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A review on solar-assisted fourth- and fifth-generation district heating networks

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Solar-assisted district heating is a key decarbonization pathway for urban heat supply, yet its integration within low-temperature networks remains technically demanding and context-dependent. This review examines how solar thermal collectors, seasonal thermal energy storage, and heat pumps interact in fourth-generation (4GDH) and fifth-generation (5GDHC) district heating and cooling architectures. In 4GDH, centralized solar fields with large-scale storage achieve solar fractions of 40–70%, heat pump SCOP of 3.5–5.0, and distribution losses of 5–15%. In 5GDHC, an ambient neutral ring at 15–18 °C enables decentralized heat pumps with SCOP of 4.0–6.0, at the cost of thermodynamic degradation and summer conflicts between solar feed-in and cooling demand. Performance ranges are consolidated in structured comparative tables. A synthesis of 11 case studies identifies three recurring configurations: high-solar-fraction borehole storage (feasible but costly); cost-optimized pit storage 4GDH (40–50% solar fraction at 55–60 €/MWh), and emerging 5GDHC networks with heating, cooling and PV or hybrid PV-thermal integration. Levelized heat costs range from 45 €/MWh for cost-optimal 4GDH configurations to over 200 €/MWh for high-solar-fraction systems. The review identifies storage sizing, control strategy, and system boundaries as key sources of performance variability and outlines open research priorities.

KEYWORDS
fourth- and fifth-generation district heating, heat pumps and power-to-heat technologies, low-temperature district heating, renewable heat integration, seasonal thermal energy storage, urban energy systems

1 Introduction

The decarbonization of urban energy systems represents one of the most critical challenges in the transition toward climate-neutral cities. According to the latest assessment from the International Energy Agency (IEA, 2025), the buildings sector accounts for approximately 30% of global final energy consumption. Within this, space heating and domestic hot water production represent the dominant share, constituting around 70% of residential energy use in advanced economies. To put these figures in perspective, energy efficiency improvements since 2010 have resulted in global energy-related CO_2 emissions being nearly 7 gigatonnes per year lower than they would otherwise have been, equivalent to approximately 20% of total emissions (IEA, 2025). These figures point to the urgency of systemic solutions for urban heat supply, particularly in dense urban environments. District heating and cooling networks have long been recognized as a key infrastructure for enabling large-scale integration of renewable energy sources and waste heat, offering advantages in terms of efficiency, reliability, and centralized control (Werner, 2017; Katcher et al., 2025). However, conventional district heating systems, typically operating at high supply temperatures, face increasing limitations when coupled with low-exergy renewable sources such as solar thermal energy and ambient heat (Rezaie and Rosen, 2012; Werner, 2017).

District heating networks have responded through a significant technological evolution over the last two decades. Fourth-generation district heating (4GDH) introduced low-temperature operation, with reduced supply and return temperatures, to reduce distribution losses, improve efficiency, and facilitate integration of renewable and residual heat sources (Lund et al., 2014, 2018). Fifth-generation district heating and cooling (5GDHC) extended this further, adopting ultra-low-temperature operation, bidirectional heat exchange, decentralized substations, and strong coupling with electricity networks through heat pumps and power-to-heat technologies (Buffa et al., 2019; Lindhe et al., 2022). These new network generations transform district heating from a unidirectional heat distribution system into an active, flexible thermal infrastructure capable of supporting multi-vector energy interactions and sector coupling (Lund et al., 2014, 2018; Buffa et al., 2019; Lindhe et al., 2022).

Solar energy fits naturally within this evolution. Large-scale solar district heating has demonstrated technical maturity and long-term reliability, particularly when combined with thermal energy storage (Perez-Mora et al., 2018). Distributed solar thermal systems and photovoltaic-driven heat pumps are increasingly considered complementary options within these networks, enabling the integration of renewable and low-temperature heat sources (Lund et al., 2021). Recent projects have also demonstrated the integration of photovoltaic (PV) in 5GDHC networks combining heating and cooling, with bidirectional operation and decentralized heat pumps serving both thermal demands. Low-temperature operation in 4GDH and 5GDHC systems improves collector efficiency, extends feasible operating periods, and reduces the temperature lift required for auxiliary heat pumps (Volkova et al., 2019; Zhu et al., 2023). Solar-assisted district heating has moved beyond niche applications and can now be scaled to district-level urban heat supply (Buffa et al., 2019; Gao et al., 2024).

Despite these advances, the effective integration of solar energy at the district scale remains strongly dependent on the availability of adequate thermal energy storage. Seasonal thermal energy storage plays a fundamental role in decoupling solar heat production from demand, enabling high solar fractions and stable year-round operation (Bogdanovics et al., 2024; Sornek et al., 2025). Low-temperature district networks are particularly well suited to host seasonal storage solutions such as borehole thermal energy storage, pit thermal energy storage, and large-scale water tanks, owing to reduced thermal losses and improved charging and discharging efficiency (Sornek et al., 2025). Recent studies have highlighted how the interaction between network design, storage sizing, and operational strategies critically determines the overall performance of solar-assisted systems (Vandermeulen et al., 2018; Testasecca et al., 2025).

Although there is extensive literature on solar district heating, seasonal thermal energy storage, and advanced district heating concepts, these topics are often addressed from fragmented perspectives or with a predominant focus on individual technologies. Reviews specifically devoted to solar district heating typically emphasize collector performance and storage technologies, while devoting limited attention to how fourth- and fifth-generation district heating network architectures reshape the constraints, opportunities, and integration strategies for solar-assisted systems (Perez-Mora et al., 2018; Huang et al., 2019). Conversely, reviews on fourth- and fifth-generation district heating primarily concentrate on network design, heat pump integration, and sector coupling, with limited attention to the systemic role of solar energy and long-term storage (Buffa et al., 2019; Speich et al., 2024). This separation highlights a clear research gap at the intersection between network evolution and renewable heat integration.

This review adopts a scoping approach, focusing on studies that examine solar energy integration within district heating networks at the system or network level. The literature was identified through systematic searches of Scopus and Web of Science, supplemented by citation tracking from key review papers and consultation of international program reports. The search covered peer-reviewed journal articles and book chapters published between 2012 and 2026. Studies were included if they addressed solar thermal integration, heat pump deployment, or seasonal storage within fourth- or fifth-generation district heating networks, with emphasis on quantitative or comparative system-level analysis. Component-level studies without network context were excluded. The final corpus comprises over 50 sources.

Rather than cataloguing individual technologies, this review focuses on how modern district heating architectures interact with solar energy systems and seasonal thermal energy storage, and how low-temperature operation opens new design and operational options. Recent advances in system integration, storage concepts, and modeling approaches are critically synthesized. A comparative synthesis of case studies across different climates and system architectures complements the quantitative performance ranges presented in the review. Key technical challenges are identified and future research directions outlined to support large-scale deployment in sustainable urban environments.

Both fourth- and fifth-generation district heating networks are addressed deliberately. The two paradigms differ substantially in their solar integration strategies: 4GDH is the established framework for centralized solar systems with large seasonal storage, while 5GDHC is an emerging architecture enabling distributed prosumer configurations and stronger sector coupling. A review limited to one paradigm would miss how integration strategies must evolve as networks transition toward ultra-low-temperature operation. Comparing both paradigms reveals design trade-offs and transition pathways that are not apparent when either is examined in isolation.

2 Evolution of district heating networks: from fourth- to fifth-generation systems

The transition toward low-carbon urban heat supply has driven a deep transformation of district heating and cooling networks over the past two decades. As shown in Figure 1, this evolution is commonly described in terms of successive "generations" of district heating systems, reflecting not only changes in supply temperature levels, but also deeper shifts in network architecture, system boundaries, and the role of end users within the energy system (Lund et al., 2014, 2018; Werner, 2017). In the context of solar-assisted district heating and domestic hot water production, the distinction between fourth-generation district heating (4GDH) and fifth-generation district heating and cooling (5GDHC) systems is particularly relevant, as it reshapes the technical constraints and opportunities for renewable heat integration (Buffa et al., 2019; Lindhe et al., 2022).

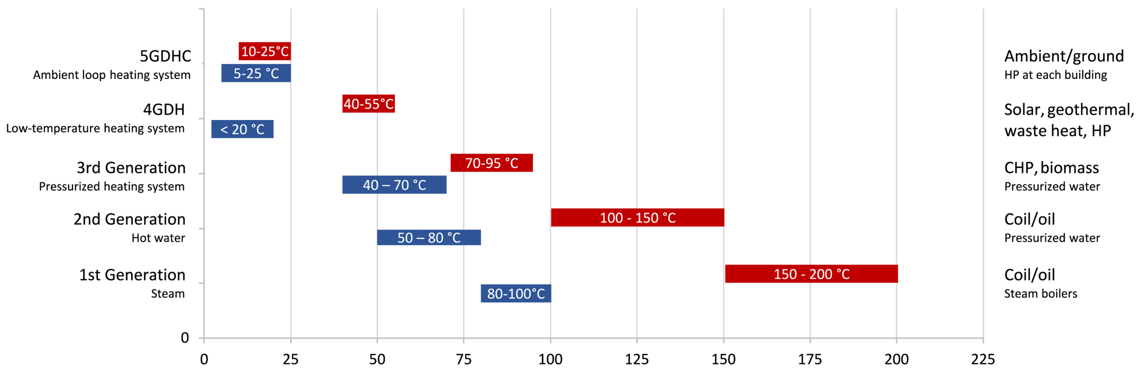

FIGURE 1
Supply and return temperature ranges across district heating generations. Supply (red) and return (blue) network temperatures from first- to fifth-generation systems. For 5GDHC, the ambient loop operates at 5–25 °C; building-level temperatures reach 45–60 °C (heating) and 6–12 °C (cooling) after decentralized heat pump upgrading.

