energy.2020.117177.

5GDHC is exemplary of this shift, introducing bidirectional piping that closes local energy loops and turns every building into a potential node for exchange.

System components and equipment

Designing these advanced networks requires updated system components. In 4GDH systems, although many components resemble those in earlier generations, they are optimised for lower temperatures. Central heat generation units remain (e.g. large combined heat and power plants, biomass or biogas boilers, industrial heat exchangers, or large-scale heat pumps), but often multiple distributed plants feed the network. The distribution network itself uses pre-insulated pipes (typically steel or polymer) designed for lower supply temperatures and pressure losses.

In 5GDHC networks, the component configuration is significantly different. Given the network water is only ambient-temperature, each building or consumer requires a decentralised heat pump (typically a water-to-water heat pump) at its energy transfer station (ETS).[10] This heat pump upgrades the ambient loop water to the required supply temperature for space heating and domestic hot water (e.g. boosting from ~15 °C loop to 50-60 °C for use). Likewise, for cooling, the same or a similar heat pump (or reversible chiller) removes heat from the building and channels it into the ambient loop (warming the loop water).

Each ETS in 5GDHC usually also contains a thermal energy storage tank (for example, a hot water tank for buffering domestic hot water) to optimise the heat pump operation.[11] The distribution network in 5GDHC consists of a pair of main, often plastic, pipes since temperatures are low, and these may not require heavy insulation (the loop is thermally "neutral" with minimal heat loss to soil). Additional components can include booster pumps for each loop or cluster, mixing valves, and central equipment to manage any large shared sources. For instance, a shallow geothermal well, aquifer system, or central heat exchanger to a seasonal storage can be integrated at a central point to help maintain the ambient loop

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[10] Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., & Fedrizzi, R. (2020). Fifth-Generation District Heating and Cooling Substations: Demand Response with Artificial Neural Network-Based Model Predictive Control. *Energies*, *13*(17), 4339. https://doi.org/10.3390/en13174339

[11] ibid.

temperature. In the Heerlen system, a flooded mine reservoir serves as a large heat/cold source, with heat exchangers connecting it to the backbone loop.[12]

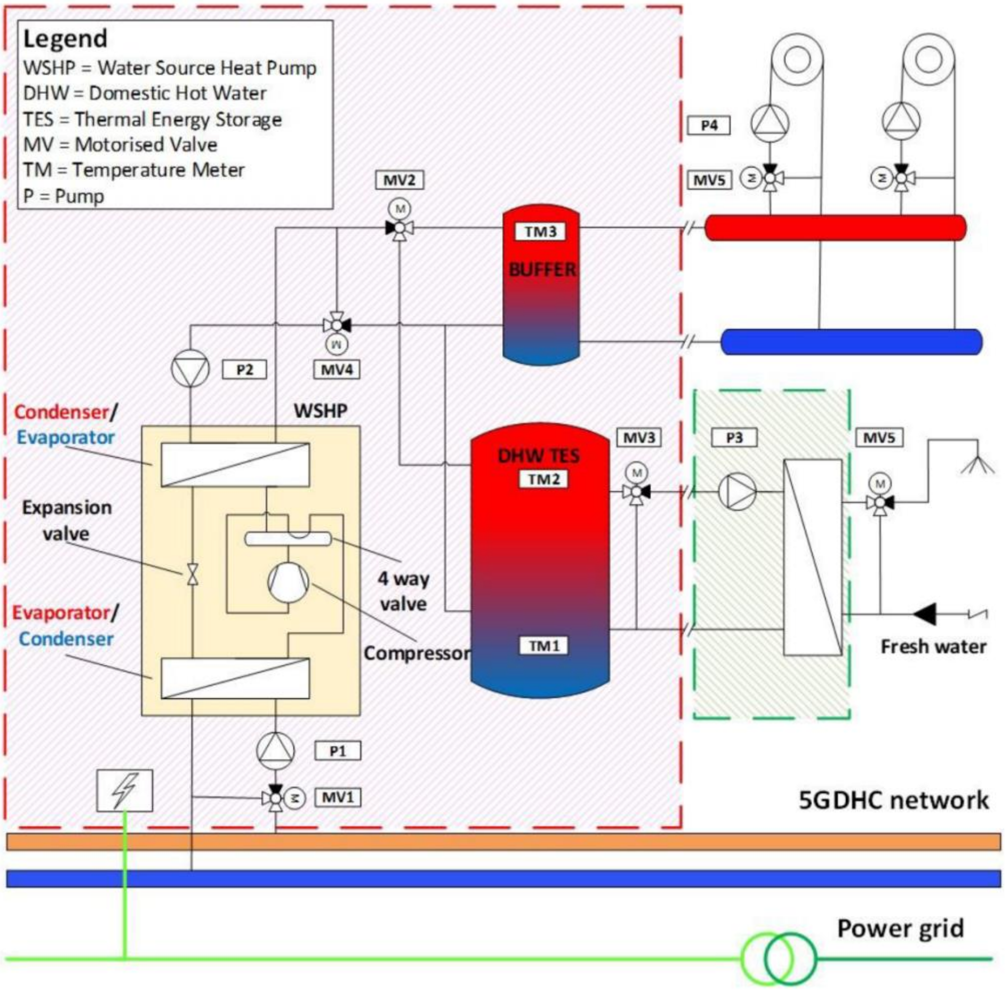

Figure 3: Schematic representation of an Energy Transfer Station (ETS) in a 5GDHC network. The diagram illustrates the key components and fluid flows within the ETS, including a Water Source Heat Pump (WSHP), Domestic Hot Water Thermal Energy Storage (DHW TES), buffer tank, and control elements like motorised valves (MV), temperature meters (TM), and pumps (P).[13]

In summary, 5GDHC shifts equipment to the building side (heat pumps and tanks at each consumer), while the network infrastructure itself is simpler (just warm/cold pipelines with

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[12] Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H., ibid.

[13] Source: Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., & Fedrizzi, R. (2020). ibid.

circulation pumps). This distributed equipment model increases complexity at the user level but gains efficiency by tailoring supply temperatures on-site.

Integration of local and renewable energy sources

A major advantage of 5GDHC networks is the integration of diverse local renewable and waste energy sources. Since a 5GDHC loop runs at ground temperature (~10-20 °C typically), any low-grade heat source can be directly added to the loop without prior upgrading.[14] In this context, a key goal of 5GDHC is to harness all available heat and cold in the urban environment. This means ambient environmental heat can directly feed the network. Groundwater, lakes and rivers, and even urban air can be tapped via heat exchangers. For instance, water from a lake might circulate through a heat exchanger to slightly warm the cool loop (or precool the warm loop), boosting the natural thermal level. Near-surface geothermal energy can similarly be linked at the network level to moderate the loop temperature.

In addition, industrial waste heat and surplus heat from commercial facilities (data centers, waste-to-energy plants, factories) can be captured into the network. All available urban excess heat streams can thus become usable: supermarkets' refrigeration reject heat, data center cooling output, metro or train station ventilation heat, even building Heating, Ventilation, and Air Conditioning (HVAC) waste heat. One defining feature of 5GDHC is that it enables circular energy flows in a community: waste heat from one building's cooling is supplied as useful heat for another building's heating demand. In effect, the city itself becomes an energy source, recycling internal gains. For example, a supermarket's cooling system might provide heat to the 5GDHC loop, offsetting heating demand in nearby offices. Conversely, during winter a building's surplus warmth can feed neighbours' cooling loads.

Additionally, renewable energy integration is maximised in 5GDHC systems. For example, a field of solar thermal panels or geothermal probes can inject heat into the ambient loop when available; and if the loop temperature rises slightly above ground neutral, that heat is either used by other buildings' heat pumps or stored for later. 5GDHC therefore "closes the loop" by balancing heating and cooling: any residual imbalance during the summer can be handled with seasonal storage or a central heat sink.[15] Conversely, any shortfall during

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[14] Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., & Fedrizzi, R., ibid.
[15] Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H., ibid.

the winter can be met by drawing heat from a central renewable plant or the ground. This ultra-flexible source integration is key to achieving highly renewable, locally supplied thermal energy. Overall, 5GDHC forms a *thermal commons* for a district, allowing local sources to be shared.

Thermal storage solutions

Incorporating thermal storage is an essential strategy in advanced DHC design to buffer fluctuations and enhance flexibility. In 5GDHC networks, thermal storage plays multiple roles across different scales. Each building-level ETS usually has a domestic hot water (DHW) tank or thermal battery, which not only provides the conventional function of storing hot water but also acts as a buffer for the heat pump operation.[16] This distributed storage can be "smart-charged": for example, heating the tank when electricity prices are low or when there is surplus renewable electricity, and then using that hot water later when needed. Advanced control of these mini-storages can flatten the electric load of heat pumps: by running heat pumps a bit ahead of demand to charge tanks, the system reduces peak electricity draw and can shift ~10-15% of load off peak times.[17] Additionally, the ambient loop itself functions as a storage to some extent due to its water volume and the thermal mass of the ground.

However, to handle seasonal imbalances, larger storage is required. 5GDHC designs often integrate seasonal or inter-seasonal storage like aquifer thermal energy storage (ATES) or borehole thermal energy storage (BTES). These act as a "thermal bank" for the network: for example, excess heat from buildings in summer is stored in groundwater, raising its temperature slightly, and in winter the process is reversed to supply heat back to the loop.[18] In the Alpine context, underground caverns, mine shafts, or even large water tanks can serve a similar purpose of absorbing summer heat and providing it in winter (or conversely storing winter cool for summer air conditioning). The large scale of 5GDHC networks allows optimal design of such storage vessels and integration of many diverse load profiles to maximise their utilisation.[19]

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[16] Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G., & Fedrizzi, R., ibid.
[17] ibid.
[18] Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H., ibid.
[19] ibid.

In summary, thermal storage solutions (from small decentralised tanks to big seasonal reservoirs) are integral to 5GDHC networks. They provide buffering that improves efficiency, peak shaving capacity, and the ability to incorporate intermittent renewable heat sources. Proper planning of storage (type, size, siting) is therefore a key technical consideration to ensure heat availability and network balance year-round.

Smart controls and digitalisation

Smart control and digitalisation are essential components for the efficient operation of 5GDHC networks, given the complex, bidirectional energy flows and the numerous decentralised heat pumps and thermal storage units involved. These systems require real-time coordination to balance supply and demand, optimise energy use, and maintain network stability. Several advanced control strategies have emerged to address these challenges.

IoT and sensor systems: Fifth-generation DHC networks can benefit from pervasive sensing and communication. Distributed sensors in pipes and substations can report temperature, flow and pressure, enabling automated monitoring and early fault detection. By interconnecting smart devices and sensors to form intelligent heating ecosystems, Internet-of-Things (IoT) platforms have been shown to ensure more energy-efficient and economical networks,[20] anticipating faults and inefficiencies.

AI and machine learning: AI algorithms analyse these data streams to forecast demand and optimise operations. Machine-learning models can predict building heat loads, adapt control setpoints, and detect equipment faults before failures occur. Deploying such data-driven tools is critical for modernising district heating systems.[21] By anticipating load variations and equipment issues, these models improve efficiency and enhance resilience.

Predictive control: Advanced predictive control algorithms use system models and forecasts to optimise operation over time. For example, model predictive control (MPC) continuously adjusts heat-pump outputs, valve settings and storage charging to minimise costs or peak loads while meeting comfort. Buffa et al. (2020) implemented an MPC on a 5GDHC transfer station, and showed it could shift about 14% of electrical load from on-peak to off-peak

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[20] https://www.ise.fraunhofer.de/en/research-projects/ai4cities.html

[21] Ntakolia, C., Anagnostis, A., Moustakidis, S., & Karcanias, N. (2022). Machine learning applied on the district heating and cooling sector: A review. *Energy Systems*, 13, 1–30

hours by exploiting thermal storage.[22] This predictive strategy couples the heating network with electricity pricing signals, boosting overall flexibility and efficiency.

Digital twins: Digital twins are detailed virtual models of the district heating system that run in parallel with the physical network. They combine live sensor data with physics-based or data-driven simulations, allowing operators to test "what-if" scenarios safely. For instance, a recent study used a digital twin of a district heating network to integrate waste heat from a plant.[23] The twin's simulations helped optimise the heat supply-demand balance, cutting fuel use and costs while ensuring reliability.

User-side digital interfaces: Finally, user-facing digital interfaces (smartphone apps, web dashboards or smart thermostats) close the loop to building occupants. These interfaces provide real-time feedback on energy use and prices, and enable users or automated building systems adjust their heating schedules. With these tools, consumers can shift heating in response to grid signals or time-of-use rates. In this way, digitalisation empowers end-users via demand management, allowing buildings to lower loads when needed. Engaging users in this way adds flexibility and contributes to the overall efficiency and resilience of the 5GDHC network.

