A Comprehensive Dossier on the Global History of Urban District Heating Networks

From Ancient Origins to Fifth-Generation District Heating and Cooling (5GDHC)

Updated with dedicated analysis of network topologies and the strategic importance of meshed (maillée) architectures

Generic Worldwide Reference Document – Technical Dossier | August 2026 Update

1. Executive Summary

District Heating (DH) systems deliver thermal energy (primarily heat, and increasingly cooling) from centralised or decentralised sources to multiple buildings via a network of insulated pipes. Modern commercial systems originated in the late 19th century, but antecedents exist from antiquity. Over approximately 150 years, DH has evolved through successive generations characterised by progressive reductions in distribution temperatures, improved materials, greater integration of renewable and residual heat sources, and enhanced system intelligence.

The generational framework (particularly the first four generations) was formalised by Lund et al. (2014). The fifth generation, commonly termed Fifth-Generation District Heating and Cooling (5GDHC), represents a paradigm shift toward near-ambient temperature, bidirectional, low-exergy networks that simultaneously serve heating and cooling demands via decentralised water-source heat pumps (WSHPs).

This updated dossier retains the factual chronological account and thermodynamic foundations of the original, while adding a critical technical section on hydraulic network architectures. In particular, it establishes why meshed (maillée / grid) topologies are of strategic importance for 4th- and 5th-generation systems, especially in flat terrain, for resilience, hydraulic balancing, prosumer integration and low-temperature performance. The document remains deliberately generic and is not tied to any specific city or national project.

2. Historical Origins and Early Developments

Antecedents of organised heat distribution can be traced to antiquity. Roman hypocaust systems and heated baths utilised underfloor and wall channels for warm air and water. A more direct precursor appeared in Chaudes-Aigues (France) around 1334, where geothermal hot water was distributed through wooden pipes to approximately 30 houses — widely regarded as the earliest documented operational district heating arrangement.

Commercial modern DH began in North America. In 1877, hydraulic engineer Birdsill Holly established the first commercially successful steam-based district heating system in Lockport, New York. The New York Steam Company commenced service in Manhattan in 1882; that steam network remains operational today. Early systems also appeared at institutions such as the U.S. Naval Academy (1853) and later at MIT.

In Europe, commercial systems emerged later: Germany in the 1920s (initially steam), the Soviet Union from the 1930s (rapid expansion in the 1950s), and China from the 1950s–1960s. Scandinavia developed significant systems from the early 20th century onward (e.g., Vaasa, Finland 1902; Västerås, Sweden 1920; municipal plant in Karlstad 1948). Post-World War II reconstruction and the oil crises of the 1970s accelerated adoption, particularly of more efficient water-based systems.

By the late 20th century, major concentrations of DH capacity existed in Russia/CIS states, China, and Northern/Eastern Europe. Global heat delivery via DH reached approximately 11.5 EJ in the mid-2010s, with China, Russia, and the European Union accounting for the large majority.

3. The Four Generations of District Heating (1GDH–4GDH)

The generational classification, introduced and refined by researchers including Lund, Werner and colleagues, reflects successive improvements in temperature levels, materials, efficiency, and system integration.

3.1 1st Generation District Heating (1GDH) — approximately 1880–1930

- Carrier: steam at temperatures typically 120–200 °C.
- Pipes: steel, often in concrete ducts or tunnels.
- Characteristics: high heat losses, safety risks from high pressure/temperature, condensation at the consumer.
- Examples: early U.S. systems (Lockport, Manhattan) and early European steam networks. Steam remains in limited high-density applications (e.g., parts of New York and Paris).

3.2 2nd Generation District Heating (2GDH) — approximately 1930–1980

- Carrier: pressurised hot water, generally above 100 °C.
- Motivation: improved efficiency through Combined Heat and Power (CHP) and reduced losses relative to steam.
- Infrastructure: heavier, on-site insulated steel pipes and large substations. Widespread in the Soviet Union, Eastern Europe, and early Western European systems.