2.1 Fourth-generation district heating: low-temperature centralized networks

Fourth-generation district heating systems represent a major departure from conventional high-temperature district heating by explicitly targeting low supply and return temperatures (Lund et al., 2014, 2018). The core objective of this paradigm is to reduce distribution thermal losses, improve overall system efficiency, and enable the integration of low-exergy renewable and residual heat sources such as solar thermal energy, geothermal heat, industrial waste heat, and large-scale heat pumps (Rezaie and Rosen, 2012; Werner, 2017). As shown in Figure 2, 4GDH networks typically operate with supply temperatures in the range of 40–55 °C and return temperatures ideally below 20 °C, representing a significant reduction compared to the 80–120 °C supply and 40–60 °C return temperatures characteristic of conventional third-generation systems (Lund et al., 2014, 2018; Werner, 2017). This temperature reduction is not merely incremental but constitutes a qualitative shift that enables the direct integration of heat sources whose maximum delivery temperature would be incompatible with conventional high-temperature networks.

From a system perspective, 4GDH retains a predominantly centralized architecture, with heat generation concentrated in one or several production plants and distributed unidirectionally to end users (Lund et al., 2014; Volkova et al., 2019). However, the reduction in network temperature levels introduces important system-level benefits. Lower operating temperatures decrease heat losses in the distribution network, reduce thermal stress on piping infrastructure, and enhance the performance of renewable heat sources whose efficiency strongly depends on temperature differentials (Li et al., 2017; Volkova et al., 2019).

In solar-assisted configurations, the lower return temperatures characteristic of 4GDH directly translate into higher collector efficiencies and extended operating periods, particularly during mid-seasons, with annual solar thermal yields of 400–450 kWh/m^2/year reported for flat-plate collectors in large-scale systems (Perez-Mora et al., 2018; Huang et al., 2019). Despite these advantages, fourth-generation systems still face intrinsic limitations when very high renewable shares are targeted. The centralized and largely unidirectional nature of the network constrains the extent to which decentralized heat production and bidirectional energy exchange can be exploited (Calise et al., 2023). Moreover, while 4GDH significantly improves the integration of solar thermal energy, the temporal mismatch between solar heat production and space heating demand remains a major challenge, especially in climates with strong seasonal variability (Bogdanovics et al., 2024; Sornek et al., 2025). Large-scale thermal energy storage is, therefore, a critical component for achieving high solar fractions. Recent projects such as the Bracht pilot in Germany (Solmax, 2025) demonstrate that PTES-based 4GDH systems can achieve solar fractions of 71% at scales of approximately 180 dwellings, indicating that the performance frontier has moved beyond the 40–50% range of first-generation Danish installations.

2.2 Fifth-generation district heating and cooling: ultra-low-temperature and bidirectional networks

Fifth-generation district heating and cooling systems further extend the low-temperature concept by adopting ultra-low-temperature operation and rethinking the role of the distribution network (Buffa et al., 2019; Lindhe et al., 2022). Rather than functioning solely as a heat delivery infrastructure, 5GDHC networks operate as ambient thermal grids that enable bidirectional heat exchange between multiple producers and consumers (Buffa et al., 2019; Gjoka et al., 2023). Supply temperatures are typically close to ambient or ground temperature levels, and the distinction between heat sources and heat sinks is becoming increasingly blurred. Network temperatures in 5GDHC systems are typically maintained between 5 and 25 °C, with the ambient loop operating at a floating temperature of approximately 15–18 °C, closely following ambient or ground conditions (Boesten et al., 2019; Buffa et al., 2019; Quirosa et al., 2022). As shown in Figure 3, cooling supply temperatures at the building level range from 6 to 12 °C, while heating supply is achieved locally by individual decentralized heat pumps that upgrade the low-grade thermal energy of the network to 45–60 °C as required by end-use systems (Calise et al., 2023; Buonomano et al., 2025). A defining feature of 5GDHC systems is the decentralization of heat upgrading. Instead of producing heat centrally at the required supply temperature, the network distributes low-grade thermal energy that is locally upgraded by decentralized heat pumps at the building or substation level (Lindhe et al., 2022; Chicherin, 2025). This architectural shift allows the network to simultaneously support heating and cooling

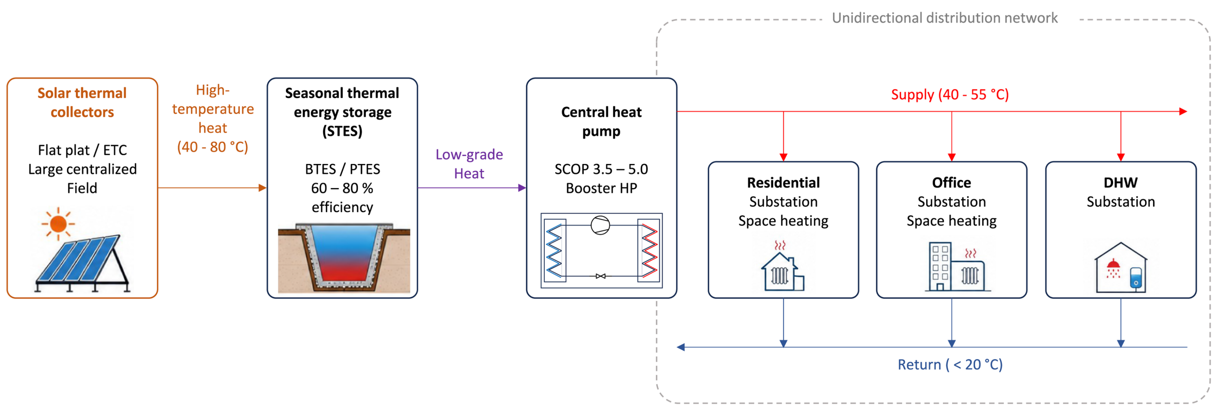

FIGURE 2
Schematic architecture of a solar-assisted fourth-generation district heating (4GDH) network. Solar thermal collectors feed high-temperature heat (40–80 °C) into seasonal thermal energy storage (STES), from which low-grade heat is upgraded by a central heat pump (SCOP 3.5–5.0) for unidirectional distribution at 40–55 °C supply and below 20 °C return. End-use substations serve residential, office, and domestic hot water (DHW) applications.