Flexibility and scalability of system design

Fifth-generation networks should be designed with flexibility and future scalability in mind, recognising that energy demand and supply options will evolve. Flexibility refers to the system's ability to handle varying conditions, such as fluctuations in demand, integration of different energy supplies, and participation in cross-sector energy balancing. The lower operating temperature advances 5GDHC's flexibility, as these systems can use the electricity grid as a support, via heat pumps or electric boilers that can be turned on to absorb surplus renewable electricity, effectively coupling the power and heat sectors. As already mentioned, this sector coupling is a valuable flexibility service: it allows DHC networks to act as a "thermal battery" for the grid, charging heat storage when power is plentiful and reducing electric consumption when the grid is strained.

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[22] Buffa, S., Soppelsa, A., Pipiciello, M., Henze, G. P., & Fedrizzi, R. (2020). Ibid.

[23] Værbak, M., Jørgensen, B. N., & Ma, Z. (2024). Leveraging digital twins for sustainable district heating: A study on waste heat from Power-to-X plants. In *Proceedings of the 13th Energy Informatics Conference* (LNCS 15271, pp. 210-227)

In 5GDHC, this flexibility is built into the concept: distributed heat pumps mean the entire heating load is electrified (albeit efficiently via heat pumps). By controlling those pumps and their thermal stores, the network can modulate its electric draw significantly to aid grid stability. Moreover, 5GDHC's ability to exchange heat between buildings provides thermal flexibility. This reduces reliance on any single source and improves resiliency to outages or demand spikes.

Scalability is another key consideration for planners. The system should be able to expand and adapt over time. In the case of 5GDHC, scalability has been demonstrated through the cluster approach. A city can start with a few cluster loops serving pilot areas (for example, a new low-energy development or a retrofitted district). As confidence and demand grow, additional clusters can be built and linked via a backbone, as was done in the Mijnwater project in the Netherlands.[24] This cell-like growth means investments can be staged, and the network can evolve into a larger integrated system over time. One challenge, however, is ensuring that control strategies and infrastructure keep pace. A small 5GDHC in a single district can operate somewhat simply, but a city-wide 5GDHC with many clusters requires a more sophisticated control and market structure.

From a policy and planning perspective, flexibility and scalability translate to future-proofing the heating infrastructure. Investing in 5GDHC means creating systems that can absorb new technologies (like next-generation heat pumps or power-to-heat devices), shift to even lower temperatures as building retrofits progress, and expand coverage without massive reinvestment. For example, a 5GDHC network can start by serving a mix of buildings and later incorporate an industrial park that has excess heat to contribute, thereby increasing its renewable fraction further.

In this way, modern district energy networks remain a flexible backbone for local energy transitions, rather than a rigid infrastructure. This is particularly relevant for regional and municipal authorities in Alpine areas and beyond: by adopting 5GDHC design principles, they can build heating and cooling networks that are scalable, smart, and ready to integrate the rich variety of renewable resources their territories offer. That way, they can enable low-carbon, secure, and efficient energy systems for the long term.

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[24] Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H., ibid.

Regulatory Framework for 4GDH/5GDHC Networks in the Alpine Space

Modern H&C networks must be developed within the context of EU, national, and regional regulations. These regulatory requirements ensure that networks align with broader energy policy goals (like decarbonisation and efficiency) and that they operate fairly and safely. This section presents key regulatory requirements and policy frameworks in effect at different levels.

EU-level directives and frameworks

- **Energy Efficiency Directive (EED):** The revised EED (Directive 2023/1791) mandates strategic heat planning. Member States must submit comprehensive heating and cooling assessments and identify efficient solutions. Notably, local heat planning becomes compulsory: all municipalities above 45,000 people must develop local heating and cooling plans mapping demand and renewable/waste heat potential. The EED also tightens the definition of “efficient” DHC. From 2028 onward, systems must have at least 50% renewable energy, 50% waste heat, 50% renewable energy and waste heat, 80 of high-efficiency cogenerated heat or at least a combination of such thermal energy, with gradually stricter requirements every few years up to 100% by 2050. Alternatively, networks can meet GHG intensity limits per kWh of heat (e.g. ≤150 grams/kWh by 2026, ≤100 grams by 2035, and 0 grams/kWh) to qualify as efficient. These EED provisions effectively push 5th-generation district systems to use low-carbon heat sources and to integrate planning into policy.

- **Renewable Energy Directive (RED):** The RED III (Directive 2018/2001) and it amendment, the RED III (Directive 2023/2413), set targets for renewable heating and cooling and address DHC networks specifically. Article 23 requires countries to increase the renewable share in heating and cooling by around +1.1% annually. Article 24 obliges Member States to facilitate integration of renewable and waste heat into DHC systems; for example, by ensuring that DHC operators open their networks to third-party renewable heat producers or by giving consumers the right to disconnect if the network’s supply isn’t green enough. These provisions aim to mainstream renewable energy in district networks, aligning with 5GDHC principles of multi-source, low-temperature operation. Alpine regional and local authorities planning new networks should account for these rules, creating business models for third-party waste heat supply and ensuring renewables can be readily connected.

- **Energy Performance of Buildings Directive (EPBD):** The EPBD (Directive 2024/1275) reinforces the link between buildings and district systems. It proposes that by 2050 all buildings must be zero-emission, meaning no on-site fossil fuel use. Heat supply via a decarbonised district heating network emerges as an advantageous solution toward this goal. New buildings in the EU will face bans on fossil-fueled boilers in coming years, which in practice encourages connection to renewable-based district heating or use of heat pumps. The EPBD also introduces Minimum Energy Performance Standards for existing buildings, pushing renovations that often include switching to efficient heating sources.

- **State Aid Rules:** EU competition law (particularly the 2022 Climate, Energy and Environmental Aid Guidelines) explicitly recognises district heating and cooling as eligible for public support. To comply with State aid rules, public funding for DHC projects must facilitate environmental objectives (e.g. GHG reduction) without unduly distorting the market. In practice, this means that aid is typically approved only for networks that are efficient or transitioning to efficiency as defined by the EED. For instance, the EU has fast-tracked approval of national schemes subsidising "green" district heating conversions, subject to the networks achieving high shares of renewables or waste heat.[25]

- **REPowerEU:** Launched in May 2022 as the EU's strategic response to energy market disruptions, REPowerEU establishes a comprehensive framework that significantly impacts district heating and cooling development. REPowerEU explicitly identifies the modernisation of district heating systems as a strategic priority. The plan emphasises accelerating heat pump deployment across all applications. For district heating specifically, REPowerEU promotes the transition away from fossil fuels through renewable integration and waste heat recovery.

National frameworks in Alpine countries

- **Austria:** Austrian energy policy supports district heating and cooling, although there is no consolidated national policy framework for heating and cooling plans in place.[26]

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[25] Insight EU Monitoring. (2025, April 11). *Czechia: EU Commission approves €2bn state aid increase for green district heating*. https://ieu-monitoring.com/editorial/czechia-eu-commission-approves-e2bn-state-aid-increase-for-green-district-heating/607995

[26] https://energy-cities.eu/countries/austria/

Given that energy policy related responsibilities are divided between the federal and the regional level, a significant part of DHC planning is driven at the provincial and local level. The government's vision is to achieve fossil-free heating by 2040, as outlined in the country's Renewable Heat Act (EWG). This law complements provincial initiatives: for example, the city of Vienna's *Heating Plan 2040* aims to convert one of Europe's largest district networks entirely to renewable and recovered heat by 2040. Other regions like Salzburg or Styria have integrated heat zoning in spatial planning, encouraging new developments to connect to biomass or geothermal-fed district systems where available. While Austria does not mandate municipal heat plans for every city, many cities voluntarily create urban heat strategies and GIS-based heat atlases to identify 5GDHC opportunities.

- **France**: France's regulatory framework for district heating and cooling (DHC) is shaped by a combination of national legislation and local planning requirements. The cornerstone of this framework is the Energy Transition Law for Green Growth (2015), which mandates that intercommunalities with over 20,000 inhabitants develop Sustainable Energy and Climate Action Plans (SECAPs) to decarbonize their energy systems. These SECAPs must include comprehensive strategies for reducing carbon emissions from heating and cooling, integrating local renewable energy sources, and enhancing energy efficiency. Additionally, municipalities that operate public DHC networks are required to produce a Master Plan (Schéma Directeur) every ten years, outlining their long-term plans for decarbonizing and expanding these networks. This planning obligation includes assessments of local energy resources, potential for renewable integration, and strategies for reducing dependence on fossil fuels. However, despite these requirements, the development of detailed heating and cooling plans remains largely voluntary, resulting in significant regional disparities. To address this, the French government has introduced financial support mechanisms, such as the Fonds Chaleur, which provides subsidies to municipalities for the deployment of renewable and recovered heat technologies. France also ties incentives to network greening – consumers pay a reduced VAT rate (5.5% instead of 20%) on heat if the network uses >50% renewable or recovered heat.[27]

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[27] Cerema. (2022, August 11). *District Heating and Cooling in France: Figures and Outlook*. https://reseaux-chaleur.cerema.fr/espace-documentaire/district-heating-and-cooling-france

- **Germany**: Germany's regulatory framework for heating and cooling is shaped by a combination of federal and regional policies aimed at achieving climate neutrality by 2045. Key to this approach is the Building Energy Act (Gebäudeenergiegesetz - GEG), which sets efficiency standards for buildings and mandates the integration of renewable energy sources in new heating systems. Municipal heat planning is also becoming a central component, with the federal government introducing requirements for local heating and cooling strategies. Municipalities are expected to assess current heating demand, identify potential renewable and waste heat sources, and outline decarbonisation strategies. Larger cities (with populations over 100,000) must submit their heat transition plans by 2026, while smaller municipalities have until 2028. Additionally, Germany supports this transition through substantial funding programs like the Federal Funding for Efficient Heating Networks (BEW), which provides grants for expanding district heating networks that utilise renewable energy or waste heat.

- **Italy**: In Italy, district heating and cooling (DHC) systems are primarily governed by local and regional authorities, as there is no comprehensive national framework law specifically dedicated to heat networks. However, national legislation mandates that municipalities with populations exceeding 50,000 inhabitants develop plans for DHC network expansion, aiming to increase the utilisation of energy produced from renewable sources. The National Plan Integrated for Energy and Climate (NECP) has set a renewable energy share target for the heating and cooling sector at 33.9% by 2030. The integration of renewables into DHC is further encouraged through incentive schemes such as the Conto Termico program, which allocates €900 million annually to support the adoption of renewable heating technologies like solar thermal, biomass, and heat pumps. Additionally, the White Certificates (Certificati Bianchi) scheme offers tradable certificates to entities that achieve verified energy savings, including through the implementation of efficient DHC systems. Many Italian district systems are developed via municipal concessions to utilities, under oversight of the national energy regulator. Northern regions often include district heating in urban energy plans. For example, Milan and Turin have energy zoning that favors connecting new developments to existing networks.

- **Slovenia**: Slovenia relies on integrated local energy planning and EU-aligned national strategies to advance district heating. Under the *Energy Act*, municipalities are obliged to prepare Local Energy Concepts: that is, comprehensive plans for energy supply and demand at the local level. These concepts include assessments of district heating potential and scenarios to increase renewable heating; they are not however fully aligned with spatial and zoning aspects. National policy also promotes use of waste heat and renewables: Slovenia's 2050 Heating and Cooling Strategy and its National Energy and Climate Plan (NECP) set targets to raise the share of renewables in heating. While Slovenia does not impose obligatory connection to district heating, it treats district heating as a public utility service in many urban areas, meaning that project developers must obtain licenses and meet technical standards. The country currently lacks a dedicated financial framework to support the preparation of LEKs or other strategic energy planning activities. While some national funding calls may cover the implementation phase of these plans, their availability and scope vary significantly depending on the changing priorities of national programs. As a result, municipalities often depend on EU funding and project calls to finance both the planning and implementation stages.

Permitting and administrative procedures for 4GDH/5GDHC networks

The development of 5GDHC systems in the Alpine Space is not only shaped by high-level policy objectives, but also by a dense web of permitting, licensing, and administrative procedures. These requirements (ranging from construction authorisations to environmental approvals) are critical determinants of whether and how fast a network can be realised. As was found and corroborated in ALPHA's earlier activities, district heating systems in the Alpine space still face implementation bottlenecks due to regulatory and administrative competences often being fragmented across local, regional, and national levels.

Typical Permitting and Licensing Requirements

At the project level, the deployment of 4GDH/5GDHC systems involves navigating multiple administrative layers. Core permitting tasks generally include:

- **Construction and excavation permits**, especially for laying pipes in public roads, protected zones, or under private land. These require coordination with local authorities, utilities, and sometimes cultural heritage or environmental bodies.

- **Environmental Impact Assessments** (EIAs) for larger-scale or potentially sensitive projects. Depending on the country and project type, EIAs may be mandatory or screened for significance. 5GDHC systems using ambient loops or aquifers may also require hydrogeological permits or groundwater abstraction licences.

- **Urban planning and zoning compliance**, including consistency with municipal land-use plans or designated energy zones. In countries like France and Germany, alignment with local energy or heat zoning frameworks is a prerequisite.