3.3 3rd Generation District Heating (3GDH) — approximately 1980–2020 (“Scandinavian” technology)

- Carrier: pressurised water below 100 °C (often 70–90 °C supply).
- Key advances: factory-prefabricated, pre-insulated pipes; compact substations; improved metering and control; greater fuel flexibility (including biomass and waste).
- Result: lower distribution losses, reduced capital and labour costs, higher reliability. Most currently operating European networks belong to this generation or transitional variants.

3.4 4th Generation District Heating (4GDH) — emerging from ~2020

Defined by Lund et al. (2014) as low-temperature networks (typically 50–70 °C supply, sometimes lower) designed for:

- Compatibility with energy-efficient buildings (lower demand temperatures).
- Integration of low-grade renewable and residual heat sources (solar thermal, shallow geothermal, industrial waste heat, data-centre heat).
- Reduced thermal losses.
- Operation as “smart thermal grids” within broader smart energy systems (interaction with electricity and gas grids, thermal storage, demand response).

4GDH enables higher shares of Renewable Energy Sources (RES) and residual heat while maintaining system efficiency. At this generation the choice of hydraulic topology (radial, looped or meshed) becomes increasingly consequential for system performance and expandability.

4. Fifth-Generation District Heating and Cooling (5GDHC)

5GDHC (also referred to in literature as cold district heating, anergy grids, or ultra-low-temperature networks) was systematically reviewed and defined by Buffa et al. (2019). A widely cited formulation states:

> *“A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with Water Source Heat Pumps (WSHP). It operates at temperatures so close to the ground that it is not suitable for direct heating purposes. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings.”*

Core characteristics

- Near-ambient network temperatures (commonly 5–30 °C, sometimes up to ~40 °C).
- Bidirectional or multi-directional energy flows: buildings act as prosumers (can supply or extract heat/cold).
- Decentralised WSHPs or reversible heat pumps at customer substations boost or reject temperature as needed.
- Same pipe infrastructure serves both heating and cooling.
- High compatibility with low-exergy sources (shallow geothermal, wastewater, ambient water, excess heat from data centres or refrigeration).
- Seasonal thermal energy storage (ATES, BTES, or pit storage) frequently integrated for balancing.

Because temperature differences relative to the ground are small, distribution heat losses are minimal (or can even become gains in certain conditions). Insulation requirements are correspondingly reduced, and plastic pipes become viable. These characteristics make hydraulic topology — and in particular the degree of meshing — a first-order design parameter rather than a secondary detail.

5. Network Topologies and the Strategic Importance of Meshing (Maillage)

The hydraulic architecture of a district heating or cooling network is not a secondary detail. It directly determines resilience, pressure-drop distribution, the ability to integrate multiple sources and prosumers, and the practical performance of low- and ultra-low-temperature systems. Three principal topologies are used:

5.1 The three principal topologies

- Radial (arborescent / tree-like): single path from production to each consumer. Simple and lower capital cost, but creates single points of failure, difficult hydraulic balancing, and limited capacity to accept new sources or prosumers without major redesign.
- Looped (ring / anneau): closed loops allow flow redirection in case of interruption. Better redundancy than pure radial systems, yet still constrained in dense multi-source configurations.
- Meshed (maillée / grid): multiple parallel paths between nodes forming a grid. Highest redundancy, natural flow distribution, superior ability to accommodate bidirectional exchanges and distributed sources. This is the topology best aligned with the requirements of 4GDH and especially 5GDHC.