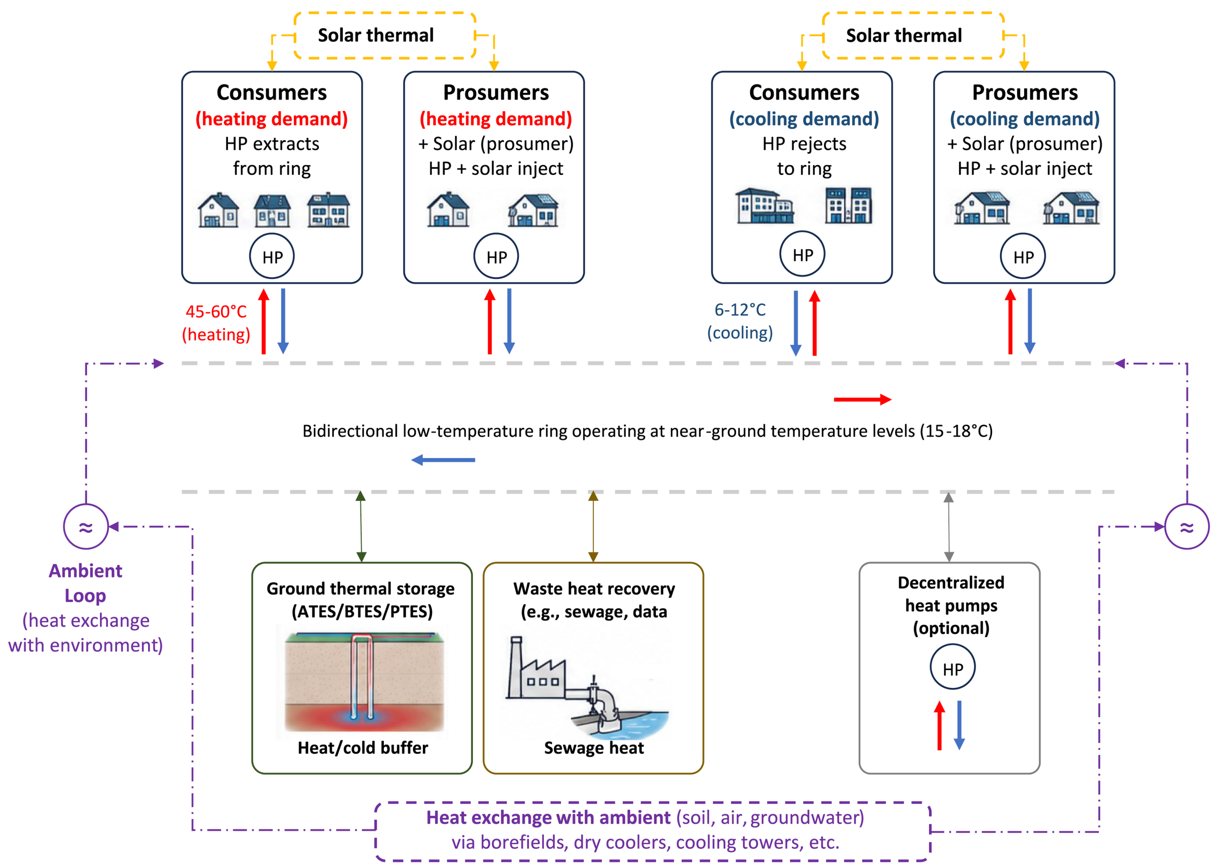

FIGURE 3
Schematic architecture of a solar-assisted fifth-generation district heating and cooling (5GDHC) network. Buildings extract heat from or reject heat into a shared ambient loop via decentralized heat pumps, delivering 45–60 °C for heating and 6–12 °C for cooling. Thermal balance is maintained through heat exchange with the environment via borefields, groundwater, and dry coolers.

demands, facilitate waste heat recovery, and enable prosumer-based configurations in which buildings can inject or extract thermal energy depending on operational conditions (Sdringola et al., 2025; Testasecca et al., 2025). For solar-assisted applications, the implications of this paradigm are substantial. Ultra-low network temperatures maximize the efficiency of solar thermal collectors and facilitate their integration as distributed or semi-centralized heat sources (Volkova et al., 2019; Quirosa et al., 2022). The strong coupling between thermal and electrical systems inherent in 5GDHC architectures, however, introduces new trade-offs. The reliance on decentralized heat pumps increases electricity demand (Buonomano et al., 2025; Soleimani et al., 2025). System performance is consequently highly sensitive to control strategies, electricity carbon intensity, and the availability of power-to-heat flexibility. Consequently, the performance of solar-assisted 5GDHC systems cannot be assessed solely on the basis of thermal efficiency, but must be evaluated through integrated energy, environmental, and economic indicators (Li and Abu Bakr, 2025). Recent projects such as Ülemiste in Tallinn (Chicherin and Zhuikov, 2026) and GreenSCIES in London (Revesz et al., 2022) have demonstrated that PV integration and bidirectional operation are technically feasible, though their economic performance remains highly context-dependent.

A particularly relevant operational challenge in solar-assisted 5GDHC systems concerns the simultaneous management of summer solar heat surplus and cooling demand. During summer months, high solar irradiation generates surplus thermal energy that could be injected into the ambient loop, while buildings simultaneously require cooling. Since the network can absorb heat from both solar collectors and building cooling rejection, the ring temperature may rise above optimal operating levels, degrading cooling efficiency and increasing the temperature lift required by individual heat pumps. This thermal conflict is further compounded when decentralized solar feed-in is uncontrolled, potentially saturating the network's heat absorption capacity. The exergy value of solar heat fed into a 5GDHC network is inherently low: high-grade solar radiation is downgraded to network temperatures of 15–20 °C, incurring an exergy loss that must be compensated by electrical work at decentralized heat pumps. Calise et al. (2023) report exergy efficiencies of 40–65% for 5GDHC configurations, which, given the low thermodynamic quality of the network, indicates a relatively efficient use of high-grade electrical input. Thermodynamic quality must therefore be accounted for alongside thermal efficiency. Effective management of this conflict requires active control strategies, including selective solar source disconnection during peak cooling periods, integration of ground-coupled heat exchangers as heat sinks, or dedicated cold storage (Boesten et al., 2019; Quirosa et al., 2022; Calise et al., 2025). This challenge is specific to solar-assisted 5GDHC systems and should be addressed explicitly at the design stage. Hybrid configurations combining PV with solar thermal collectors, as seen in recent case studies (Euroheat & Power, 2024; Buonomano et al., 2025) can mitigate this conflict by diversifying the renewable energy supply and reducing the thermal load on the network during peak cooling periods.

The transition from fourth- to fifth-generation district heating networks marks a shift from temperature-driven optimization toward flexibility-driven system design (Lund et al., 2014; Buffa et al., 2019). Low- and ultra-low-temperature operation should not be interpreted merely as a means of reducing heat losses, but as a key enabler of systemic flexibility. Lower temperature levels expand the range of usable renewable and residual heat sources, enhance the effectiveness of thermal energy storage, and allow district heating networks to function as active components of multi-energy systems (Vandermeulen et al., 2018; Sornek et al., 2025).

Fourth- and fifth-generation district heating systems are not incremental upgrades of conventional networks: they represent distinct architectural paradigms with different implications for solar-assisted district heating and domestic hot water production. The following sections build on this distinction (Werner, 2017; Gjoka et al., 2023).

3 Solar energy integration and seasonal storage

From a solar integration perspective, this evolution changes design priorities. While 4GDH systems prioritize centralized solar fields and large seasonal storage to achieve high solar fractions (Perez-Mora et al., 2018; Bogdanovics et al., 2024), 5GDHC systems enable hybrid architectures combining centralized and decentralized solar generation, distributed storage, and dynamic interaction with electricity networks (Sdringola et al., 2025; Testasecca et al., 2025).

3.1 Centralized solar district heating systems

Centralized solar district heating (SDH) represents the most established approach for integrating solar energy at the district scale. In this configuration, large ground-mounted solar collector fields are connected to the district heating network through a central energy hub, often combined with thermal energy storage to mitigate the temporal mismatch between solar availability and heat demand (Perez-Mora et al., 2018; Huang et al., 2019). Extensive operational experience, particularly in Northern and Central Europe, has demonstrated the technical maturity and long-term reliability of centralized SDH systems when properly integrated with low-temperature networks (Werner, 2017; Perez-Mora et al., 2018; Huang et al., 2019).

Solar fractions achievable in centralized 4GDH configurations depend primarily on storage availability, not collector technology. Without seasonal storage, centralized solar fields typically cover 15–30% of annual heat demand, supplying domestic hot water and mid-season space heating. When coupled with large-scale BTES or PTES, solar fractions of 40–70%, and above 70% in favorable climates, have been demonstrated (Bogdanovics et al., 2024; Lepiksaar et al., 2025). Flat-plate and evacuated-tube collectors are both widely deployed; evacuated-tube designs offer advantages in cold climates, though the reduced temperature differential in 4GDH networks partially narrows the performance gap between collector types (Perez-Mora et al., 2018; Huang et al., 2019). Recent projects such as Bracht in Germany (Solmax, 2025) have shown that PTES-based 4GDH can reach solar fractions above 70%, exceeding the performance of earlier Danish installations.

Despite their proven performance, centralized SDH systems face spatial and economic constraints in dense urban environments, where the availability of land for large collector fields and seasonal storage is often limited (Sneum et al., 2025). These constraints have motivated increasing interest in alternative or complementary solar integration strategies that exploit distributed generation and closer coupling with end users.

3.2 Distributed solar thermal and prosumer-based configurations

Distributed solar integration represents an increasingly relevant alternative to purely centralized SDH, particularly in the context of low-temperature and fifth-generation district heating networks. In these configurations, solar thermal collectors are installed at the building or substation level; this heat is then injected locally into the network or used directly for domestic hot water production. The emergence of bidirectional networks and decentralized substations in 5GDHC systems enables buildings to act as thermal prosumers, dynamically switching between consumption and production modes depending on local conditions (Buffa et al., 2019; Sdringola et al., 2025).

Distributed solar thermal systems offer several potential advantages. By producing heat closer to the point of use, they can reduce distribution losses and alleviate the need for large centralized collector fields. Moreover, decentralized solar generation can be more easily integrated into existing urban fabrics, using rooftops and façades that would otherwise remain unused. In fifth-generation networks, the combination of distributed solar thermal systems with ultra-low network temperatures further enhances collector efficiency and facilitates the injection of low-grade solar heat into the network (Volkova et al., 2019; Quirosa et al., 2022). Real-world examples include the GreenSCIES project in London (Revesz et al., 2022), where PV-equipped buildings act as prosumers within a 5GDHC network, and the Vielha pilot in Spain (García Céspedes et al., 2025), where public buildings with decentralized heat pumps and PV generation operate as both producers and consumers of thermal energy.