- **Network operation licenses or concession agreements**. In certain cases, district heating often operates under a municipal concession or classification scheme which grants legal authority to develop and operate the system.

- **Grid interconnection approvals and metering authorisation**, especially if combined heat and power (CHP) or electricity-driven heat pumps are involved.

- **Public consultation and participation procedures**, which may be required under national planning law or EU strategic environmental assessment (SEA) obligations.

The complexity and sequencing of these steps vary across countries. For example, in Austria and Germany, permitting pathways differ by federal state, and often require coordination with environmental, transport, and building authorities. Several of these issues and barriers have already been mapped by partners in the context of the ALPHA project.

Key Economic Considerations for 4GDH and 5GDHC Networks

Economic viability is a cornerstone of any heating and cooling network project. Key economic parameters include assessing market demand, ensuring financial feasibility (CAPEX/OPEX), exploring funding mechanisms, and conducting cost-benefit analyses that consider both direct and societal impacts. Modern H&C networks must be economically sustainable to attract investment and end-users, while delivering affordable heat to consumers.

Market demand and heat density

A fundamental economic criterion for district H&C is the heat (and cooling) demand density in the area to be served. High energy demand over a concentrated area generally improves viability, as the fixed costs of network infrastructure can be spread over larger consumption. During the planning stage, detailed needs assessment is performed by mapping the current and projected heating and cooling demands of buildings in the target area (often using GIS tools and energy audits). As part of this process, planners identify anchor loads (e.g. large public buildings, hospitals, industries) that can guarantee consumption. The presence of cooling demand (e.g. in the case of office clusters or commercial refrigeration) adds value by enabling year-round utilisation heat recovery from cooling. Economic feasibility often hinges on achieving a critical mass of customers. Thus, stakeholder engagement and sometimes connection mandates or incentives are used to secure enough subscribers. Experience shows that the financial viability of new DHC systems is highly dependent on achieving the forecasted demand. Instead, underestimating "demand risk" can lead to revenue shortfalls.[28] For example, if fewer buildings connect than expected or if energy efficiency measures reduce consumption faster than anticipated, the network may struggle to cover its fixed costs.

CAPEX, OPEX and viability factors

Capital Expenditure (CAPEX): Building a 5GDHC network requires significant upfront investment in distribution pipes, plant or heat pumps, and customer connections. A key cost driver is the distribution network. High building density and connection rates are critical for

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[28] Galindo Fernández, M., Roger-Lacan, C., Gährs, U., & Aumaitre, V. (2016). *Efficient district heating and cooling systems in the EU: Case studies analysis, replicable key success factors and potential policy implications*. Prepared by Tilia GmbH for the Joint Research Centre of the European Commission.

economic viability, since dense clusters spread infrastructure cost across more consumers.[29] A common benchmark is that a linear heat density above ~2 MWh heat demand per metre of network length is needed for profitable district heating.[30] In practice, this means focusing on areas with enough heat demand (e.g. urban centers or clustered loads) to justify network extension. Connection policy also matters: ensuring a high proportion of buildings connect (through incentives or requirements) reduces the risk of under-utilised capacity.

Fourth- vs. fifth- generation costs: 5GDHC uses lower temperatures and often plastic piping, theoretically cutting pipe material costs. However, studies show 5GDHC network CAPEX ends up similar to 4GDH, because the ambient design needs larger pipe diameters to carry the same heat. Moreover, 5GDHC's bidirectional loops can't fully exploit demand diversity, requiring higher installed capacity to meet peaks. Thus, the cost savings from cheaper uninsulated pipes are offset by the need for bigger pipes and more pumping equipment. Both 4GDH and 5GDHC still rely on expensive groundwork for pipe installation, which often dominates project cost. Keeping CAPEX in check requires careful network design (optimising routing, phasing expansion) and leveraging existing infrastructure where possible.

Operational Expenditure (OPEX): Day-to-day costs include fuel or electricity for heat generation, pump electricity, maintenance, and staffing. 5GDHC networks typically shift more cost to electricity (due to running many heat pumps) and maintenance of distributed units. Thermal losses in pipes represent another OPEX factor, which is however minimised in 5GDHC by using near-ambient temperatures. Efficient operation (using digital controls, leak detection, etc.) can significantly reduce OPEX. For example, digital optimisation of flow and return temperatures can lower pumping energy and return cooler water, improving overall efficiency.

Energy pricing and competitiveness: The price at which heat is sold (tariff) must be competitive with alternatives (such as individual gas boilers or heat pumps) for customers to connect. Many European countries regulate district heat tariffs or tie them to fossil fuel

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[29] Kearney. (2025, February 11). *Local district heating: Scaling profitably with tailored and modular solutions*. Retrieved from https://www.kearney.com/industry/energy/article/local-district-heating-scaling-profitably-with-tailored-and-modular-solutions

[30] JASPERS Team. (2024, September 30). *JASPERS guide to decarbonisation of district heating systems*. European Investment Bank. https://jaspers.eib.org/files/library/2024/jaspers-guide-to-decarbonisation-of-district-heating-systems.pdf

prices for fairness. For instance, Dutch regulators set a maximum heat tariff linked to gas prices).[31] Generally, two-part tariffs are used: a fixed charge (capacity or connection fee) to cover network CAPEX and a variable charge per kWh or GJ to cover fuel/OPEX.[32] Evidenty, high tariffs may deter consumers from connecting.

Notably, volatile fossil gas prices and rising carbon costs have improved the economics of low-carbon district heating. As of the early 2020s, EU carbon allowance prices have surged,[33] increasing the cost of gas and coal heating. This favors systems that utilise renewables, waste heat, or electrified heat pumps. For example, the 5GDHC network in Heerlen (Netherlands) offers heat ~10% cheaper than conventional gas heating, and its tariff is decoupled from fossil fuel price swings.[34] Price stability and discount can provide consumers with the economic incentive to switch to the district system.

Funding and financing mechanisms

Implementing 5GDHC projects requires mobilising substantial upfront capital, often beyond the means of municipal budgets alone. A mix of public and private financing mechanisms can be used to fund these networks:

- **Public grants and subsidies**: European and national grants play a pivotal role, especially for innovative or low-carbon district systems. EU programs and structural funds offer capital grants or project development assistance to kick-start projects. National governments also provide investment subsidies or tax rebates for renewable district heating (such as support for geothermal drilling or biomass boilers).

- **Loans and concessional finance**: Long-term loans from public banks (like the European Investment Bank, EIB, or national development banks) are commonly used

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[31] Netherlands Authority for Consumers and Markets (ACM). (2024, December 17). *Maximum heat tariffs in 2025: Variable tariff slightly lower, fixed costs almost the same*. https://www.acm.nl/en/publications/maximum-heat-tariffs-2025-variable-tariff-slightly-lower-fixed-costs-almost-sameACM

[32] Verstraten, P., & Huygen, A. (2023, April 5). *Differences in district heating tariffs between European countries*. DBDH. https://dbdh.org/differences-in-district-heating-tariffs-between-european-countries/

[33] Sitarz, J., Pahle, M., Osorio, S., Luderer, G., & Pietzcker, R. (2024). EU carbon prices signal high policy credibility and farsighted actors. *Nature Energy*, 9, 691-702. https://doi.org/10.1038/s41560-024-01505-x

[34] https://www.districtenergyaward.org/wp-content/uploads/2019/09/b9508b8e8e7d4e76a0621b8d0c49c629tmp1.pdf

to finance district heating infrastructure. These loans often have low interest rates and long tenors to match the infrastructure lifespan. For instance, in 2025 the EIB provided a €70 million loan to a German municipal utility (Reutlingen) to expand its electricity and district heating grids.[35] Such financing lowers the cost of capital, making tariffs more affordable.

- **Guarantees and risk-mitigation**: Given that district projects face demand risk, credit guarantees or insurance can improve bankability. Government or EU guarantee schemes can partially underwrite loans, lowering risk for lenders. This is especially helpful for 5GDHC, which may have newer technology risk or unproven business models. Public-private partnership contracts sometimes include minimum off-take guarantees or fallback payments by municipalities if heat sales disappoint, which essentially amounts to a form of risk-sharing to attract private investors.
- **Energy performance contracting (EPC) and ESCO Models**: An Energy Service Company (ESCO) can finance and operate the heating/cooling system, recouping investment through long-term heat sale agreements. Under an EPC, the ESCO guarantees a certain performance or cost saving to the client.[36] Such third-party financing is useful when municipal budgets are constrained. Successful examples include public-private ESCOs running district systems in France and Germany, and the Mijnwater company in Heerlen which is municipally owned but operates akin to an ESCO (providing full service and reinvesting profits locally).[37]

Emerging business models, risk sharing, and market integration

Beyond traditional utility models, 4GDH/5GDHC networks are spurring new business approaches and economic considerations:

- **Prosumer participation**: 5GDHC networks are inherently bidirectional, allowing buildings or facilities to both consume and supply heat. This enables "prosumers"

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[35] European Investment Bank. (2025, January 14). *Germany: EIB supports expansion of electricity and district heating networks in Reutlingen*. https://www.eib.org/en/press/all/2025-006-eib-supports-expansion-of-electricity-and-district-heating-networks-in-reutlingen

[36] Midlen, A. (2019, July). *HeatNet NWE: Guide to financing 4th generation district heating and cooling (4DHC)*. Interreg North-West Europe. https://guidetodistrictheating.eu/wp-content/uploads/2020/01/HeatNet-NWE_Guide-to-Financing-4DHC_District-Heating.pdf

[37] https://www.districtenergyaward.org/wp-content/uploads/2019/09/b9508b8e8e7d4e76a0621b8d0c49c629tmp1.pdf

(producer-consumers) such as data centers, supermarkets, or wastewater plants to feed surplus heat into the grid. From an economic point of view, this requires new arrangements for the compensation of prosumers for their heat contributions. For example, a data center might sell waste heat to the network at an agreed price per kWh, reducing the network's need to buy fuel. This distributed ownership of heat supply can lower overall system costs (by utilising free waste heat) while giving prosumers a revenue stream.

- **Community and cooperative models:** Some district heating ventures are owned by cooperatives of heat users or by municipalities with community ownership ethos. This model can accept a longer payback horizon and prioritise social benefits (like CO_2 reduction and energy security) alongside profits. It also builds public trust, which can improve connection rates.

- **Role of carbon pricing and incentives**: The trajectory of carbon prices under the EU Emissions Trading System (ETS) and national carbon taxes is tilting the economics in favor of low-carbon district heating. Many large heat plants already pay for CO_2 emissions under the ETS. A high carbon price makes biomass, heat pumps, and waste heat utilisation economically attractive compared to gas or coal boilers. Moreover, the EU is implementing ETS2 (for buildings and transport) by 2027, which will put a carbon cost on individual heating fuels across all Member States.[38] This could effectively act as a forward-looking subsidy for district heating: as fossil heating costs rise, consumers will seek alternatives, hence connecting to a renewable-based district system becomes financially sensible.

- **Integration with power markets (Sector coupling)**: Modern district energy networks are increasingly seen as flexibility assets in the broader energy market. Integration with power systems adds new value streams: for example, large heat pumps in a 5GDHC can consume surplus renewable electricity when power prices are low or negative, converting it to heat stored in the network.[39] This not only provides cheap heat but also helps balance the electricity grid by soaking up excess wind or solar.

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[38] Sitarz, J., Pahle, M., Osorio, S., Luderer, G., & Pietzcker, R. C. (2024). EU carbon prices signal high policy credibility and farsighted actors. *Nature Energy*, 9, 691-702. https://doi.org/10.1038/s41560-024-01505-x

[39] International Energy Agency. (2020, January 15). *Heat pumps in district heating and cooling systems*. https://www.iea.org/articles/heat-pumps-in-district-heating-and-cooling-systems

Thermal energy storage (hot water tanks, boreholes, etc.) linked to district heating allows decoupling of heat production from consumption.

In summary, 5GDHC networks offer a pathway to decarbonise urban heating and cooling, but careful attention to economics is essential. Strong demand in dense areas and supportive market trends (like high fossil prices and technology learning-curve cost reductions) create a favorable outlook. Still, projects must optimise CAPEX and OPEX through smart planning and digital operation, and secure financing via diverse mechanisms. Municipal authorities and energy planners can leverage EU funds, green finance, and innovative contracting (EPC/ESCO models) to turn long-term energy savings into upfront investments. Emerging models –from prosumer integration to sector coupling– further enhance viability by unlocking new value.

Environmental Considerations for 4th- and 5th-Generation District Heating and Cooling Networks

Fifth-generation district heating and cooling systems can play a key role in municipal climate strategies by integrating renewable energy, reusing waste heat, and dramatically cutting CO_2 emissions from the heating and cooling sector. The following sections outline the core environmental considerations and benefits related to a 5GDHC design, with a focus on policy-relevant insights for planners and engineers.

