Low-Temperature Thermal Energy Networks: A Comparative Review of Configuration Options

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A Comparative Review of Configuration Options

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Abstract

Modern low-temperature Thermal Energy Networks (TENs) exist along a broad temperature continuum. Some have characterized these modern TENs as either moderate-temperature networks (sometimes called 4th generation or 4G) or ambient networks (sometimes called 5th generation or 5G), but there is no clear-cut threshold between these two configurations. The "generation" terminology, while common, is misleading because configurations have developed in parallel since the early 2000s and continue to evolve in parallel. Both configurations can achieve deep decarbonization with similar resource mixes and phases, both increase energy efficiency by reducing heat losses compared to older steam or high-temperature hot water systems, and both can reduce electric grid strain relative to building-by-building electrification. Neither configuration is universally optimal. The optimal system design depends on site-specific factors including heating and cooling demand balance, building stock characteristics, available heat sources, rights-of-way constraints, and electric and gas distribution conditions. Case studies from Germany, the Netherlands, and Canada illustrate the viability of moderate-temperature, ambient-temperature, and mixed-temperature configurations. The report concludes that a technology-neutral policy framework that sets performance-based targets rather than prescribing specific network configurations is likely to deliver superior deployment outcomes that meet a variety of policy objectives.

Keywords

thermal energy networks, district energy, building decarbonization, district heating and cooling, energy regulation, climate policy, heat planning

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Acronyms and Abbreviations

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CHP	Combined Heat and Power
DHW	Domestic Hot Water
DOC	Demand Overlap Coefficient
GHG	Greenhouse Gases
H + C	Heating and Cooling
H2	Hydrogen
HP	Heat Pump
HX	Heat Exchanger
IEA DHC	International Energy Agency District Heating and Cooling Programme
NEU	Neighbourhood Energy Utility
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
ORNL	Oak Ridge National Laboratory
PCM	Phase Change Material
RNG	Renewable Natural Gas
TEN	Thermal Energy Networks
TES	Thermal Energy Storage
UTENJA	Utility Thermal Energy Network and Jobs Act
4G	4th Generation
5G	5th Generation

Units of Measurements

^{0}C	degrees Celsius
^{0}F	degrees Fahrenheit
ΔT	temperature differential
MW	megawatts
sf	square feet

Executive Summary

Thermal energy networks (TENs), also known as district energy systems, have supplied heating and cooling to buildings for centuries, evolving through successive generations of technology, from steam systems to pressurized hot water to the lower-temperature networks increasingly deployed today. Legacy technologies employ high-temperature distribution systems that typically require fossil fuel combustion and are also relatively inefficient due to high thermal losses. As climate policy goals have advanced and building energy performance standards have tightened, interest in lower-temperature TENs has grown significantly given their typically lower emissions profiles and higher efficiencies compared to legacy high-temperature district energy systems, as well as their potential to reduce risks and costs compared to building-by-building electrification.

Modern low-temperature TENs span a broad range of configurations. At one end, moderate-temperature networks (sometimes referred to as "4th generation" or 4G networks in the literature) distribute heated or chilled water at supply temperatures below approximately 160°F (70°C) and typically use centralized or semi-centralized heat production. At the other end, ambient-temperature networks (sometimes referred to as "5th generation" or 5G networks) operate near ground temperature (approximately 40–77°F [5–25°C]) with decentralized heat pumps at each building to provide heating and cooling. In practice, many systems combine elements of both approaches in mixed-temperature configurations.

The "generation" terminology, while increasingly common, is misleading. It implies that ambient-temperature networks are a successor to or improvement upon moderate-temperature networks. The International Energy Agency's District Heating and Cooling Programme has recommended against the term "5th generation," instead classifying these systems as "thermal source networks", a subclass within the broader family of low-temperature networks (IEA DHC 2024). Both configurations have developed in parallel since the early 2000s (although the 4G/5G terminology emerged later) and continue to evolve in parallel.

This report provides an evidence-based comparative review of these configurations, finding that:

1. Moderate-temperature and ambient-temperature networks are complementary configurations along a temperature spectrum, not competing technologies. Within each broad category, there are many possible design choices such as pipe arrangements, heat sources, degree of centralized versus decentralized heat production, and peaking and redundancy strategies.

2. The optimal configuration depends on site-specific context, including density and diversity of heating and cooling demands, building stock characteristics, available thermal resources and their temperatures, electric grid capacity, gas infrastructure transition strategy, rights-of-way constraints, and local policy goals.
3. Both configurations can achieve low-carbon or zero-carbon performance. The resource mixes and phasing may differ, but both support emissions reduction pathways that balance cost, reliability, and environmental objectives.
4. Both configurations can integrate a wide range of low-carbon thermal resources — including geothermal heat exchange, waste heat from data centers and industrial processes, solar thermal energy, and heat pumps powered by renewable electricity. The manner of integration differs (centralized versus distributed, direct use versus temperature boosting), but neither configuration is limited to a narrower set of resources than the other.
5. Both network configurations can reduce strain on electric distribution grids relative to building-by-building electrification (when sited and designed appropriately), and both can support the managed transition of gas infrastructure, though the phasing and mechanics differ between configurations.
6. Mixed-temperature networks — combining moderate-temperature and ambient-temperature sub-networks — are increasingly common in practice, further demonstrating that these are complementary approaches.
7. A technology-neutral policy framework that sets performance-based targets, rather than prescribing specific network configurations, can deliver effective outcomes by enabling locally appropriate and resource-efficient solutions while driving progress toward climate goals.