However, prosumer-based solar integration also introduces new challenges. The simultaneous injection and withdrawal of heat at multiple network nodes increases system complexity and requires advanced control strategies to maintain hydraulic and thermal stability (Angelidis et al., 2026). Furthermore, the contribution of distributed solar systems to overall district-scale performance is highly sensitive to building typology, load profiles, and the coordination between local production, network operation, and auxiliary technologies such as heat pumps (Wang et al., 2021; Sdringola et al., 2025). These aspects underscore the need for a network-centric evaluation of distributed solar configurations, rather than assessments based solely on individual building performance.

3.3 Temperature levels and collector performance

In fifth-generation networks, where supply temperatures are close to ambient or ground levels, solar thermal collectors can operate under near-optimal conditions for extended periods of the year. The lower temperature levels of 5GDHC networks also enable the integration of alternative solar-driven configurations, such as photovoltaic-assisted heat pumps, which can complement or partially replace conventional solar thermal collectors depending on local conditions and system design (Pakere and Blumberga, 2020; Soleimani et al., 2025). Simulation studies, such as the Lhasa case by (Chen et al., 2025), indicate that PVT collectors coupled with PTES can achieve solar fractions of 77–81% while generating net electricity, with a 27% reduction in required collector area compared to thermal-only collectors.

Nevertheless, the benefits of low-temperature operation are not without trade-offs. In ultra-low-temperature networks, the usable temperature level of solar heat may be insufficient to directly meet domestic hot water requirements, requiring local temperature upgrading through decentralized heat pumps (Lund et al., 2021). System performance is therefore a balance between improved solar collection efficiency, reduced distribution losses, and increased electricity consumption for heat upgrading. This balance is strongly context-dependent and highlights the importance of integrated performance assessment, which is addressed in subsequent sections of this review.

3.4 Seasonal thermal energy storage

Large-scale solar integration into district heating and domestic hot water networks is constrained by the temporal mismatch between solar availability and thermal demand. Seasonal thermal energy storage (STES) bridges this gap, decoupling heat production from consumption over monthly and annual cycles. In low- and ultra-low-temperature networks, STES is not merely a buffer: its performance is tightly coupled to network design, operating temperatures, and solar integration strategies (Bogdanovics et al., 2024; Sornek et al., 2025).

Several studies have demonstrated that solar fractions increase substantially when seasonal storage is introduced, with overall system performance governed by the combined sizing of collector fields, storage volume, and network temperature levels, not individual component optimization (Lepiksaar et al., 2025; Sornek et al., 2025). STES is therefore a core design variable, not an auxiliary technology. A variety of seasonal thermal energy storage technologies have been developed and deployed in the context of solar district heating, including borehole thermal energy storage (BTES), pit thermal energy storage (PTES), large-scale water tanks, and aquifer thermal energy storage (ATES). Among these options, BTES and PTES are particularly well suited to low-temperature district heating networks due to their scalability and compatibility with moderate temperature levels (Perez-Mora et al., 2018; Sornek et al., 2025).

BTES systems store heat in the subsurface using arrays of vertical boreholes and are typically characterized by large storage capacities and long service lifetimes. Their performance strongly depends on the ground thermal properties, borehole spacing, and charging temperatures. Low network temperatures reduce thermal gradients between the storage medium and the surrounding ground, mitigating heat losses and improving long-term storage efficiency (Eisapour et al., 2024). BTES is therefore particularly attractive in combination with fourth-generation district heating networks and centralized solar collector fields. The Drake Landing Solar Community in Canada (Sibbitt et al., 2012) remains a reference for BTES-coupled systems, having achieved a 97% solar fraction in a cold continental climate with 5,200 degree-days, albeit at high capital and embodied energy costs.

PTES systems, consisting of large excavated pits filled with water and insulated at the surface, offer high storage capacities at relatively low specific investment costs when sufficient land is available. Operational experience from large-scale installations has demonstrated their suitability for achieving very high solar fractions in centralized solar district heating systems (Perez-Mora et al., 2018; Lepiksaar et al., 2025). However, their applicability in dense urban environments can be limited by space availability. Context-specific storage selection is therefore essential.

Large-scale water tanks and ATES systems are also employed in specified applications, particularly where geological conditions allow or where integration with cooling demands is beneficial. In fifth-generation district heating and cooling networks, ATES systems can provide both seasonal heat and cold storage, further enhancing system flexibility (Sornek et al., 2025).

The design of seasonal thermal energy storage in solar-assisted district heating systems involves fundamental trade-offs between storage capacity, collector area, network temperature levels, and overall system cost. Numerous studies have shown that increasing storage volume generally leads to higher solar fractions and improved annual utilization of solar collectors, but with diminishing returns beyond certain thresholds (Bogdanovics et al., 2024; Sornek et al., 2025). Consequently, optimal storage sizing must be determined at the system level, accounting for both energetic and economic criteria. Low-temperature operation mitigates some of these trade-offs by reducing storage losses and enabling effective utilization of lower-grade thermal energy. In fourth-generation district heating systems, seasonal storage allows solar heat collected at relatively low temperatures to be stored and later upgraded, if necessary, by centralized or decentralized heat pumps. In fifth-generation networks, the ultra-low-temperature environment further expands the range of feasible storage strategies, but simultaneously increases reliance on auxiliary electricity-driven technologies for temperature upgrading (Testasecca et al., 2025). Storage sizing cannot be considered independently from decisions on solar collector technology, network temperature levels, and heat pump deployment, as overall system performance depends on their integrated design within smart energy systems (Lund et al., 2014).

4 Heat pumps, power-to-heat, and system flexibility

Solar energy and seasonal thermal storage in low- and ultra-low-temperature networks cannot be separated from heat pump and power-to-heat (P2H) deployment. As supply temperatures fall, direct use of low-temperature heat for space heating and domestic hot water becomes progressively limited, increasing reliance on temperature upgrading (Topal and Arabkoohsar, 2024).

4.1 Role of heat pumps in solar-assisted low-temperature district heating

In fourth-generation district heating systems, heat pumps are typically deployed at centralized production sites or as booster units within substations to upgrade solar heat, geothermal energy, or stored thermal energy to the required supply temperature levels. Reduced network return temperatures directly improve heat pump performance by lowering the temperature lift, thereby increasing the seasonal coefficient of performance (SCOP) from approximately 2.0–3.0 at conventional temperature levels to 3.5–5.0 in well-designed low-temperature configurations (Bordignon et al., 2022; Alarnaot-Alarnaout et al., 2025).

In fifth-generation district heating and cooling networks, the role of heat pumps becomes even more prominent. Ultra-low-temperature networks distribute thermal energy at near-ambient temperature levels, and decentralized heat pumps located at the building or substation level provide the final temperature upgrade required for heating and domestic hot water. This decentralized architecture enables bidirectional heat exchange, simultaneous heating and cooling, and efficient recovery of low-grade waste heat from buildings and urban infrastructures (Buffa et al., 2019; Lindhe et al., 2022; Chicherin, 2025). Operational data from projects such as GreenSCIES (Revesz et al., 2022) and Ülemiste (Chicherin and Zhuikov, 2026) confirm SCOP values in the upper end of this range under favourable operating conditions.

For solar-assisted systems, the interaction between heat pumps and solar thermal collectors is highly synergistic. Solar heat can be used directly when temperature levels are sufficient, or indirectly as a low-temperature heat source that reduces the electricity demand of heat pumps during upgrading phases. Several studies have shown that the combined operation of solar thermal systems and heat pumps leads to higher overall system efficiency compared to configurations relying on either technology alone, particularly when coordinated through appropriate control strategies (Bordignon et al., 2022; Eisapour et al., 2024).

4.2 Power-to-heat and system flexibility

Power-to-heat technologies extend the role of heat pumps beyond temperature upgrading by enabling active coupling between thermal and electrical energy systems. By converting surplus electricity into thermal energy that can be stored or directly supplied to the district heating network, P2H systems provide a valuable source of flexibility for integrating variable renewable electricity generation (Vandermeulen et al., 2018; Sornek et al., 2025).

In solar-assisted district heating networks, P2H plays a dual role. First, it allows excess photovoltaic electricity to be converted into heat, complementing solar thermal generation and increasing the overall utilization of renewable energy resources (Pakere and Blumberga, 2020; Soleimani et al., 2025). Second, when combined with seasonal thermal energy storage, P2H enables temporal shifting of electricity consumption, reducing curtailment and supporting grid balancing at the district scale (Sornek et al., 2025).

Low-temperature networks are well suited for P2H integration: reduced operating temperatures improve the effectiveness of storing electrically generated heat and reduce storage losses (Vandermeulen et al., 2018). That said, the effectiveness of P2H strategies depends on electricity price signals, carbon intensity of the power mix, and regulatory frameworks. Context-specific assessment is therefore needed, not generalized performance claims (Buonomano et al., 2025; Soleimani et al., 2025).