Integration of renewable energy sources

As already discussed in section 1.1.3, the fundamental shift in lower temperatures afforded by modern H&C systems enables a wide range of renewables to feed the network, such as:

- Geothermal energy: Both deep geothermal (hot aquifers) and shallow geothermal can supply heat. 5GDHC “neutral temperature” loops can directly leverage shallow geothermal heat from boreholes or minewater, as demonstrated in the Heerlen Mijnwater project.[40] Such systems use the earth as a giant thermal battery, providing emission-free baseload heating and cooling.

- Solar thermal energy: Large solar collector fields (potentially with seasonal storage) can supplement district heating supply. In practice, central solar thermal plants have been deployed to charge heat storage in summer and displace fossil fuels in winter. Seasonal solar heat storage allows renewable energy produced in summer to meet winter demand,[41] directly reducing the need for gas or coal in cold months.

- Ambient heat and renewable electricity: Modern district systems increasingly use ambient environmental heat (from air, water, or soil) upgraded by high-efficiency heat pumps. With 5GDHC, building-level electric heat pumps draw from a tepid water loop and can boost heat or provide cooling on demand, effectively coupling the grid with renewable electricity supply.

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[40] International Renewable Energy Agency. (n.d.). *9 Fifth-generation DHC systems*. Retrieved April 30, 2025, from https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-heat-and-cooling/9-Fifth-generation-DHC-systems

[41] International Renewable Energy Agency (IRENA). (n.d.). *Fourth-generation DHC systems*. Retrieved April 30, 2025, from https://www.irena.org/Innovation-landscape-for-smart-electrification/Power-to-heat-and-cooling/8-Fourth-generation-DHC-systems

By maximising local renewables, these networks cut fossil fuel dependency. Integrating geothermal, solar, and other renewable heat not only lowers greenhouse gases but also improves energy autonomy for communities.

Waste heat valorisation strategies

5GDHC systems place strong emphasis on valorising waste heat. Lower network temperatures make it feasible to harvest waste heat from a variety of sources and feed it into the district system. This circular energy flow approach improves overall efficiency and is seen as a key climate strategy for cities. Common waste heat sources include:

- Industrial processes and power plants: Factories, refineries, steel mills, and thermal power generation often reject large amounts of heat. Modern district networks can recover this heat (e.g. via heat exchangers or heat pumps) and distribute it to buildings, offsetting the need to burn new fuel.

- Urban infrastructure (incinerators, wastewater, metros): Waste-to-energy incineration plants are often coupled with 4GDH systems to utilise their hot flue gases. Barcelona's upgraded district heating/cooling network is a prime example: most of its heat is supplied by a municipal waste incinerator, which along with other efficiencies helped increase annual CO_2 savings. Similarly, cities are tapping sewage wastewater and underground metro stations as heat sources.

- Commercial buildings and data centers: Data center servers and large refrigeration systems (e.g. in supermarkets or ice rinks) reject low-grade heat that can be captured for district heating. In 5GDHC networks, this integration is quite seamless, as the network operates at neutral temperature and buildings can directly exchange heat.

Leveraging waste heat has immediate environmental benefits. First, it reduces primary energy use. As a result, CO_2 emissions drop in proportion. Second, utilising excess heat improves urban thermal efficiency: instead of dumping heat into air or water (which can cause local thermal pollution), that energy is put to productive use. The European Heat Pump Association notes that excess heat is an abundant renewable resource, capable of covering a significant share of the EU's building heating demand.[42] Modern 5GDHC networks aim to unlock this potential at scale.

CO_2 Emissions reduction and accounting

The combined effect of renewable integration, waste heat reuse, and higher efficiency is a major reduction in greenhouse gas emissions for heating and cooling. District energy allows the replacement of individual fossil-fuel boilers with cleaner distributed resources, cutting CO_2 per unit of heat. In practice, shifting from a conventional gas/oil-based heating mix to a 5GDHC supply can sharply lower the carbon intensity of heat. Notably, 5GDHC networks can run entirely on ambient heat and green electricity, meaning that if the grid power is renewable, the heating/cooling supply is virtually carbon-free.[43]

In terms of emissions accounting, 5GDHC systems benefit from favorable treatment under clean energy policies. Recovered waste heat is counted toward renewable energy targets in the EU, reflecting its contribution to emissions reduction. When calculating a network's carbon footprint, planners consider direct emissions and indirect emissions from electricity used by heat pumps. Since heat pumps have high coefficients of performance, the CO_2 emitted per kWh of heat is much lower than for on-site combustion, even with the current electricity mix.[44] Municipal energy planners are increasingly using CO_2 accounting tools to compare scenarios (e.g. upgrading a 3G network to 4GDH vs. building-by-building heat pumps).

Overall, environmental sustainability is both a motivation and a guiding criterion in designing H&C networks. These systems, if well implemented, can deliver substantial CO_2 reductions aligned with EU and Alpine climate targets, harness local renewable and waste energy flows, and reduce pollution. The requirement, increasingly formalised in policy, to

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[42] European Heat Pump Association. (2024, April 15). From waste to worth: How excess heat recovery fast-tracks the clean energy transition. https://www.ehpa.org/news-and-resources/news/from-waste-to-worth-how-excess-heat-recovery-fast-tracks-the-clean-energy-transition/

[43] Pro Energy. (n.d.). *5th generation district heating and cooling (5GDHC networks)*. Retrieved April 30, 2025, from https://www.npro.energy/main/en/5gdhc-networks

[44] European Commission. (2018, December 14). *Cities use waste heat to save energy and cut emissions*. Research and Innovation. https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/cities-use-waste-heat-save-energy-and-cut-emissions

have high renewable share and low emissions in new networks means environmental factors are essentially hard requirements.

Social Dimensions in 4th- and 5th-Generation District Heating & Cooling

Fifth-generation DHC systems are key enablers of low-carbon, efficient energy supply for communities. Beyond their technical advantages, careful attention to social dimensions is crucial in planning and implementing these networks. This ensures that the transition to clean heating and cooling is inclusive, affordable, and publicly supported. Key social considerations include impacts on household energy insecurity, equity of access, public acceptance, community participation, and local job creation.

Reducing household energy poverty and insecurity

Energy poverty remains a pressing issue in Europe, with over 10% of EU citizens –nearly 48 million people– struggling to keep their homes adequately warm.[45] Next-generation district heating networks can be a tool to alleviate this insecurity. By leveraging renewable and waste heat sources at lower operating temperatures, 5GDHC systems can deliver heat more efficiently and at potentially lower and more stable costs than fossil-based individual heating. This improves energy affordability and shields households from volatile fuel prices, enhancing “energy secure” heating supply.

To protect vulnerable users, planners should design fair tariff structures and support schemes. This may include subsidised connection costs for low-income households or social tariffs to ensure basic heating is affordable. Strong regulatory oversight is also important: without it, district heating operators could exploit their monopoly position, harming consumers and deterring network adoption.[46] EU policies are increasingly addressing these issues. The Renewable Energy Directive, for instance, encourages opening heat networks to diverse renewable suppliers (Article 24) to spur competition and reduce prices.

Ensuring equity in access to clean energy

Equitable access to clean heating and cooling is a fundamental social goal. District heating planning should ensure that benefits reach all communities and not only high-density or affluent areas. This means extending networks or alternatives to neighbourhoods that currently rely on expensive, polluting heating (for example, old electric or coal heaters

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[45] https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20250123-2

[46] Gorroño-Albizu, L., & de Godoy, J. (2021). Getting fair institutional conditions for district heating consumers: Insights from Denmark and Sweden. *Energy*, *237*, 121615. https://doi.org/10.1016/j.energy.2021.121615

often found in rural or low-income areas). Integrating 5GDHC into urban social housing developments or retrofitting existing public housing can provide tenants with more affordable and sustainable heat. In parallel, strategies are needed for less-dense areas that 5GDHC might not reach. For example, such strategies can take the form of supporting mini-grids or heat pump programs so that rural households are not left behind in the clean energy transition. Equity also involves fair distribution of costs: infrastructure investments should be financed in ways that do not over-burden those least able to pay.

Another aspect of equity pertains to inclusive ownership and benefit-sharing. In some European regions, district heating systems are cooperatively or municipally owned, ensuring that profits are reinvested into the community or used to lower heat prices. This model, common in Denmark’s not-for-profit heat networks, has helped keep heating costs low and fostered public trust. Future 5GDHC grids can also empower consumers as prosumers. Overall, an equitable 5GDHC rollout means broad access to clean heat for all socio-economic groups, narrowing the urban-rural and rich-poor gaps in energy service quality.

Social acceptance and awareness of district heating

Building and maintaining social acceptance is critical for the success of advanced district heating projects. Historically, many people are simply unfamiliar with district heating, or they may have concerns about being tied to a single heat provider. Effective communication and awareness-raising can address misconceptions and highlight the advantages (such as comfort, reliability, and environmental gains). Proactive outreach is essential when upgrading heating systems. Municipalities and utilities should engage in information campaigns about how 5GDHC technology works, the sources of heat (e.g. renewable energy, waste heat), and the long-term price stability it can offer compared to volatile fossil fuels.

Transparency in pricing and operations also bolsters trust. For instance, clearly explaining how heat tariffs are set and ensuring community oversight can reassure users that the system is working in their interest. In addition, emphasising local environmental benefits (such as improved air quality from phasing out oil or coal heating) can increase public support. Addressing residents’ concerns earnestly and early can help convert any potential initial skepticism into broad-based support for 5GDHC initiatives.

Public participation and co-design

Beyond passive acceptance, active public participation in the planning process greatly enhances the success of 5GDHC projects. Involving citizens, local businesses, and other stakeholders in co-designing the heat network ensures that the project reflects community needs and values. Tools like public consultation workshops, surveys, and stakeholder committees should be built into the planning phase. By giving future users a voice in decisions (e.g. network routes, construction disruptions, tariff models, or choosing renewable heat sources), planners can pre-empt conflicts and build trust.

Public participation also opens opportunities for community co-ownership or investment in the infrastructure. Overall, a co-designed approach not only improves the technical design (through local insights) but also fosters a sense of collective ownership, greatly enhancing long-term commitment and satisfaction among users.

Job creation and skills development

The transition to 5GDHC can bring economic and employment opportunities at the local level. Deploying these modern networks requires a skilled workforce for planning, installation, and maintenance: from civil engineers and pipefitters to technicians for heat pumps and control systems. As cities and regions invest in new heating infrastructure, they can expect a boost in construction and engineering jobs. For example, the EU's recent "Renovation Wave" initiative (which includes upgrading heating systems) is projected to create over 160,000 new jobs in the building sector.[47] District heating projects directly employ local workers for tasks like pipeline excavation, boiler house construction, and insulation upgrades, while also spurring jobs in manufacturing (e.g. production of pipes, heat exchangers, and smart metering equipment).

Equally important is the development of new skills to support these advanced systems. 5GDHC networks are highly optimised and often digitally managed, so operators and technicians need training in areas like smart grid control, data analysis, and efficient heat pump operation. There is a growing recognition of the skills gap in the clean heating sector.[48]

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[47] Euractiv. (2021, December 15). *EU confronted with lack of skilled labour to support building renovation wave*. https://www.euractiv.com/section/eet/news/eu-confronted-with-lack-of-skilled-labour-to-support-building-renovation-wave/

[48] ibid.

To address this, municipalities and planners should coordinate with educational institutions and training programs to build local capacity, ensuring that the jobs created can be filled by the local workforce. This might include apprenticeships in green construction or certification courses for 5GDHC system engineers. By prioritising job training and education, the deployment of 5GDHC can contribute to long-term community development, offering new career paths and strengthening public support through tangible economic benefits.

In conclusion, integrating social considerations into 5GDHC planning is as important as the technical design. By focusing on affordability for households, equitable access, public engagement, and local economic benefits, municipalities can ensure these heating and cooling networks not only reduce emissions but also improve quality of life. This holistic, people-centered approach will build the broad support needed to successfully transform urban heating and cooling for a sustainable future.

Integration modes of A1.4 tools

The tool, developed within A1.4, was specially tailored for being used by local authorities, network operators, researchers and engineers. Its purpose is to support the screening, detailed assessment and decarbonisation planning for district heating and cooling projects. The tool contains three complementary modules.

1. GHG assessment of individual systems vs a new District Heating and Cooling network
2. GHG & efficiency assessment of existing networks
3. Decarbonisation actions that quantify efficiency gains, avoided emissions and estimated implementation costs

These modules map naturally onto the decision-making stages and can be integrated in multiple modes within the guidelines of the decision-making.

The tool can be applied at the first stage of the methodology, which involves planning and assessment, to support feasibility studies and the initial evaluation of potential areas.

Step 1.1 involves identifying and assessing potential areas. The tool supports this process by providing Modules 1 and 2, which enable the rapid screening of either existing individual systems or the current district heating network. This facilitates the evaluation of improvements to an existing network and the assessment of opportunities for implementing a new 5GDHC network.