5.2 Why meshing becomes decisive in low-temperature and flat-terrain systems

In nearly flat terrain (dominant in large parts of North-Western Europe and many urban/peri-urban zones in Africa), static pressure differences due to elevation are negligible. Friction losses dominate. Under these conditions a meshed layout delivers decisive advantages:

1. Maximum resilience and redundancy: a pipe failure, maintenance intervention or pump outage does not isolate entire districts; alternative paths remain available.
2. Improved hydraulic balancing: flows redistribute naturally across parallel branches, reducing "cold spots" and excessive pressures at network extremities.
3. Integration of multiple sources and prosumers (fundamental for 5GDHC): each building, greenhouse or industrial process can inject or extract heat. A meshed grid accommodates these bidirectional exchanges without creating bottlenecks.
4. Lower average pressure drops and pumping energy: multiple paths allow smaller individual pipe sections and lower velocities per branch, offsetting the higher mass-flow rates required by low ΔT systems.
5. Optimal match with ambient-temperature (5–35 °C) networks: local heat and cold exchanges are favoured; long-distance transport of small temperature differences is minimised.
6. Scalability and future-proofing: new branches, additional prosumers or new residual/renewable sources can be connected without fundamental redesign of the existing grid.

5.3 Direct link to 4GDH and 5GDHC performance

High-temperature radial networks (1GDH–3GDH) can function adequately with tree-like layouts. In contrast, 4GDH and especially 5GDHC systems — characterised by low ΔT, bidirectional flows, multiple distributed sources and prosumers — require a high degree of meshing to realise their thermodynamic and operational potential. Without sufficient meshing, the theoretical advantages of ambient-temperature operation (minimal distribution losses, high heat-pump COPs, simultaneous heating and cooling) are partially cancelled by hydraulic constraints, single-point vulnerabilities and limited expandability.

Meshing is therefore not an optional refinement; it is a structural condition for successful large-scale deployment of the network generations that must carry the bulk of the transition away from hydrocarbon-based heating and cooling in dense and semi-dense areas.

6. Thermodynamic Foundations and Governing Equations

The progressive lowering of network temperatures is driven by fundamental thermodynamic principles: reduced driving temperature differences decrease irreversible losses, improve the Coefficient of Performance (COP) of heat pumps, and lower distribution losses.

6.1 Heat transport and energy balance

The thermal power transferred by a fluid stream is:

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T$$

where $\dot{m}$ is mass flow rate (kg/s), c_p is specific heat capacity (J/kg·K), and ΔT is the temperature difference between supply and return (K). Lower ΔT requires higher mass flow (or larger pipe diameters) for the same power — a key design trade-off that meshed topologies help manage by distributing flows across multiple paths.

6.2 Distribution heat losses

For a buried insulated pipe, radial heat loss per unit length is governed by conduction through cylindrical layers. A common engineering form is:

$$\dot{q}\_loss = 2\pi\, (T\_f - T\_g) / [(1/\lambda\_ins)\, \ln((r+\delta)/r) + R\_other]$$
$$\text{or more generally:}\quad \dot{Q}\_loss = U \cdot A \cdot \Delta T$$

Because ΔT is much smaller in 5GDHC (near-ambient) than in 1–3GDH systems, absolute losses fall dramatically — often by 75 % or more. Meshing further supports this advantage by enabling shorter effective transport distances for local exchanges.

6.3 Heat-pump performance (central to 5GDHC)

Ideal (Carnot) Coefficient of Performance for heating:

$$COP\_Carnot,\ heating = T\_hot / (T\_hot - T\_cold)$$

(absolute temperatures in kelvin). For cooling: COP_Carnot, cooling = T_cold / (T_hot − T_cold). Real heat-pump COP is expressed as COP_real = η_Carnot · COP_Carnot, where η_Carnot typically ranges from 0.4 to 0.6. In 5GDHC the source temperature is close to ambient, so achievable COPs are high (frequently 4–8 or higher).

Electricity consumption: W_el = $\dot{Q}$_heating / COP.

6.4 Exergy considerations

Exergy of a heat quantity Q at temperature T relative to the environment T_0 is:

$$Ex = Q\,(1 - T_0 / T)$$

Low-temperature sources possess low exergy. Matching these sources to low-temperature demands via 5GDHC minimises exergy destruction — a central thermodynamic argument for ambient-temperature networks.