4.3 Trade-offs between electrical consumption and thermal performance

From an exergy perspective, the integration of solar thermal heat into low-temperature district heating networks involves an inherent quality degradation. Solar radiation is a high-exergy resource that is converted into low-grade thermal energy at typical network temperatures of 40–55 °C in 4GDH systems (Li and Svendsen, 2012) and near-ambient temperature levels in 5GDHC networks (Dang et al., 2024), resulting in a substantial reduction in thermodynamic potential. In 5GDHC systems, the additional use of decentralized heat pumps further introduces the conversion of electrical exergy into heat, increasing the number of thermodynamic transformation steps within the system. The overall energy conversion chain is therefore inherently multi-stage. The net exergy efficiency of this chain depends critically on network temperature levels and heat pump Seasonal Coefficient of Performance (SCOP), as higher SCOP reduces the electrical exergy input required per unit of heat delivered. From an economic perspective, the reliance on electricity for temperature upgrading introduces an additional cost component, partially offsetting the benefits of solar heat integration. This trade-off becomes particularly pronounced in summer, when solar heat surplus cannot be efficiently stored or absorbed by the network without risking temperature imbalances or operational constraints, and its economic value depends on the real-time electricity price and carbon intensity (Calise et al., 2023; Soleimani et al., 2025).

Beyond the thermodynamic considerations outlined above, the broader coupling of solar energy, heat pumps, and P2H technologies introduces system-level trade-offs that require careful evaluation. The reduction of network temperature levels decreases distribution thermal losses and enhances solar collector efficiency, but simultaneously increases reliance on electricity-driven heat pumps for temperature upgrading (Testasecca et al., 2025). Improvements in thermal performance may therefore be partially offset by increased electricity consumption, particularly in ultra-low-temperature networks.

Several studies have highlighted that the net environmental and economic performance of such systems depends on the balance between reduced thermal losses, improved solar utilization, and additional electrical demand (Calise et al., 2023; Soleimani et al., 2025). In particular, the carbon intensity of electricity supply and the temporal alignment between solar availability, electricity prices, and heat demand emerge as critical determinants of system sustainability. Hybrid configurations combining PV with heat pumps, as seen in Mirafiori Nord (Euroheat & Power, 2024) and Sorrento (Buonomano et al., 2025), can improve this balance by supplying renewable electricity directly to the heat pumps, reducing both operational costs and carbon intensity.

Heat pump and power-to-heat integration involves complex interactions between subsystems and cannot be adequately assessed through isolated component-level analysis (Kim et al., 2022). Performance depends simultaneously on thermal efficiency, electrical consumption, storage dynamics, and system-level flexibility, which cannot be meaningfully assessed separately.

5 Modeling, control, and performance assessment

System performance in solar-assisted low- and ultra-low-temperature district heating depends not only on network architecture or technology selection, but also on modelling assumptions, control strategies, and optimization frameworks. This is especially apparent in 4GDH and 5GDHC networks, where greater system flexibility and multi-energy interactions amplify sensitivity to operational decisions. Differences in reported performance indicators across the literature often reflect methodological choices as much as genuine technological potential (Buonomano et al., 2023; Karanth et al., 2026).

5.1 Modeling approaches for solar-assisted district heating networks

A wide range of modeling approaches have been employed to analyze solar-assisted district heating systems, spanning from steady-state and rule-based models to fully dynamic, high-resolution simulations. Early studies often relied on simplified energy balance models, which provide valuable insights at the planning stage but are limited in their ability to capture transient effects, storage dynamics, and network interactions (Talebi et al., 2016; Li et al., 2017).

More recent works increasingly adopt dynamic simulation environments capable of representing the coupled thermal–hydraulic behavior of district heating networks, solar collectors, storage systems, and end-user substations. Dynamic system-level simulation frameworks such as TRNSYS, Modelica-based environments, and integrated energy system models enable time-resolved analysis at hourly or sub-hourly resolution (Buonomano et al., 2023; Bogdanovics et al., 2024). These tools allow a more realistic assessment of solar utilization, storage performance, and auxiliary energy demand.

At the district scale, system-level modelling frameworks have also been applied to capture interactions between thermal and electrical infrastructures, especially in fifth-generation networks with strong coupling to heat pumps and power-to-heat technologies (Buonomano et al., 2025; Li and Abu Bakr, 2025). Such models enable the evaluation of trade-offs between thermal efficiency, electrical consumption, and renewable integration, but often require extensive input data and careful calibration to ensure robustness.

5.2 Control strategies and their impact on system performance

Beyond model structure, control strategies play a decisive role in determining the effective performance of solar-assisted district heating systems. Rule-based control approaches remain widely used due to their simplicity and ease of implementation, particularly in existing networks. However, several studies have demonstrated that rule-based strategies often fail to fully exploit the potential of low-temperature operation, seasonal storage, and flexible power-to-heat integration (Vandermeulen et al., 2018; Buonomano et al., 2024).

Advanced control strategies, including model predictive control (MPC) and optimization-based scheduling, have been shown to significantly improve system performance by dynamically coordinating solar generation, storage charging and discharging, heat pump operation, and network temperature levels. These approaches explicitly account for future system states, weather forecasts, and demand profiles, enabling more efficient use of renewable resources and storage capacity (Vandermeulen et al., 2018; Buonomano et al., 2024).

In fifth-generation district heating networks, decentralized and hybrid control architectures are increasingly explored to manage bidirectional heat flows and prosumer-based configurations. While such strategies can enhance local self-consumption and flexibility, they also introduce new challenges related to coordination, data availability, and system stability (Sdringola et al., 2025; Testasecca et al., 2025). The choice of control paradigm therefore represents a critical design decision that directly influences reported energy, environmental, and economic outcomes.

5.3 Optimization frameworks and sensitivity to assumptions

Optimization techniques are widely used to support the design and operation of solar-assisted district heating systems, particularly when multiple technologies and conflicting objectives are involved. Mixed-integer linear programming (MILP), nonlinear optimization, and multi-objective evolutionary algorithms have been applied to determine optimal system configurations, storage sizing, and operational strategies under technical and economic constraints (Carpaneto et al., 2015; Sameti and Haghighat, 2019).

However, optimization results are inherently sensitive to modelling assumptions, boundary conditions, and objective function formulation. Parameters such as electricity prices, carbon intensity factors, discount rates, and assumed demand profiles can significantly affect optimal solutions and reported performance indicators (Calise et al., 2025). This sensitivity makes transparent reporting essential: isolated numerical results are difficult to aggregate meaningfully without knowing the assumptions that produced them. The following subsections therefore consolidate key energy, environmental, and economic indicators from recent literature on solar-assisted low- and ultra-low-temperature district heating systems, reporting each alongside its system context to provide a basis for cross-architecture comparison. Table 1 summarizes these ranges.

5.4 Energy performance indicators

5.4.1 Solar fraction and renewable heat contribution

Reported solar fractions in district heating systems vary widely depending on network temperature, storage integration, and system scale. In fourth-generation district heating systems without seasonal storage, solar fractions are typically limited to 15–30%, with solar energy primarily covering domestic hot water demand and mid-season loads (Perez-Mora et al., 2018; Huang et al., 2019). When seasonal thermal energy storage is integrated, centralized solar district heating systems in low-temperature networks consistently achieve solar fractions in the range of 40–70%, with several large-scale installations

TABLE 1 Representative ranges of key performance indicators reported for solar-assisted low- and ultra-low-temperature district heating and domestic hot water systems.

Performance indicator	4GDH	5GDHC	Conditions/notes	References
Network supply temperature	40–55 °C	15–18°C (neutral ring)	Building-level HP output: 45–60 °C heating, 6–12 °C cooling in 5GDHC	Lund et al. (2014, 2018) and Buffa et al. (2019)
Network return temperature	<20 °C	≈neutral ring temperature	Ultra-low return enables high SCOP and low distribution losses	Werner (2017) and Quirosa et al. (2022)
Solar fraction (without STES)	15–30%	20–40% (HP-coupled)	DHW + mid-season heating; limited by seasonal mismatch	Perez-Mora et al. (2018) Huang et al. (2019)
Solar fraction (with large-scale STES)	40–70% (>70% achievable)	–	Requires BTES/PTES; climate and sizing sensitive	Bogdanovics et al. (2024) and Lepiksaar et al. (2025)
Effective renewable heat coverage (incl. HP + P2H)	–	Up to 80–90%	Solar-assisted HP + P2H contributions combined	Li and Abu Bakr (2025) and Testasecca et al. (2025)
Heat pump SCOP	3.5–5.0 (centralized / booster)	4.0–6.0 (decentralized)	Seasonal values (SPF); sensitive to temperature lift and part-load operation	Bordignon et al. (2022) and Buonomano et al. (2024)
Distribution thermal losses	5–15%	3–8%	vs. 15–30% in conventional high-temperature DH	Li et al. (2017) and Sarbu et al. (2022)
STES round-trip efficiency	60–80% (BTES/PTES)	– (ground exchange)	BTES ~60–75%; well-insulated PTES up to ~80%	Bogdanovics et al. (2024) and Eisapour et al. (2024)
STES specific cost	24–38 €/m^3 (large PTES, >100,000 m^3); 80–250 €/m^3 (PTES/BTES, 1,000–10,000 m^3)	–	Strongly scale-dependent; costs decline with volume. BTES at lower end of range, TTES at upper end	Schmidt et al. (2018) and Dahash et al. (2021)
CO_2 emission reduction	60–80%	>80–90%	vs. fossil baseline; electricity carbon intensity is a key variable	Calise et al. (2023) and Massulli et al. (2025)
Levelized cost of heat (LCOH)	45–200 €/MWh	100–180 €/MWh	Lower bound for moderate solar fraction (11–18%) without large-scale STES; upper bound for high solar fraction with STES. Gas boiler baseline: 30–80 €/MWh; standalone HP: 60–120 €/MWh	Perez-Mora et al. (2018) and Li and Abu Bakr (2025)
Simple payback period	8–20 years	10–25 years	5–12 years with 20–40% subsidy; 15–25 years without	Arabkoohsar and Andresen (2017) and Massulli et al. (2025)