Step 1.2 focuses on assessing needs and demand. While the tool cannot fully cover this, collected GIS data and other inputs can be integrated later for the GHG and efficiency assessment.

Step 1.3 involves resource and site surveys. The tool can support this process through its proposed decarbonisation actions. It provides users with guidance on which resources to consider and whether they are feasible in a specific area, thereby supporting the feasibility check in Step 1.4.

Step 1.5 covers stakeholder mapping and engagement. Here, the tool provides an overview of potential decarbonisation actions, efficiency values and greenhouse gas (GHG) emissions. This information can strengthen stakeholder engagement and ensure that the planned actions are more reasonable and understandable.

In Step 1.7 in particular, the preliminary results generated by the tool can be used for pre-feasibility analysis and scenario development. A detailed branch analysis, along with GHG calculations and comparisons to a new network, provides valuable input for this step.

Even after the first stage, the planning and assessment, the tool can be useful in the second stage, the detailed engineering. In the early phase 2.1 in particular, a preliminary demand and network assessment enables a faster transition into detailed engineering design. Additionally, the estimated decarbonisation measure costs provided by the tool can directly support Step 2.3 if improvements or decarbonisation actions are being considered.

Finally, the tool can also be used in Step 3.4 to evaluate continuous improvement actions before further planning efforts are undertaken.

In summary, the tool supports the methodology throughout by visualising ideas and facilitating informed decision-making.

Process Flow for Developing Modern H&C Systems

Having analysed the key parameters and requirements for state-of-the-art H&C networks in section 2, this section outlines a structured process flow for their development. Implementing a modern heating/cooling system is a stepwise process that moves from initial planning through design, and into construction and operation. In what follows, these stages are clearly defined, each with specific tasks, decision points, and criteria. The process is presented in a logical flow that authorities, engineers, and stakeholders can follow to ensure all parameters have been taken into consideration.

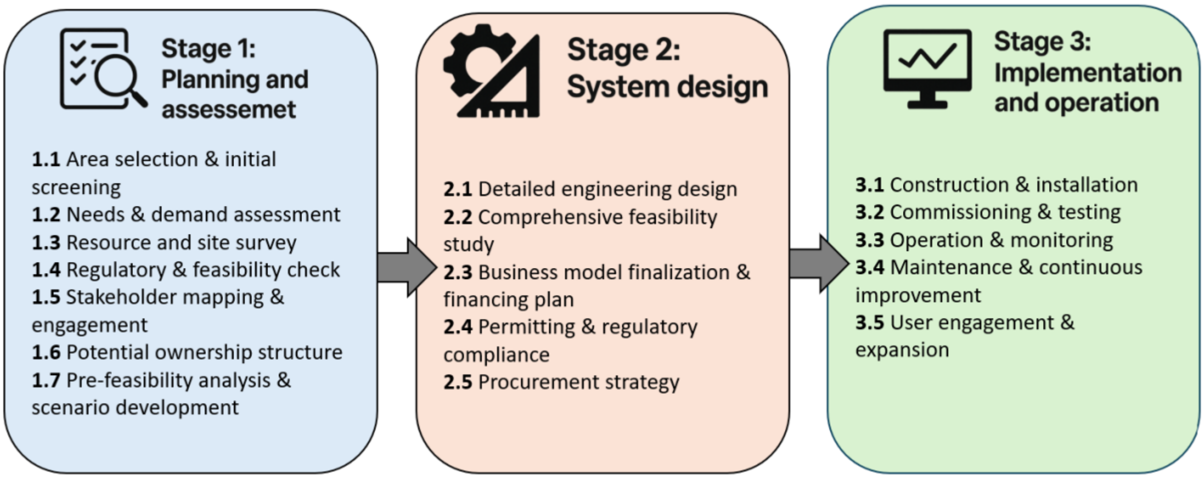

Figure 4: Decision-making methodology for modern H&C network development

Getting started: Identifying the right stage for your project

In order to identify the right starting point within the decision support methodology, a few selected questions at the beginning guide the user to the right stage depending on the actual situation of their project. Thus, a target-oriented use of the materials can be ensured. Nevertheless, we recommend that the user has also a look at all singles steps in order to identify potential open gaps or improvement measures, but it should be ensured that a user e.g. with an existing project is already guided to the steps addressing the particular situation.

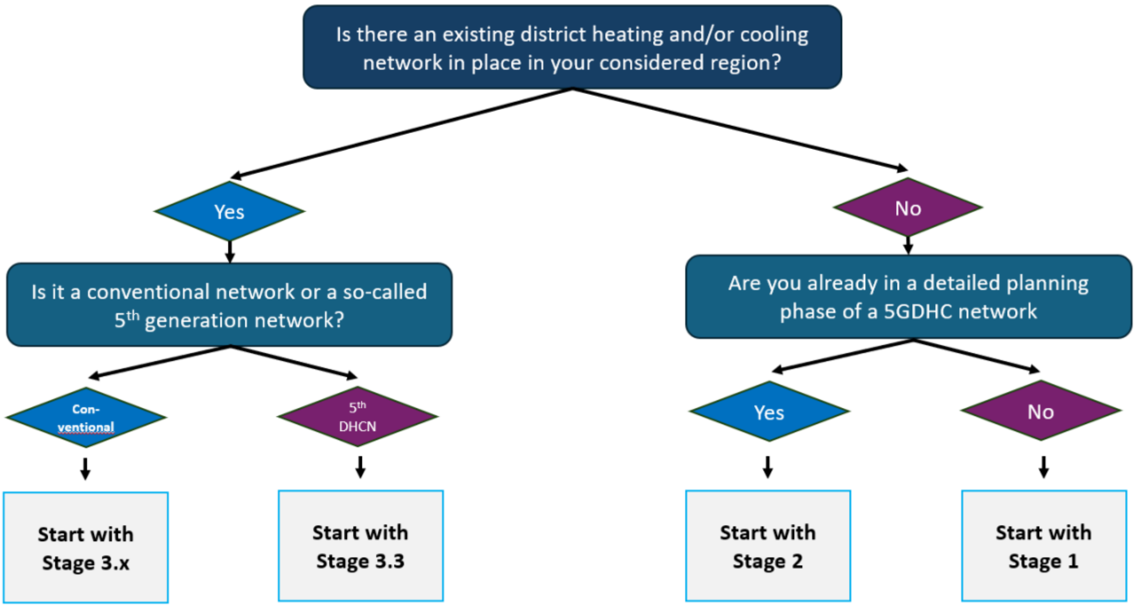

Figure 5: Initial decision support methodology to identify the most suitable corresponding stage

Stage 1: Planning and assessment

The first stage lays the groundwork, answering the fundamental question: *Is a modern H&C network feasible and beneficial in this context, and if so, what should it look like at a high level?* Therefore, in this initial phase planners establish the project's rationale, explore options, and decide whether to proceed. The goal is to assess needs and opportunities, develop and compare alternative solutions, and determine the most feasible and beneficial concept

Step 1.1: Area selection and initial screening

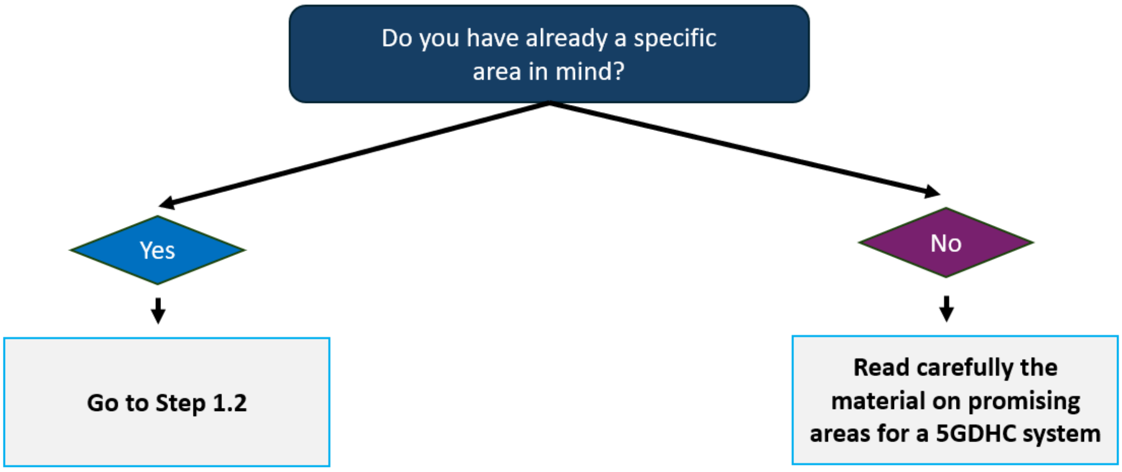

Figure 6: Main question of the decision support methodology for step 1.1

Before embarking on detailed heat mapping and demand assessment, planners must first identify and evaluate potential target areas for the DHC network. This preliminary step involves assessing multiple candidate areas to determine which locations offer the greatest potential for an efficient, cost-effective, and sustainable network. Criteria for selecting these target areas may include:

- Proximity to available heat sources, such as industrial waste heat, thermoelectric plants, data centers, or renewable energy resources like geothermal wells and solar thermal arrays.
- Density and clustering of heat demand: including residential, commercial, and industrial consumers that could form a critical mass of thermal load.
- Urban planning considerations: such as zoning policies, redevelopment plans, or existing energy infrastructure that could influence the network’s viability.
- Regulatory and permitting context: to ensure the area is not restricted by environmental protection laws or land-use limitations.

In practice, geographic information system (GIS) tools can assist in this screening by overlaying potential heat sources with heat demand densities. Planners often utilise existing heat atlases or GIS datasets to quickly pinpoint zones meeting the above criteria. Collaborating with urban planners or GIS specialists at this stage ensures that factors like zoning and future development plans are correctly accounted for in area selection. Once a target area is selected, the process moves to a more detailed evaluation of heating and cooling demand in the identified zone.

Step 1.2: Needs and demand assessment

With the target area having been identified, the process continues with a thorough heat and potentially also cold demand analysis. Planners collect data on current heating and cooling demands, typically via energy audits of buildings, utility bills, or existing studies.[49] They identify clusters of demand and estimate future trends, taking into account population growth or decline, building renovations, and climate change impacts on heating versus cooling needs. A spatial mapping, often GIS-based, is created to visualise heat demand density across neighbourhoods. This map helps pinpoint zones where a district network could be most effective; that is, where demand is high enough to justify a pipe network.

Where measured consumption data is scarce, planners may deploy building energy simulation software (e.g. EnergyPlus or IDA-ICE) to model representative building loads.[50] For example, combining building typologies with occupancy simulations and thermal modeling can generate temporally resolved heat demand time series at the building level.[51] Bringing in an energy audit expert or building energy engineer can further improve accuracy by validating assumptions (for instance, checking that modeled demand matches any available gas or fuel usage records.

Standardised tools and methodologies are crucial for consistent and accurate demand estimation. The Degree Days (DD) method is commonly used to estimate energy demand by analysing the sum of differences between outdoor temperatures and a base temperature

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[49] NXITY. (2024, May). *District heating planning guideline*. DBDH. https://dbdh.org/wp-content/uploads/2024/05/District-Heating-Planning-Guideline-NXITY.pdf

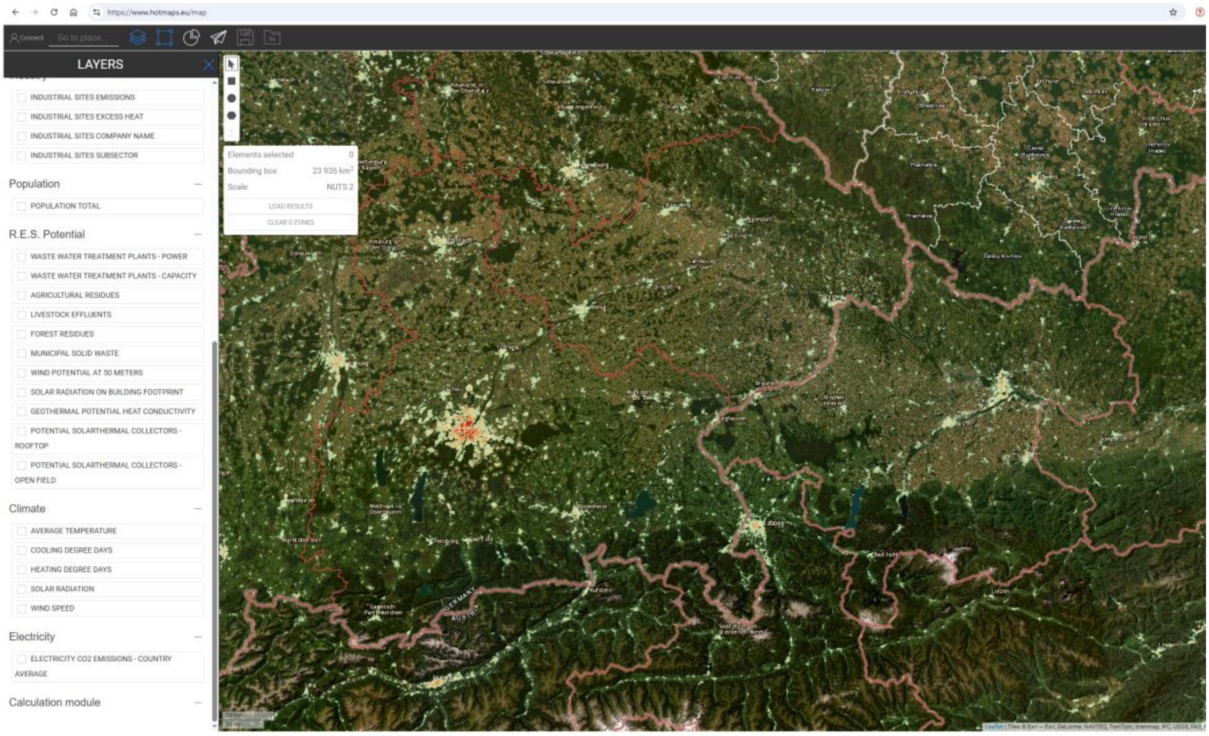
[50] Mazzeo, D., Matera, N., Cornaro, C., Oliveti, G., Romagnoni, p., De Santoli, L. (2020). EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module. *Energy and Buildings*, 212,109812. https://doi.org/10.1016/j.enbuild.2020.109812.