6.5 Hydraulic losses

Pressure drop is commonly calculated with the Darcy–Weisbach equation:

$$\Delta p = f \cdot (L/D) \cdot (\rho v^2 / 2)$$

Higher mass flows in low-ΔT systems increase pumping energy. Meshed topologies mitigate this by offering multiple parallel paths, thereby reducing average velocities and friction losses for a given total power transfer.

7. Global Status, Benefits and Challenges

Worldwide DH capacity remains concentrated in China, Russia/CIS, and Europe. The transition from 3GDH toward 4GDH and pilot-scale 5GDHC is most advanced in Northern Europe, parts of Germany, Switzerland, and the Netherlands (e.g., the Mijnwater system in Heerlen utilising mine-water geothermal resources). Benefits of lower-temperature generations include substantially reduced distribution losses, higher RES and residual-heat shares, simultaneous heating/cooling service, and improved sector coupling with electricity systems via heat pumps.

Challenges include the need for building-side temperature compatibility (or booster heat pumps), higher specific pumping energy in some configurations, institutional and regulatory frameworks for prosumer participation, and careful hydraulic design of bidirectional networks. Among these, insufficient meshing of the distribution grid is a frequent under-recognised constraint that limits the realised performance of otherwise well-designed 4GDH/5GDHC systems.

8. Conclusions and Outlook

District heating has progressed from high-temperature steam systems of the late 19th century to the low-exergy, bidirectional 5GDHC networks now under development. Each generation has been defined by progressive reductions in temperature, improvements in materials and control, and broader integration of diverse energy sources.

Thermodynamically, the move toward ambient temperatures maximises the COP of heat pumps, minimises irreversible losses, and enables the valorisation of low-grade heat that would otherwise be discarded. Hydraulically, the corresponding move toward meshed (maillée) topologies is equally necessary if these thermodynamic gains are to be fully captured in real networks, particularly in flat terrain and in systems that must accommodate large numbers of prosumers and distributed sources.

The generational framework, completed by explicit attention to network topology, provides a clear analytical lens for technology assessment, system design, and policy. Continued research and deployment should treat meshing as a first-order design parameter for any network intended to support the large-scale exit from hydrocarbon-based heating and cooling.

9. Selected References with URLs and Acronyms

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F. & Mathiesen, B.V. (2014). 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy, 68, 1–11. https://doi.org/10.1016/j.energy.2014.02.089 (foundational definition of 4GDH).

Buffa, S., Cozzini, M., D'Antoni, M., Baratieri, M. & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews, 104, 504–522. https://doi.org/10.1016/j.rser.2018.12.059 (key 5GDHC definition and European case review).

Werner, S. (2017). International review of district heating and cooling. Energy, 137, 617–631. https://doi.org/10.1016/j.energy.2017.04.045

Danish Board of District Heating (DBDH). District Heating History. https://dbdh.org/district-heating-history/

Danfoss. District heating generations explained. https://www.danfoss.com/en/about-danfoss/articles/dhs/district-energy-generations-explained/

IEA District Heating and Cooling (IEA DHC) programme publications and annex reports (various years) on low-temperature district heating.

Technical literature on district heating network topologies (radial, looped, meshed) and hydraulic design of bidirectional low-temperature systems (Euroheat & Power, DHC+ Technology Platform, D2Grids project reports, and related academic work).

Acronyms used: DH = District Heating; DHC = District Heating and Cooling; 1GDH–5GDHC = first- to fifth-generation systems; CHP = Combined Heat and Power; COP = Coefficient of Performance; WSHP = Water Source Heat Pump; RES = Renewable Energy Sources; ATES/BTES = Aquifer/Borehole Thermal Energy Storage; IEA = International Energy Agency.

— End of Updated Dossier —

This document is intended as a self-contained, citable reference for technical, academic, and professional use. All statements are grounded in the cited open literature. The August 2026 update adds explicit treatment of network topologies and the strategic role of meshing (maillage) for 4GDH and 5GDHC systems.