exceeding 70% under favorable conditions (Bogdanovics et al., 2024; Lepiksaar et al., 2025). In 5GDHC networks, solar energy contributions are more varied. While direct solar fractions expressed at the network level are often lower due to ultra-low supply temperatures, the effective renewable heat contribution increases when accounting for solar-assisted heat pump operation and power-to-heat integration, with reported renewable coverage reaching up to 80–90% in optimized configurations (Li and Abu Bakr, 2025; Testasecca et al., 2025). The upper end of this range is exemplified by the Lhasa simulation study (Chen et al., 2025), which reports solar fractions of 77–81% for PVT-PTES systems, and by the Drake Landing project (Sibbitt et al., 2012), which achieved 97% in its fifth year of operation, albeit at high capital cost.

5.4.2 Heat pump performance

The coefficient of performance of heat pumps integrated in low-temperature district heating networks is strongly influenced by network temperature levels and heat source characteristics. Reported seasonal coefficient of performance (SCOP) values for centralized or booster heat pumps in fourth-generation networks typically range between 3.5 and 5.0, while decentralized heat pumps in fifth-generation systems frequently achieve SCOP values between 4.0 and 6.0 under low temperature-lift and favorable source conditions. These values represent seasonal averages (accounting for partial-load and variable-source conditions) rather than instantaneous COP, and correspond to what is also reported in the literature as Seasonal Performance Factor (SPF; Bordignon et al., 2022; Alarnaot-Alarnaout et al., 2025; Chicherin et al., 2025). Real-world SCOP, however, is highly sensitive to control strategies, part-load conditions, and source temperature variability; therefore, reported values should be interpreted as best-practice estimates rather than guaranteed outcomes (Buonomano et al., 2024; Sdringola et al., 2025).

5.5 Network losses and storage performance

5.5.1 Distribution losses

One of the most consistent findings across the literature is the substantial reduction in distribution thermal losses achieved through low-temperature operation. Conventional high-temperature district heating systems typically exhibit distribution losses in the range of 15–30%, whereas fourth-generation networks reduce these losses to approximately 5–15% (Li et al., 2017; Sarbu et al., 2022). In ultra-low-temperature and fifth-generation systems, reported losses are often below 5%, particularly when supply temperatures are close to ambient levels (Sarbu et al., 2022; Testasecca et al., 2025).

5.5.2 Seasonal storage efficiency

Round-trip efficiencies of seasonal thermal energy storage systems are strongly dependent on storage technology and operating temperature. Borehole and pit thermal energy storage systems integrated in low-temperature networks typically achieve annual efficiencies between 60 and 80%, with higher values associated with lower charging and discharging temperatures and optimized insulation (Bogdanovics et al., 2024; Eisapour et al., 2024). Several studies report diminishing returns beyond specific storage-to-collector ratios, indicating that oversizing storage volumes does not necessarily translate into proportional gains in usable stored energy (Sornek et al., 2025).

5.6 Environmental performance

5.6.1 CO_2 emission reductions

Solar-assisted district heating systems consistently demonstrate significant reductions in greenhouse gas emissions compared to conventional fossil-based heat supply. Reported CO_2 reductions for fourth-generation district heating systems with integrated solar energy and heat pumps typically range between 60 and 80%, depending on the electricity mix and storage configuration (Calise et al., 2023; Massulli et al., 2025). In fifth-generation systems with high renewable electricity penetration and optimized control, emission reductions of 80–90% or more have been reported at the district scale (Li and Abu Bakr, 2025; Testasecca et al., 2025). Several studies emphasize that emission performance is highly sensitive to the carbon intensity of electricity supply, particularly in ultra-low-temperature networks with extensive heat pump deployment (Soleimani et al., 2025). This finding reinforces the need for integrated assessment of thermal and electrical decarbonization pathways.

5.7 Economic performance

5.7.1 Levelized cost of heat

Reported LCOH values for solar-assisted district heating systems span a wide range that depends critically on system boundaries, solar fraction target, storage technology, and regulatory context. In fourth-generation district heating, cost-optimal configurations targeting moderate solar fractions (11–18%) have been reported at 45–64 €/MWh in recent European market analyses (Popovski et al., 2024), while high-solar-fraction systems coupled with large-scale STES show LCOH values of 80–200 €/MWh. The integration of heat pumps can substantially reduce system LCOH: a Danish case study reports a system LCOH of 68.6 €/MWh with an air-water heat pump, versus 94 €/MWh for the same system without heat pump assistance, alongside a system COP improvement from 1.22 to 2.62 (Xu et al., 2024). These values are not directly comparable to the broader aggregated ranges frequently cited in the literature, as differences in system boundary definitions, included cost components, and discount rate assumptions can produce substantially different LCOH figures even for technically similar systems (Louvet and Vajen, 2025). In fifth-generation systems, economic performance is more heterogeneous. While some studies report competitive or lower LCOH values compared to fourth-generation systems, others highlight higher costs associated with decentralized heat pumps, bidirectional substations, and network retrofitting of existing networks, particularly in dense urban areas (Calise et al., 2025; Li and Abu Bakr, 2025). The dominant economic drivers across both paradigms are: electricity price, storage CAPEX, network temperature, target solar fraction, demand structure (heating vs. cooling ratio), and subsidy availability. The lower bound of the 4GDH LCOH range (45–64 €/MWh) is consistent with cost-optimized Danish PTES systems while (Sørensen and

Schmidt, 2018; Perez-Mora et al., 2018), the 5GDHC range (100–180 €/MWh) is exemplified by the Sorrento simulation study (Buonomano et al., 2025).

5.7.2 Payback period and investment risk

Reported payback periods for solar-assisted district heating systems typically range between 8 and 20 years, with shorter paybacks associated with high solar utilization, low network temperatures, and supportive policy frameworks. Several authors emphasize that economic viability is strongly influenced by non-technical factors such as land availability, ownership models, and regulatory stability; governance considerations are discussed in subsequent sections (Herreras Martinez et al., 2023; Speich et al., 2024).

The specific cost of seasonal thermal energy storage is a major driver of overall system economics, and its correct interpretation requires careful attention to units and system boundaries. Large PTES installations in Denmark have been documented at 24–38 €/m^3 of storage volume for capacities above 100,000 m^3, with a practical benchmark of approximately 30 €/m^3 for utility-scale projects (Schmidt et al., 2018). Smaller PTES systems and BTES installations at volumes of 1,000–10,000 m^3 show higher specific costs of 80–250 €/m^3, reflecting the loss of economies of scale (Schmidt et al., 2018). Comparing these values in terms of levelized cost of stored heat (LCOS), a metric recommended over simple specific investment cost to account for round-trip efficiency, storage utilization, and service lifetime (Dahash et al., 2021), reveals that well-operated PTES and large water tank systems often achieve competitive LCOS values when integrated in low-temperature district heating networks. Comparing solar-assisted 4GDH with conventional alternatives: reported LCOH values of 45–200 €/MWh (depending on solar fraction and configuration) overlap with the upper range of gas boiler heat (30–80 €/MWh at European gas prices of 0.03–0.10 €/kWh) but are generally competitive with, or below, standalone heat pump systems (60–120 €/MWh, electricity-price dependent). A simplified break-even analysis shows that solar-assisted district heating reaches payback periods of 5–12 years relative to a fossil baseline when subsidy schemes cover 20–40% of CAPEX, and 13–20 years without public support, with one optimization study reporting approximately 13.7 years for a system-optimal configuration (Abokersh et al., 2020). In 5GDHC configurations, payback periods vary far more widely: community-based investment models with solar prosumers have demonstrated paybacks of approximately 6.4 years (Russo et al., 2026), while predominantly centralized 5GDHC retrofits in dense urban areas can exceed 25–33 years (Calise et al., 2025), underscoring that the 5GDHC economic case depends strongly on who invests, who benefits, and the local heating-to-cooling demand ratio.

5.8 Synthesis and limitations of comparative analysis

The comparative evidence reviewed in this section highlights consistent performance trends associated with low-temperature operation, solar integration, and seasonal storage. The wide dispersion of reported numerical results underscores the limitations of direct comparison across studies. Differences in modeling approaches, boundary conditions, and assumptions regarding energy prices and carbon intensity can significantly affect reported indicators. Context-aware interpretation is therefore essential: the ranges in Table 1 reflect what has been demonstrated under specific conditions, not universal performance bounds.