[51] Malacek, S., Portela, J., Werner, Y. M., & Wogrin, S. (2025). Generating building-level heat demand time series by combining occupancy simulations and thermal modeling. *arXiv*. https://doi.org/10.48550/arXiv.2503.05427

over a defined period. Additionally, the standard load profile method, originally developed for the gas industry, can forecast thermal load profiles for various building types.[52]

To support this spatial analysis, a range of open-source tools is available to assist in mapping and visualising heat demand. These tools enhance the accuracy and comparability of assessments across different regions.

One potential open-source tool to estimate heating degree days is for example HOTMAPS. As shown below, for any potential region, the user can select a certain region and gather information about the heating and cooling degree days.



Elements selected 0
Bounding box 23 935 km²
Scale NUTS 2

Figure 7: Hotmaps User Interface

In parallel, the desired service scope is clarified: Will the system provide heating only, or also cooling? Will domestic hot water be included (affecting summer demand)? The assessment must also account for seasonal profiles. For instance, a ski town might have very high winter heating demand but low summer load, whereas a mixed city might have significant summer cooling from tourism or offices. Understanding these patterns is crucial

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[52] Kicherer, N., Benalcazar, P., Lorenzen, P., Kozlenko, O., Tomtulu, S., & Trosdorff, J. (2025). Heat4Future: A strategic planning tool for decarbonizing district heating systems. *MethodsX, 14,* 103222. https://doi.org/10.1016/j.mex.2025.103222

for later design of production and storage. Public authorities often play a role here, providing data or coordinating surveys. The outcome is typically a heat demand plan that quantifies total connectable load and potential customers.

Step 1.3: Resource and site survey

Next, the team evaluates what local energy resources are available to supply the network. To support this evaluation, local resource evaluation tools might help identify local potential. This includes an inventory of renewable sources (for example, geothermal potential; solar irradiation; biomass availability; wind or hydro power that could provide electricity for heat pumps) and waste heat sources (e.g. industries, data centers, incineration plants, or even large cooling plants that reject heat).[53] Each source is characterised by its temperature level, availability (year-round or seasonal, continuous or intermittent), quantity (for instance, an industry might offer 5 MW of waste heat), and location in relation to the demand centers. This survey may involve contacting facility owners for waste heat and perhaps test drilling or studies for geothermal. Simultaneously, the planners consider potential plant sites: that is, locations for central equipment like a heating plant or pumping station. Ideal sites might be near a large heat source or centrally located in the demand area (to minimise pipe distances), while having suitable zoning (industrial or utility zoning).

At this point, specialised assessment tools and expertise are useful. For instance, solar resource maps or databases (such as national solar atlases) can quantify solar thermal potential, while geothermal databases and simulation tools (e.g. GEOPHIRES for deep geothermal feasibility) help estimate geothermal capacity.[54] Planners might also consult biomass supply studies or wind resource assessments if those are relevant. Engaging domain experts is critical: a geologist or geothermal engineer can evaluate subsurface data for geothermal viability, and industrial process engineers can help quantify available waste heat from factories or data centers. Publicly available mapping platforms like *Hotmaps* integrate many of these data layers, allowing teams to map local renewable and waste heat resources

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[53] Bertelsen, L. (n.d.). *Planning a district heating system*. Danish Board of District Heating (DBDH). Retrieved April 30, 2025, from https://dbdh.dk/planning-a-district-heating-system/

[54] Akar, S., Oh, H., Beckers, K., Vivas, C., Salehi, S. (2024). Economic Analysis for a Potential Geothermal District Heating System in Tuttle, Oklahoma. *Energy Conversion and Management*, 308. https://doi.org/10.1016/j.enconman.2024.118390.

alongside demand.[55] The combination of Steps 1.2 and 1.3 essentially pairs the demand map with the supply map. This is often an iterative process of matching sources to needs.

Step 1.4: Regulatory and feasibility check

Before proceeding, a check against regulatory requirements should be done. As part of this step, the team reviews local laws with a view to addressing questions such as: Is there a mandate or target that favors a district solution (e.g. city energy plan calls for a certain percentage of district heating by 2030 or 2040)? Are there any legal barriers or permits needed (for example, drilling permits for geothermal, water rights for using a river's heat, or permissions for roadworks)? If the area spans multiple municipalities, inter-municipal cooperation agreements might be required. Zoning laws might need updates to allow an energy center at a chosen site.

In addition to the above, planners interrogate building codes and regulations, which may affect the network's design and implementation. For example, they need to ascertain whether buildings can readily connect as well as if they are new or being renovated. The availability of low-temperature heating systems is a critical parameter in this context; otherwise, building will need an interface heat exchanger. In Alpine countries, typically there is support for such networks, but this step ensures alignment with all municipal plans. For instance, such a DHC project should be included in the city's Sustainable Energy and Climate Action Plan (SECAP), if one exists. In sum, a feasibility check from a technical-regulatory perspective as part of the first stage might produce a preliminary "go/no-go" and/or suggest adjustments. For example, if a critical anchor load like a hospital is legally unable to switch off its boiler for backup reasons, the plan might need be adjusted to accommodate that.

It is often advisable to involve regulatory experts or legal advisors at this stage. They can identify special requirements and guide the project through compliance hurdles (for example, determining if a full Environmental Impact Assessment will be mandated and preparing the necessary studies). Early budgeting for permitting is

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[55] https://www.hotmaps-project.eu/

important: obtaining various permits may entail application fees and consultancy costs (for environmental or safety assessments). By conducting this regulatory review early, the team can also estimate timelines for approvals and adjust the project schedule accordingly. In some cases, this check might reveal fatal flaws (for instance. if local law prohibits certain technologies or if the proposed site is in a protected area), saving wasted effort by stopping an unviable project early.

Step 1.5: Stakeholder mapping & engagement

Key stakeholders should be identified early. These include local authorities, utility companies, building owners (especially large heat users like hospitals or housing associations), potential heat suppliers (industries), and the community.[56] In practice, a structured stakeholder analysis should be performed to guide engagement efforts. This involves systematically identifying all parties who impact or are impacted by the project, and assessing their interests and level of influence. Tools such as stakeholder matrices (mapping stakeholders by influence and interest) can help prioritise who to involve closely. Based on this analysis, planners may hold public workshops, set up advisory committees, or use online surveys to gather input. It is often beneficial to have a community engagement specialist facilitate meetings or communications.

The development of an engagement plan to involve stakeholders in the planning process is of critical importance for the success of the project. Early engagement ensures that the project addresses local priorities and that potential customers are on board, which is in turn critical for network viability.[57] It also helps surface local knowledge (e.g. planned developments or social concerns) and foster a sense of ownership. Throughout planning, transparency and communication significantly reduce the risk of opposition and improve the design.

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[56] Sustainable Energy Authority of Ireland. (2024, March). *District heating feasibility study: Standardised template: A how-to guide*. https://www.seai.ie/sites/default/files/2025-03/District-Heating-Feasibility-Study-Template-How-to-Guide.pdf

[57] Carbon Trust. (2016, November 16). *Five steps to engaging with stakeholders in district energy projects*. https://www.carbontrust.com/news-and-insights/insights/five-steps-to-engaging-with-stakeholders-in-district-energy-projects

Step 1.6 Potential ownership structure and preliminary business model

Before the system design is further specified in stage 2, it is crucial to clarify the potential ownership and governance structure of the project. Unresolved questions regarding the financing and control of the heating network can lead to significant delays or even halt the project entirely. Therefore, different potential ownership models are examined early in the process. Once a comprehensive feasibility study confirms the project's technical and financial viability, the business model and financing plan are finalised. This step includes determining who will build, own, and operate the network, as well as defining the revenue model under which it will function. In this context, several ownership and operation models are evaluated. These are assessed based on their implications for financing, risk allocation, and governance. Key evaluation criteria include required rate of return, access to capital, operational responsibility, and stakeholder acceptance. The selected model will significantly influence the project's long-term success and sustainability.

Public utility model (Municipal ownership)

In this model, the DHC network is fully owned and operated by a public entity, typically a municipality or a publicly owned utility. This approach is common in Nordic countries, like Sweden and Denmark, where municipalities have a strong tradition of local energy planning and public ownership. Key advantages of the public utility model include:

- Local control: Municipalities have direct control over pricing, service quality, and network expansion, aligning operations with local energy and climate goals.
- Stable revenue streams: The public entity can secure long-term, stable revenue from user fees while reinvesting profits in community projects or network expansion.
- Public interest focus: Decisions can prioritise long-term sustainability over short-term profits.
- Access to public funding: Municipal ownership often allows for access to low-cost capital through government grants or green bonds.

However, this model can be financially demanding, as municipalities bear full responsibility for upfront capital investment, operational risks, and long-term maintenance.

Public-Private Partnership (PPP)

In a PPP model, the public sector collaborates with a private company to build, operate, and maintain the DHC network. This model is widely used in complex infrastructure projects, including energy systems, as it combines public oversight with private sector efficiency and innovation. Key features include:

- Risk Sharing: Financial and operational risks are shared between the public and private partners, reducing the burden on municipal budgets.
- Access to Private Capital: Private partners often provide significant upfront investment, reducing the need for public borrowing.
- Incentive for Efficiency: Private operators have a profit motive, which can drive efficiency in construction, operation, and maintenance.
- Long-term Contracts: Agreements typically span 20-30 years, ensuring long-term commitment to performance and service quality.

However, PPPs can be complex to structure and require careful contract design to ensure public interests are protected.

Cooperative model (User ownership)

In a cooperative model, the network is owned and operated by the users themselves, either directly or through a cooperative organisation. This approach is common in community energy projects and can be particularly effective in smaller networks where user engagement is high. Key benefits include:

- Democratic governance: Users have direct control over decisions, ensuring alignment with community interests.
- Lower costs: Cooperatives can operate on a not-for-profit basis, reducing the need for high returns to external investors.
- Community engagement: This model fosters strong local support, as users are directly invested in the network’s success.
- Access to community funding: Cooperatives can access unique funding sources, like community shares or crowdfunding, and may benefit from volunteer labor.

However, this model can struggle to secure large-scale financing and may lack the technical expertise of commercial operators.

During this step, involving financial and legal advisors becomes crucial. Financial consultants can build sophisticated models to project cash flows under the chosen business model, and perform stress tests. They will also advise on funding sources: for example, a municipality might explore issuing a green bond or tapping into national/EU. Private developers, on the other hand, might work with banks on project financing or seek equity partners.

Being specific in the financing plan lends credibility and helps secure those funds. On the legal side, if a PPP or cooperative is chosen, expert legal counsel should draft the agreements or bylaws to clearly define roles, revenue sharing, and risk allocation. This prevents misunderstandings and ensures compliance with regulations (for instance, EU procurement rules in case of PPPs, or cooperative laws in case of a community model).

By this stage, one model is typically chosen and key partners identified. The financial plan is then detailed: capital sources (e.g. municipal funds, commercial loans, EU grants) are lined up, and operating cost/revenue projections are refined into a business case. Tariff structures or heat pricing schemes are drafted to ensure cost recovery while remaining affordable and competitive. Often, contracts or agreements with major stakeholders are secured now. Such commitments reduce demand risk and help attract financing. The output of this step is therefore a final business plan and governance structure, which will feed into investment decisions and procurement.

Step 1.7: Pre-feasibility analysis and scenario development

With demand, supply and ownership options in hand, a preliminary assessment can be conducted to identify the most promising network configurations before committing to full-scale feasibility studies.[58] This step involves sketching out network routes on a map, estimating pipe lengths and diameters, and roughly balancing supply and demand for each concept. Multiple scenarios should be developed to capture the range of potential design approaches. For example, planners might compare a wider network serving an entire town to a smaller cluster approach, or evaluate the trade-offs between a higher-temperature 4GDH design and an ambient 5GDHC loop. For each scenario, high-level costs and potential

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[58] Sustainable Energy Authority of Ireland. (2024, March). Ibid.

CO_2 savings are estimated, and possible impediments are identified (e.g., no available route for pipes in one area or insufficient waste heat for a given concept). The goal at this stage is to screen out unfeasible concepts and identify a shortlist of viable options for more detailed study.

Preliminary modeling tools can greatly aid this scenario comparison. For example, the open-source THERMOS software allows planners to generate heat/cold demand maps and model optimal pipe network layouts, even estimating pipe lengths, digging costs, and sizing for different configurations.[59] Likewise, a GIS-based can perform rough dimensioning of pipeline routes and evaluate multiple network expansion scenarios quickly. In addition, the tool A1.4, as already introduced in before, can also be applied here, as it supports feasibility checks and provides valuable input for scenario evaluation. Using such tools, the team can attach approximate costs to each scenario. It is also wise to include a techno-economic analyst or energy systems engineer in this step to run these simulations and interpret results. By quantitatively comparing scenarios on metrics like estimated capital cost, annual operating cost, CO_2 saved, and feasibility of construction, planners can transparently justify why certain concepts advance to the next stage while others are dropped.

Stage 2: System design

Once promising scenarios have been selected through the pre-feasibility analysis and the initial green light is given, the project moves into detailed system design. In this stage, engineers and planners flesh out the technical solution in detail, selecting technologies, addressing financial planning, and optimising the design for performance, cost, and compliance.

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[59] https://www.thermos-project.eu/thermos-tool/tool-access/

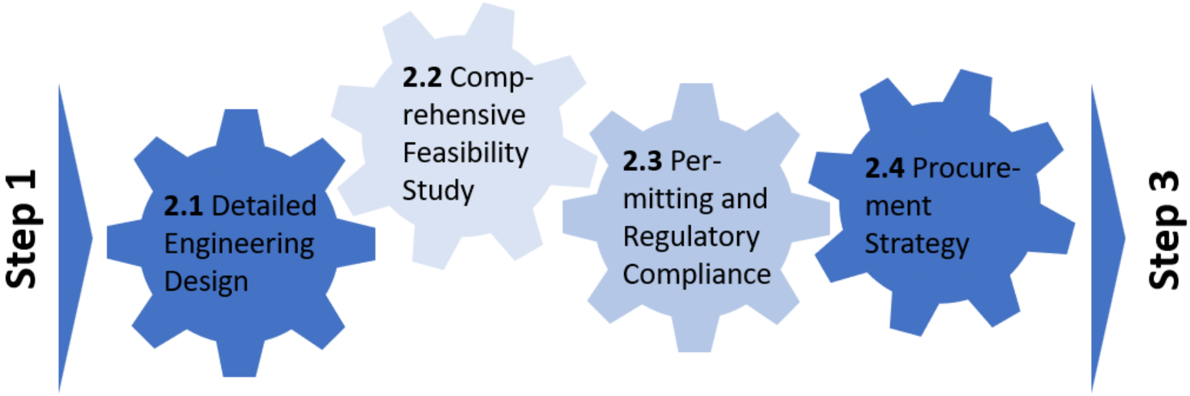

Figure 8: Key Components of Step 2 - From Engineering Design to Procurement

Step 2.1: Detailed engineering design

During this critical step, engineers translate the chosen concept into detailed designs for the network and its components. To aid with that detailed design, the preliminary results provided by the tool of A1.4 can be utilized to enhance and accelerate the detailed engineering. This includes network layout design (precise pipe routing, diameter selection, insulation specs) and hydraulic modeling to ensure adequate pressure and flow for all consumers. The design also specifies the energy production units. If multiple sources are used, the design involves the planning of the control strategy; that is, which source leads and which serves as a backup. All system components –from pumps to heat exchangers and control systems– are specified based on supplier data.

In determining the pipe routing, the design team will typically review underground utility maps and often conduct on-site surveys to avoid clashes with existing infrastructure. Modern practice includes using tools like ground-penetrating radar to locate buried pipes or cables,[60] so that trench routes can be planned around them and costly re-routing during construction is minimised. For the hydraulic and thermal design, specialised software is usually employed. For example, Termis (a widely used district heating simulation platform) can model network pressure drops and heat losses under various load conditions,[61] and Modelica or TRNSYS models might be used for dynamic simulations of 5GDHC systems to ensure

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[60] https://www.iqgeo.com/blog/navigating-underground-utility-constraints-with-comsof-heat-for-district-energy-projects

[61] Filonenko, K., Howard, D., Buck, J., Veje, C. Comparison of two simulation tools for district heatingapplications. *In Proceedings of the 9th International Conference on Energy Reliability REMOO-2019*, HongKong, China, 16-18 April 2019

stability under changing flows. By leveraging such tools, engineers can verify that pipe diameters, pump capacities, and heat production units are correctly sized.

The detailed design phase also calls for a multi-disciplinary team: mechanical engineers design the thermal network and plant, civil engineers address routing, trenching and structural needs, electrical engineers size the electrical connections (for large heat pumps, booster pumps, control systems), and control engineers plan out the automation and communication systems.

Thermal storage is integrated as needed. This can take the form of a hot water tank to buffer daily peaks or a borehole storage field if seasonal shifting is planned.[62] The electrical infrastructure for the system is also planned, since heat pumps require significant electrical supply. In the Alpine context that is charecterised by very cold winter nights and possibly very hot summer days, design must consider peak conditions, ensuring that the network can meet extreme demands.

Attention is given to efficiency optimisations, such as minimising pipeline heat losses and balancing heating and cooling loads in 5GDHC to reuse waste heat. Planners should also incorporate future-proofing. For example, by oversizing certain pipe segments or allocating space in energy centers to allow for expansion, and ensuring the design is flexible to accommodate new heat sources or storage as they become available. Throughout the design, an iterative approach may be used to arrive at a robust engineering solution that meets the goals set out in the feasibility stage.

A critical aspect during design is choosing technologies that are compatible with the concept that was approved. For instance, if pursuing a 5GDHC approach, the designer must ensure all connected buildings will have internal systems (like fan coils, low-temp radiators, or floor heating) that can deliver comfort with the lower temperature heat supplied via their heat pumps. If some buildings need higher temperature, the design may include boosting solutions for those specific needs. Energy efficiency measures in buildings thus go hand-in-hand with network design. For instance, it might be more cost-effective to invest in insulating a group of buildings so that a lower supply temperature suffices, rather than

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[62] Pans-Castillo, M., Claudio, G., & Eames, P. (2023). *Modelling of 4th generation district heating systems integrated with different thermal energy storage technologies – Methodology* [Journal contribution]. Loughborough University. https://hdl.handle.net/2134/21696557.v1

designing the network for higher temperatures. Therefore, Stage 2 can include coordination with building retrofit programs. Additionally, integrating smart control technologies is of particular relevance here. These may include smart meters and control valves that allow lower flow temperatures when demand is low or that allow the network to modulate in response to electricity grid signals.[63]

At this design stage, simulation tools are often used: thermal network simulation to test scenarios, building simulations to ensure supply adequacy, and perhaps computational models to optimise the network.[64] The goal is an optimised design that meets demand with minimal energy input and cost. For 5GDHC, designers also plan the control algorithm that will manage the bidirectional flows.[65] Additionally, any interfacing with existing systems. In some cases, a new 5G loop can be coupled to an existing 3G/4G network via heat exchangers, acting as a low-temperature extension.

The ultimate output of this step is a set of engineering drawings, equipment schedules, and technical specifications that can be used for procurement and construction. It might also include a 3D layout of plant rooms, along with integration plans for customer buildings.

Step 2.2: Comprehensive feasibility study

With the detailed design in place, a comprehensive feasibility study is conducted to confirm the technical, economic, and environmental viability of the proposed network. This study is a deep dive into technical, economic, and environmental aspects,[66] building on the designs from Step 2.1. It typically includes refined demand modeling (hourly/seasonal profiles), detailed hydraulic calculations, energy balance to size the production units and storages. It also includes an economic analysis (capital and operating cost estimates, cash flow, and

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[63] Zhang, Y., Wang, X., Li, H., & Chen, J. (2024). Feasibility assessment of next-generation smart district heating networks: A case study in a large building complex. *Energy*, *295*, 120456. https://doi.org/10.1016/j.energy.2024.120456

[64] Kuntuarova, S., Licklederer, T., Huynh, T., Zinsmeister, D., Hamacher, T., & Perić, V. (2024). Design and simulation of district heating networks: A review of modeling approaches and tools. *Energy*, 305, 132189. https://doi.org/10.1016/j.energy.2024.132189

[65] nPro. (n.d.). Fifth generation district heating and cooling (5GDHC networks). https://www.npro.energy/main/en/5gdhc-networks

[66] ibid; Zhang, Y., Wang, X., Li, H., & Chen, J. (2024). Feasibility assessment of next-generation smart district heating networks: A case study in a large building complex. *Energy*, *295*, 120456. https://doi.org/10.1016/j.energy.2024.120456

rate of return) as well as an environmental assessment (e.g. CO_2 emissions reduction, air quality impacts).

Risk assessment is integrated here, covering financial risks (like fuel price or electricity price volatility for heat pumps) and strategic risks (such as regulatory changes or customer connection uncertainty). Critically, this step also feeds into the business model (ownership and operation structure) and financing approach for each option, which are decided as part of the next step.

The comprehensive feasibility analysis often leverages integrated techno-economic software tools. For example, planners may use programs like EnergyPRO or HOMER to simulate the hourly operation of the system under different scenarios (varying fuel costs, different source dispatch strategies, etc.) and to optimise the mix of heat production units. These tools can calculate key economic indicators such as NPV (Net Present Value) and IRR (Internal Rate of Return) for the project, given detailed input on costs and revenues. In parallel, the team should gather vendor quotes or reference cost data for major components to refine the CAPEX numbers.

Sensitivity analysis is a big part of this step: using spreadsheet models or software, the team will test how results change if, say, electricity prices are 20% higher, or if heat demand grows slower than expected. This requires both engineering and financial expertise, so it’s common that the feasibility team includes an energy economist or financial analyst alongside the technical engineers. On the environmental side, specialised tools might be used to estimate emissions savings (for instance, calculating the CO_2 intensity of the supplied heat versus the baseline).

All these analyses culminate in a feasibility report that not only states whether the project is viable but also provides detailed evidence for the chosen design, showing that it meets technical requirements, is economically feasible, and brings environmental benefits as claimed. Such rigor is often necessary to secure funding or approvals in subsequent stages.

Step 2.3: Business model finalization and financing plan

Based on the previously identified potential ownership structure and business plan (cf.

Once the comprehensive feasibility study has validated the project's technical and financial viability, the project's business model and finance plan are finalised. This involves confirming who will build, own, and operate the network and under what revenue model. The finalisation is based on the findings from the previously identified potential ownership structure and business plan (cf. Stage 1.6).

During this step, involving financial and legal advisors becomes crucial. Financial consultants can build sophisticated models to project cash flows under the chosen business model, and perform stress tests. They will also advise on funding sources: for example, a municipality might explore issuing a green bond or tapping into national/EU. Private developers, on the other hand, might work with banks on project financing or seek equity partners.

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Step 2.4: Permitting and regulatory compliance

Before construction, the project must secure all necessary permits and approvals. This includes building permits for energy centers, excavation permits for road works, environmental permits, and possibly agreements for crossing third-party property (e.g. utility easements). The design documents from Step 2.1 form the basis of permit applications. If an Environmental Impact Assessment (EIA) is needed (for larger projects, perhaps), it will be prepared, detailing expected environmental effects and mitigation plans.[67] Ensuring compliance at this stage avoids legal delays later. Additionally, alignment with higher-level plans is confirmed at this stage. In the EU and Alpine Space context, this might also involve aligning with public spending rules or state-aid regulations if public funds are used. Close coordination with regulatory authorities is recommended so as to pre-empt any issues

The design should reflect any regulatory constraints. If necessary, the design is adjusted to meet any permit conditions or community requirements. For example, noise regulations may require adding sound dampening at the plant, or water regulations might impose a maximum temperature for any discharge. Safety standards are also built-in: for example, designing pressure relief valves and backup power for pumps to ensure safe operation.[68] If the project involves multiple jurisdictions, coordination is crucial. By the end of this step, the project should have in hand (or be close to obtaining) the key licenses to construct and operate the system. Also, if applying for grants or subsidies, the detailed design and its expected performance (renewable share, efficiency) will be submitted to funding agencies for approval.