5.9 Comparative case study synthesis

To complement the performance ranges presented in Table 1, this section synthesizes data from well-documented large-scale installations and simulation-based case studies. The selected cases, summarized in Table 2, illustrate how climate, storage technology, and system architecture interact to determine real-world performance across both heating-only and combined heating and cooling configurations. A critical distinction is made between realized systems, for which operational data are available, and simulated or conceptual systems, which provide insights into potential performance under optimized conditions but require further validation.

Table 2 presents 11 cases spanning different climates and system architectures. The first group comprises solar thermal or photovoltaic-thermal systems in 4GDH configurations, including the Danish PTES plants at Marstal (Perez-Mora et al., 2018) and Dronninglund (Sørensen and Schmidt, 2018), the Bracht pilot in Germany (Solmax, 2025), the Lhasa simulation from China (Chen et al., 2025), and the Mirafiori Nord hybrid system in Turin (Euroheat & Power, 2024). These cases demonstrate the technical maturity and cost-effectiveness of centralized solar thermal with seasonal storage in heating-dominated climates, with solar fractions ranging from 45% (Marstal) to over 80% (Lhasa simulation) and LCOH values of 55–60 €/MWh for the Danish systems. The Drake Landing project in Canada (Sibbitt et al., 2012), while not representative of cost-optimal design, remains a milestone demonstration of technical feasibility, achieving 97% solar fraction in a cold continental climate with 5,200 degree-days, albeit at prohibitive costs for replication.

The second group consists of 5GDHC systems integrating both heating and cooling. These include realized projects such as GreenSCIES in London (Revesz et al., 2022), Ülemiste in Tallinn (Chicherin and Zhuikov, 2026), and the Vielha pilot in Spain (García Céspedes et al., 2025), as well as simulated cases like Madrid (PCM storage; Calise et al., 2025) and Sorrento (Buonomano et al., 2025). These configurations leverage bidirectional operation and decentralized heat pumps to serve both heating and cooling demands, often recovering waste heat from cooling processes or storing summer heat for winter use. However, they face higher capital costs and greater operational complexity, reflected in LCOH values of 100–180 €/MWh for the Sorrento case, compared to the 55–60 €/MWh of the Danish PTES systems.

Across cases, three distinct models emerge. A high-solar-fraction BTES model, exemplified by Drake Landing (Sibbitt et al., 2012), proves technical feasibility but at prohibitive costs. A cost-optimized PTES 4GDH model, represented by the Danish systems (Sørensen and Schmidt, 2018; Perez-Mora et al., 2018) and Bracht (Solmax, 2025), delivers robust performance with validated operational data and represents the current state of the art for large-scale heating-only deployment. An emerging 5GDHC model with combined heating and cooling, seen in Ülemiste (Chicherin and Zhuikov, 2026), Vielha (García Céspedes et al., 2025), GreenSCIES (Revesz et al., 2022), and simulated in Madrid (Calise et al., 2025) and Sorrento (Buonomano et al., 2025), introduces multi-energy functionality and bidirectional operation but requires further validation and cost reductions. The cases also reveal that PV-only and hybrid PV-ST configurations are

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TABLE 2 Key performance data from selected large-scale and case-study solar-assisted district heating systems.

Project/case	Country	Climate	Generation	Solar technology	STES type	Solar fraction/ renewable share	Includes cooling?	LCOH [€/ MWh]	Status	Reference
Drake landing	Canada	Cold continental	4GDH	2,293 m^2 flat-plate ST	BTES 34,000 m^3	97%	No	–	Realized	Sibbitt et al. (2012)
Marstal	Denmark	Nordic	4GDH	33,000 m^2 flat-plate ST	PTES 75,000 m^3	~45%	No	~60 €/MWh	Realized	Perez-Mora et al. (2018)
Dronninglund	Denmark	Nordic	4GDH	37,500 m^2 flat-plate ST	PTES 60,000 m^3	~51%	No	~55 €/MWh	Realized	Sørensen and Schmidt et al. (2018)
Bracht	Germany	Continental	4GDH	Solar thermal field	PTES (high-temp)	71%	No	–	Realized	Solmax (2025)
Lhasa (sim.)	China	Cold continental	4GDH	PVT 9,000–13,000 m^2	PTES 36,000 m^3	77–81%	No	–	Simulated	Chen et al. (2025)
GreenSCIES	UK	Oceanic	5GDHC	PV	ATES + thermal/ electrical	–	Yes	IRR 10, −80% CO_2	Realized	Revesz et al. (2022)
Madrid (PCM)	Spain	Mediterranean	5GDHC	PV	PCM	~87%	Yes	Payback 19 years	Simulated	Calise et al. (2025)
Mirafiori Nord	Italy	Mediterranean	4GDH (retrofit)	ST 242.3 kW + PV 45 kWp	Water 2,500 m^3	–	No	−8,000 t CO_2/ year	Realized	Euroheat & Power (2024)
Ülemiste	Estonia	Continental	5GDHC	–	BTES	–	Yes	–	Realized	Chicherin and Zhuikov (2026)
Vielha	Spain	Montane	5GDHC	PV	BTES	–	Yes	–	In development	García Céspedes et al. (2025)
Sorrento	Italy	Mediterranean	5GDHC	PV + solar thermal	Water tank	~80% (renewable)	Yes	100–180 €/ MWh	Simulated	Buonomano et al. (2025)

gaining traction, particularly where space constraints limit solar thermal deployment or where electricity self-consumption is prioritized.

A clear climate-technology mapping emerges from the cases. Nordic climates favour PTES-based 4GDH for heating-only applications. Cold continental climates require careful BTES or PVT-PTES sizing but can achieve very high fractions with sufficient land, as demonstrated by Drake Landing (Sibbitt et al., 2012) and the Lhasa simulation (Chen et al., 2025). Mediterranean and mixed climates are the natural domain for 5GDHC with ATES, borefield balancing, or cooling waste heat recovery, but face economic challenges. The distinction between realized and simulated cases is critical: while simulations offer valuable insights into potential performance, they cannot substitute for operational data in assessing long-term reliability, maintenance requirements, and real-world economic performance.

Recent international initiatives, including IEA SHC Task 45 (IEA SHC Task 45, 2012) and Task 55 (IEA SHC Task 55, 2016), are addressing these gaps through harmonized case study comparisons and cross-climate performance benchmarking. The case studies reviewed here confirm that high renewable heat shares are achievable across different climates and system architectures, but the optimal technology mix varies systematically depending on whether cooling is part of the service portfolio and whether PV is used alongside or instead of solar thermal. The transition from isolated demonstrations to replicable urban solutions will require standardized performance metrics that explicitly distinguish heating-only from combined heating-and-cooling systems and thermal-only from PV-integrated configurations, transparent reporting of economic assumptions, and coordinated efforts to generate cross-climate design guidance.

6 Challenges, research gaps, and future directions

Despite significant progress, several technical, economic, and methodological challenges continue to limit large-scale deployment of solar-assisted district heating and domestic hot water systems. The literature reviewed here shows that these challenges are not confined to individual technologies but arise from the interaction between network architecture, renewable integration strategies, storage solutions, and operational frameworks. Identifying and structuring these gaps is essential for advancing from isolated demonstrations toward replicable urban solutions.

6.1 Technical challenges at the system level

A primary technical challenge concerns the integration of solar energy in existing urban district heating infrastructures, which are often characterized by high supply temperatures, limited flexibility, and heterogeneous building stocks. Retrofitting conventional networks to operate at lower temperatures requires coordinated interventions at multiple levels, including network hydraulics, substations, and end-use systems. Several studies report that insufficient compatibility between building-side heating systems and low-temperature supply remains a critical barrier, particularly in legacy residential buildings (Sarbu et al., 2022; Calise et al., 2023).

The design and operation of seasonal thermal energy storage represent a further technical challenge. While storage technologies such as BTES and PTES have demonstrated high potential in low-temperature networks, their performance is strongly site-dependent and sensitive to sizing assumptions. The literature consistently reports diminishing returns when storage volumes exceed system-specific thresholds, yet clear design guidelines for optimal storage sizing across different climatic and demand contexts remain limited (Bogdanovics et al., 2024; Sornek et al., 2025). Moreover, the long-term thermal behavior of underground storage systems introduces uncertainties that are not fully captured in short-term simulation studies.

In fifth-generation district heating and cooling systems, system complexity increases substantially due to bidirectional heat flows, decentralized heat pumps, and prosumer-based configurations. Maintaining thermal and hydraulic stability under these conditions requires advanced monitoring and control infrastructures that are not yet standard practice. The interaction between distributed solar generation, local storage, and decentralized heat pumps introduces additional layers of uncertainty that complicate both system design and real-time operation (Sdringola et al., 2025; Testasecca et al., 2025).

6.2 Economic and regulatory barriers

From an economic perspective, the deployment of solar-assisted low-temperature district heating systems remains highly sensitive to capital expenditure and regulatory frameworks. High upfront investment costs for network retrofitting, large-scale solar collector fields, and seasonal storage continue to represent a significant barrier, particularly for dense urban environments where space constraints increase project complexity and cost (Marugán-Cruz et al., 2015; Perez-Mora et al., 2018).