Many projects benefit from having a permitting coordinator or team who navigates this process. They will maintain a checklist of all required permits (building, environmental, electrical, etc.) and the conditions for each. The project should also allocate budget for permitting activities: this can include application fees, legal notices, and hiring environmental consultants to carry out studies (e.g. noise impact analysis, archaeological assessments if digging in sensitive areas). Often, an Environmental Impact Assessment (if needed) requires specialised consultants and months of data collection, so a timeline buffer is included.

Throughout Step 2.4, regular meetings with authorities (e.g. city planning department, environmental agency) can address issues early. For example, if a planned pipe route crosses a protected stream, regulators might suggest an alternative route or specific construction

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[67] Ferrari, L., Morgione, S., Rutz, D., Mergner, R., Doračić, B., Hummelshøj, R. M., Grimm, S., Kazagic, A., Merzic, A., Krasatsenka, A., Rossi, S., Pauschinger, T., Nakrosiene, A., Pumputienė, E., & Pozzi, M. (2021). A comprehensive framework for district energy systems upgrade. *Energy Reports, 7*(Suppl. 4), 359-367. https://doi.org/10.1016/j.egyr.2021.08.095

[68] Billerbeck, A., Breitschopf, B., Winkler, J., Bürger, V., Köhler, B., Bacquet, A., Popovski, E., Fallahnejad, M., Kranzl, L., & Ragwitz, M. (2023). Policy frameworks for district heating: A comprehensive overview and analysis of regulations and support measures across Europe. *Energy Policy, 173*, 113377. https://doi.org/10.1016/j.enpol.2022.113377

method. By proactively addressing such feedback and adjusting design or plans, the project avoids last-minute surprises. Essentially, this step formalises the project's compliance: by its end, the project knows it can be built legally, and under what conditions (which will feed into the final design tweaks and construction planning).

Step 2.5: Procurement strategy

With design and finance finalised, the project initiates the procurement process to contract the construction works, equipment supply (boilers, pipes, heat pumps), and possibly operations. A clear procurement strategy is defined and a tendering process is launched.[69] Tender documents are prepared with detailed technical specifications, expected performance levels, and evaluation criteria. Given the innovative aspects of 5GDHC networks, procurement should emphasise quality and expertise. Proposals should thus be evaluated on not just cost, but also technical capability, experience with similar low-temperature or heat pump-based systems, reliability of proposed technology, and even contributions to local value. A weighted scoring can be applied to select the best supplier, ensuring alignment with the project's broader objectives.

It is advisable to engage a procurement specialist or legal advisor, especially if public funds are involved, to ensure the tender complies with procurement laws and that evaluation criteria are transparent and fair. The use of e-procurement platforms (online tender portals) can increase transparency and attract a wider range of bidders. On the practical side, the procurement strategy should align with the project timeline: if certain equipment has long lead times, the team might do an early procurement for those (for instance, placing an order for large heat pumps or specialised piping in advance).

Additionally, including a contingency budget in contracts or project financial planning is important – commonly around 5–10% of total project cost is set aside to cover change orders or unforeseen costs during execution. By the end of Step 2.5, not only are contractors selected, but the project schedule and budget are essentially locked in, with risk contingencies in place. This is usually when the final "go" decision is made by investors or

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[69] HeatNet NWE. (2020). *Procurement guide for 4th generation district heating and cooling (4DHC).* https://guidetodistrictheating.eu/wp-content/uploads/2020/04/HeatNet-NWE_DH-Procurement-Guide_District-Heating.pdf

city councils, as all key information (design, permits, contracts, costs) is now confirmed and the project is ready to move to construction.

Stage 3: Implementation and operation

This final stage covers the physical construction of the network, the commissioning tests to ensure it functions as designed, and the long-term operational phase including monitoring and maintenance. It is during this stage that the plans materialise into a working heating and cooling service for users.

Step 3.1: Construction and installation

The network infrastructure and energy systems are built according to the detailed designs. This involves civil works (trenching and pipe laying across the planned route and insulating), construction or installation of energy production units (central boiler/chiller plants, geothermal wells, heat pump stations, etc.), and installation of customer transfer stations or heat exchangers in buildings. Construction usually begins with the energy center or production facilities, and then the network piping and building connections.[70] Strong project management is needed to coordinate multiple contractors, schedule works, and ensure compliance with safety and quality standards. For Alpine towns, construction might be seasonally constrained.

Each building gets a substation installed (heat exchanger or heat pump, meters, controls), typically in its basement or plant room.[71] The interface with the building's internal system is established and tested. Engineers and contractors supervise the installation, ensuring it matches design specs. Unforeseen issues may arise, requiring adaptive project management. Stakeholder engagement remains important: the community and authorities should be kept informed of construction schedules and progress to maintain goodwill. By proactively managing impacts and responding to concerns, the project can avoid delays or opposition. The outcome of this sub-stage is the successful installation of all hardware, with the system physically in place.

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[70] Verenum AG. (2020). *Handbook on planning of district heating networks* (Version 1.0a). https://www.verenum.ch/Dokumente/Handbook-DH_V1.0a.pdf

[71] Urban Sustainability Directors Network (USDN). (2016, December 14). Connecting existing buildings to district heating networks: Technical report. https://www.usdn.org/uploads/cms/documents/161214_-_connecting_existing_buildings_to_dhns_-_technical_report_00.pdf

Step 3.2: Commissioning and testing

Before full operation, a period of commissioning occurs.[72] The project should follow a formal commissioning plan or protocol, often aligned with industry best. This plan breaks the commissioning process into steps: pre-commissioning checks, cold testing, hot testing, and so on.[73] A commissioning engineer (or team) is usually appointed to lead this effort independently of the construction crew, to ensure an objective verification of the system. They will use calibrated instruments to measure flow rates, temperatures, and pressures at various points and compare them against design values. For instance, they might perform differential pressure tests at the end of the network to confirm that even the furthest customer is getting adequate pressure when all other loads are on.

They will also verify control sequences: for example, they may simulate a sudden drop in demand to see if the control system properly lowers pump speeds or source output. Sometimes, if commissioning happens outside of peak season, temporary load banks or heat dump radiators might be used to mimic demand (for example, installing a bypass that can bleed heat to a cooling tower or large radiator to simulate winter heat demand in summertime). Throughout commissioning, all findings are documented in a commissioning log. Any issues (like a valve not opening correctly or a sensor misreading) are rectified, and the tests are repeated if necessary.

Customers' building interfaces are also commissioned: ensuring each substation delivers the right temperature to the building and that meters read correctly. At this stage, training is often provided to the operational staff who will run the network. Performance testing against the design should be done, so that any deficiencies can be corrected.

It's critical that by the end of this phase, the operators not only have a fully functional system but also confidence and familiarity with it; hence the inclusion of operator training and involvement. Often, the vendor of a major component (for instance, the heat pump) will have a technician present to certify that their equipment is commissioned correctly and to fine-tune it on site. Only once a final commissioning report is signed off (confirming the

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[72] Turner, P. (2020, June 15). *The commissioning process: A step-by-step guide*. Commissioning and Startup. https://commissioningandstartup.com/the-commissioning-process-a-step-by-step-guide/

[73] Blinnikova, O. (2011). Building Services Engineering Double Degree. *Mikkeli University of Applied Sciences*, Bachelor theis. Available at: https://www.theseus.fi/bitstream/handle/10024/31766/Blinnikova_Olga.pdf.

system meets performance specifications) does the project transition into the operational phase.

Step 3.3: Operation and monitoring

With commissioning complete, the H&C network enters the operational phase, delivering heating and cooling services to customers. The operator (which could be a utility company, a municipal department, or a cooperative, depending on the model) now follows an established operating procedure.[74] This includes continuous monitoring of performance: modern networks will have a system that shows real-time data, including temperatures, pressures, flow rates, pump status, and energy produced by each source. Many networks have control rooms or at least remote dashboards.[75]

The operator optimises the system on a daily/hourly basis: for instance, scheduling the use of different sources depending on cost (using more waste heat when available, or timing the electric heat pump operation to periods of low electricity prices or high renewable power generation. In 5GDHC systems, operation might involve ensuring the loop temperature stays within bounds by using a central chiller or boiler when needed to add or remove heat from the loop. Load balancing is an ongoing task; especially if new prosumers come online, the operator coordinates their interaction. Peak shaving strategies (using storage or demand response signals to big consumers) can be used to reduce strain during extreme conditions. All of this requires skilled operators and often advanced software.

Step 3.4: Maintenance and continuous improvement

A maintenance plan is implemented to keep the system reliable. This includes regular inspection of pipes (checking for leaks in manholes or via surveillance systems), servicing pumps and valves, cleaning heat exchangers, and maintaining boilers or CHP units. Heat pumps might need checks, and biomass boilers require ash removal and periodic overhauls. Modern networks deploy smart meters at customer sites, which allow remote reading and

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[74] Danfoss. (2021). *Simply simple: District heating network monitoring and operation simplified* (Publication No. AE335751528080en-020102). https://assets.danfoss.com/documents/latest/188077/AE335751528080en-020102.pdf

[75] Davydenko, L., Davydenko, N., Davydenko, V., & Sprake, D. (2022). Monitoring of energy efficiency of district heating system facilities: Methodology for determining the energy baseline. *Problems of the Regional Energetics, 53*. https://doi.org/10.52254/1857-0070.2022.1-53.06

can flag unusual consumption patterns that might indicate a problem. Maintenance also involves software updates for control systems.[76]

Monitoring data is used not just for operations but for optimisation, among other things with help of the proposed actions of tool 1.4. The data can be analysed (perhaps annually or seasonally) to find any deviations from expected performance. Continuous commissioning can thereby help gradually fine-tune the system.[77] Moreover, reporting is done to stakeholders: many systems must report their renewable fraction, efficiency, emissions, etc., to regulators or funders. If the network is not meeting some targets, the operator investigates why and implements corrections.

Step 3.5: User engagement and expansion

The relationship with customers must continue throughout the network operatin. There should be clear communication channels for customers to report issues and for the operator to provide advice. Some operators hold annual user forums or send newsletters with performance highlights. Such engagement maintains customer satisfaction and can attract new customers.[78] In many cases, once the initial network is running, attention turns to expanding it to other areas or connecting more buildings. In this context, the process flow circles back: new potential customers are assessed, and if viable, design and implement is extended. Modern networks are often built with scalability and modularity for this reason (for example, by oversizing the main pipe or having space at the plant for extra heat pumps in the future).

In day-to-day operations, customer engagement tools can improve the user experience and provide feedback. Many modern utilities offer customers an online portal or even a mobile app where they can view their heat consumption, bills, and even real-time data from their heat meter. Such transparency can build trust and help users optimise their usage (for

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[76] Rafati, A., & Shaker, H. R. (2024). Predictive maintenance of district heating networks: A comprehensive review of methods and challenges. *Thermal Science and Engineering Progress, 53*, 102722.
https://doi.org/10.1016/j.tsep.2024.102722

[77] Mortensen, L. K., & Shaker, H. R. (2024). Data-Driven Reliability Prediction for District Heating Networks. *Smart Cities*, 7(4), 1706-1722. https://doi.org/10.3390/smartcities7040067

[78] Kearney. (2025, February 11). District heating: Growing through systematic, efficient, and customer-oriented expansion. Retrieved from https://www.kearney.com/industry/energy/article/district-heating-growing-through-systematic-efficient-and-customer-oriented-expansion

example, seeing hourly usage might encourage a commercial user to adjust settings to shave peak demand). The operator should also have a clear process for handling customer issues.

When it comes to expansion, the operator will essentially repeat the earlier stages (planning, design) on a smaller scale. Data from the existing system can greatly assist this: for instance, knowing the current network's spare capacity or seeing which areas at the fringe have high demand can guide where expansions make sense. The operator might conduct new feasibility studies for each potential expansion phase, possibly using the same tools from Stage 1 and 2.

Financially, a strategy may involve using revenue from the initial network to co-fund expansions or seeking new partners if expanding into a new municipality. Any new technology integration (like adding solar thermal fields or new heat pumps) should be subjected to a rigorous evaluation, using multi-criteria decision analysis that weighs cost, benefit, and risk. For this, the operator might engage consultants or leverage R&D partnerships (for example, participating in pilot projects to test innovations). By continuously engaging users and carefully planning expansions and upgrades, the network can grow organically and remain technologically up-to-date. In essence, Step 3.5 ensures the H&C network is not static; instead, it evolves by learning from operation, keeping users happy, and scaling up to increase its impact

Conclusion

In summary, the development of a modern H&C network follows a clear progression from careful planning to diligent design, and onto skilled implementation and operation. Each stage has defined outputs and decision points, and involves the relevant stakeholders (planners and authorities in Stage 1, engineers in Stage 2, contractors and operators in Stage 3, with citizens involved throughout). Adhering to this structured process flow, as mapped above, can significantly increase the likelihood of a successful project that is delivered on time, within budget, and performs as intended in providing sustainable heating and cooling. The ALPHA project will utilise such a framework to guide its pilot implementations, ensuring that the modern 5GDHC systems developed are robust, efficient, and replicable across the Alpine Space.