Several studies highlight that economic performance indicators such as LCOH and payback period are strongly influenced by assumptions regarding energy prices, discount rates, and incentive schemes, resulting in a wide dispersion of reported values across the literature (Calise et al., 2025; Massulli et al., 2025). This variability complicates the transferability of results between regions and undermines investor confidence. In addition, the strong coupling between thermal and electrical systems in fifth-generation networks exposes solar-assisted district heating to electricity market volatility, further increasing economic uncertainty (Soleimani et al., 2025).

Regulatory and governance issues represent an equally important barrier. The absence of harmonized regulatory frameworks for low-temperature district heating, prosumer participation, and thermal energy sharing limits the scalability of innovative network concepts. Several authors emphasize that unclear ownership models, tariff structures, and responsibilities between network operators and end users can significantly delay project implementation, even when technical feasibility is demonstrated (Werner, 2017; Herreras Martinez et al., 2023; Speich et al., 2024).

6.3 Methodological gaps in modeling and assessment

A critical methodological gap identified across the literature concerns the lack of standardized performance metrics and evaluation frameworks. While numerous studies report energy, environmental, and economic indicators, differences in system boundaries, temporal resolution, and allocation methods often prevent direct comparison. For instance, solar fractions, CO_2 reductions, and LCOH values are frequently reported without consistent reference baselines or transparent accounting of auxiliary energy consumption (Gjoka et al., 2023; Li and Abu Bakr, 2025). International initiatives such as IEA SHC Task 45 (IEA SHC Task 45, 2012) and Task 55 (IEA SHC Task 55, 2016) are actively addressing these gaps through harmonized case study comparisons and design guidelines, yet their recommendations have not yet been widely adopted in the literature. This challenge is particularly significant given that the buildings sector accounts for approximately 30% of global final energy consumption (IEA, 2025), meaning that even small methodological discrepancies can lead to large absolute errors in national or global assessments.

To address this gap, future research should adopt standardized definitions for at least four elements. First, the primary energy factor for electricity must be reported under two scenarios (country-specific and a harmonized reference value), because empirical studies demonstrate substantial variability in actual primary energy factors across operating systems, ranging from 0.9 to 1.8 (Noussan, 2018), while the European standard EN 15316–4-5 provides default weighting factors that may not reflect local conditions (CEN - European Committee for Standardization, 2017). As demonstrated by Bilardo et al., static primary energy factors prescribed by national regulations often misalign with dynamic values calculated from actual energy balances, leading to significant distortions in building energy performance assessments across European countries (Bilardo et al., 2022). Second, the system boundary for LCOH should explicitly state which costs are included (capital, network, O&M, connection fees), as techno-economic analyses of 5GDHC systems show that LCOH is highly sensitive to key economic assumptions and can vary substantially across case studies (Saini et al., 2023). Third, solar fraction should be distinguished between direct solar thermal contribution and total renewable heat share including heat pump input, as recent techno-economic assessments of solar district heating systems combine direct and electrically driven solar pathways within a single indicator, which can obscure the relative contribution of different conversion routes (Braimakis, 2025). This distinction is critical because space heating and domestic hot water alone account for approximately 70% of residential energy use in advanced economies (IEA, 2025), making the accurate accounting of renewable heat sources essential for meaningful performance comparisons. Fourth, temporal resolution must move beyond a single typical year: at least three climatic years are needed to capture inter-annual variability, and for 5GDHC systems seasonal disaggregation is strongly recommended to avoid masking the summer conflict (Sornek et al., 2025; Buonomano et al., 2023).

Many modeling studies also rely on deterministic assumptions regarding demand profiles, weather conditions, and system operation, with limited consideration of uncertainty and variability. This limitation is particularly relevant for solar-assisted systems, whose performance is inherently sensitive to climatic fluctuations and long-term changes in demand due to building renovation and climate change (Huang et al., 2019; Buonomano et al., 2024).

Despite growing interest in advanced control and optimization strategies, comparative assessments of control paradigms remain scarce. While individual studies demonstrate performance improvements using model predictive control or optimization-based scheduling, systematic comparisons against simpler rule-based approaches across different network configurations are still limited. This gap limits the identification of robust control strategies that can be generalized beyond specific case studies (Vandermeulen et al., 2018; Sornek et al., 2025). The importance of filling this gap is underscored by recent IEA analysis showing that energy efficiency improvements since 2010 have resulted in global CO_2 emissions being nearly 7 gigatonnes per year lower than they otherwise would have been, equivalent to approximately 20% of total emissions (IEA, 2025). This demonstrates that the potential benefits of optimized control strategies, if widely deployed, could be substantial.

The increasing complexity of fifth-generation district heating and cooling systems highlights the need for advanced digital tools and data-driven approaches. Digital twins of district heating networks, combining high-resolution physical models with real-time data and forecasting capabilities, represent a promising direction for improving both design and operation. Such tools could support predictive control, fault detection, and adaptive optimization under changing boundary conditions, including climate variability and evolving demand profiles (Buonomano et al., 2024; Testasecca et al., 2025). The need for such dynamic optimization is further amplified by current trends: global electricity demand is set to increase by 3.3% in 2025, growing more than twice as fast as overall energy demand (IEA, 2025). As thermal networks become increasingly integrated with electricity grids via heat pumps, digital twins will be essential to manage this coupling without exacerbating grid stress.

From an energy system perspective, future research should further explore the integration of solar-assisted district heating within multi-energy systems, particularly in the context of sector coupling and energy communities. The interaction between thermal networks, electricity grids, and local renewable generation offers substantial flexibility potential, but also introduces new dependencies on electricity market dynamics and regulatory frameworks. Addressing these interactions requires interdisciplinary research that combines engineering, economics, and policy analysis (Lund et al., 2018; Soleimani et al., 2025).

7 Conclusion

The shift of district heating toward low- and ultra-low-temperature operation has changed the conditions under which solar energy and seasonal thermal storage can be integrated into urban heat supply. The evidence reviewed here shows that solar-assisted district heating is no longer held back by technological immaturity: the binding constraints are system design, integration, and governance. Shifting from technology-centric optimization toward network-level design and evaluation is the necessary next step. This review has synthesized solar-assisted district heating and domestic hot water in 4GDH and 5GDHC systems from a network-centric perspective. The core finding is that system performance cannot be attributed to individual technologies: it emerges from the coordinated design of network temperature levels, solar integration strategy, storage configuration, heat pump deployment, and control logic.

Comparative evidence indicates that low-temperature operation is a key enabler for enhanced solar utilization, reduced distribution losses, and effective seasonal thermal energy storage. Fourth-generation district heating networks offer a mature and robust pathway for centralized solar integration, particularly when coupled with large-scale storage solutions. Fifth-generation district heating and cooling systems further expand system flexibility through bidirectional operation and decentralized heat upgrading, but at the cost of increased complexity and stronger dependence on electricity-driven technologies. The synthesis of case studies presented in this review identifies three recurring models: high-solar-fraction BTES demonstrations (technically feasible but economically prohibitive for widespread replication); cost-optimized PTES 4GDH systems achieving 40–50% solar fraction at 55–60 €/MWh; and emerging 5GDHC configurations combining heating and cooling with PV or hybrid PV-thermal integration, which offer higher flexibility at increased capital cost. Across both paradigms, high renewable heat shares and deep emission reductions are achievable when solar energy, heat pumps, storage, and control strategies are designed and operated as an integrated system. Conversely, fragmented design approaches and inconsistent evaluation methodologies remain major obstacles to replicability and large-scale deployment. Solar-assisted low-temperature district heating is technically viable and mature enough for broader deployment. What is still needed is coordinated progress in system design tools, digital control, and regulatory frameworks. By framing solar integration within the broader evolution of district heating networks, this review aims to support future research and practical implementation toward resilient, low-carbon urban energy systems.

Based on the gaps identified in this review, five priority research directions are proposed. First, standardized performance metrics should be developed and adopted across the field, including primary energy factors reported under both country-specific and harmonized reference scenarios, explicit disaggregation of solar fraction into direct thermal and total renewable heat contributions, and temporal resolution of at least three climatic years to capture inter-annual variability. Second, system-level validation of advanced control strategies is urgently needed: while model predictive control has demonstrated performance improvements in simulation, systematic comparisons against rule-based approaches across different network configurations and climate zones remain scarce, requiring dedicated testbeds and long-term field trials. Third, life-cycle assessment harmonization for 5GDHC systems should be prioritized, as current studies often exclude embodied emissions of decentralized heat pumps, bidirectional substations, and buried network infrastructure, potentially underestimating environmental payback times. Fourth, business models and regulatory frameworks for solar-assisted 5GDHC require further investigation, particularly regarding ownership structures, tariff design, and risk allocation between utilities, developers, prosumers, and network operators. Fifth, integration of solar-assisted district heating into multi-energy systems and energy communities represents a promising frontier, requiring interdisciplinary research that combines engineering, economics, and policy analysis to unlock flexibility potential while managing dependencies on electricity market dynamics and carbon intensity.

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