A note on terminology: This report uses "moderate-temperature" and "ambient-temperature" to describe the two ends of a spectrum of low-temperature network configurations, distinct from legacy steam and high-temperature hot water systems. Where some literature uses the terms "4G" or "5G," this report notes the correspondence but does not adopt the generational framing, for the reasons described above.

1. Introduction

This report provides an evidence-based comparative review of low-temperature thermal energy network (TEN) configurations, also commonly referred to as low-temperature district energy systems. It examines the technical, economic, and policy considerations relevant to the selection and regulation of different types of TENs, and is intended to inform policymakers, regulators, utilities, and community stakeholders engaged in decisions about TEN deployment. The analysis is supported by case studies and policy examples from jurisdictions in Europe and North America.

TENs have supplied heating and cooling to buildings for centuries, evolving through successive generations of technology. The International Energy Agency's District Heating and Cooling (IEA DHC) Executive Committee defines four generations based on network temperature and heat transfer medium (Wiltshire et al. 2024):

- **First generation (1G):** Steam-based networks.
- **Second generation (2G):** Pressurized hot water networks operating above 212°F (100°C).
- **Third generation (3G):** Hot water networks operating between 212°F (100°C) and 158°F (70°C), typically using pre-insulated pipe systems.
- **Fourth generation (4G):** Low-temperature hot water networks operating below 158°F (70°C), designed to integrate renewable energy sources and waste heat into smart energy systems.[1]

According to the IEA DHC, the 4G category encompasses a broad continuum of network design choices. The main advantages of these lower-temperature systems are that they reduce energy losses compared to their higher-temperature predecessors and can more readily accommodate low-emission heat sources, including geothermal energy, waste heat from data centers and industrial processes, solar thermal energy, and heat pumps powered by renewable electricity. Thermal energy storage, at durations from hours to seasons, is also more readily integrated at lower network temperatures, supporting both variable renewable energy integration and peak demand management.

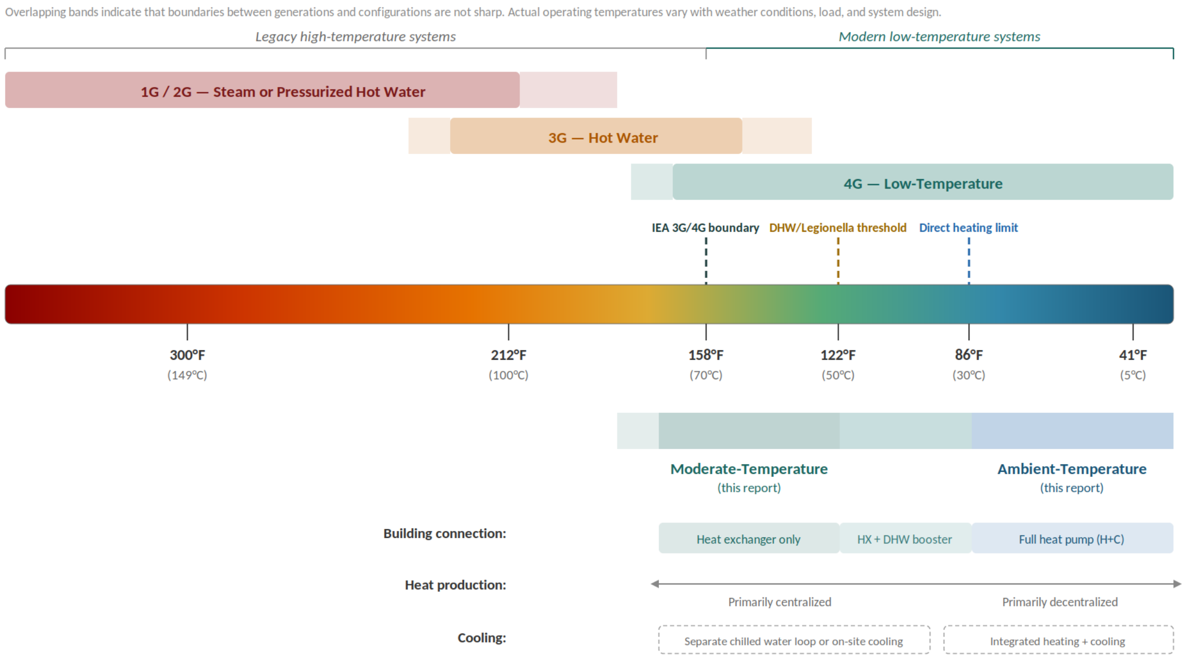
The IEA DHC Annex TS2 guidebook on low-temperature district heating implementation (Averfalk et al. 2021) further describes a range of configurations within the 4G category. These differ primarily in what equipment is required at the building connection:

- **At the upper end of the range (approximately 122–158°F / 50–70°C),** networks deliver heat through insulated pipes at temperatures directly usable by building heating systems and domestic hot water (DHW) preparation. Heat production is typically centralized or semi-centralized. Cooling, where required, is generally provided by a separate chilled water loop or by individual building-level systems. A heat exchanger transfers heat from the network to the building's internal hydronic distribution system, with no on-site heat generation equipment (i.e., heat pumps) required.
- **In the middle of the range (approximately 86–122°F / 30–50°C),** supply temperatures are sufficient for direct space heating with only a heat exchanger needed in many buildings—particularly those with underfloor heating or well-sized radiators. However, the distribution temperature is too low to meet safety requirements for DHW preparation, which necessitates a small heat pump or electric boiler in each building to bring DHW above 122°F (50°C) to reduce the risk of microbial growth (specifically *Legionella*)[2]. Heat production remains primarily centralized, and the network architecture is similar to systems at the upper end of the range as described above, with the addition of supplementary equipment at each building for DHW.
- **At near-ambient temperatures (approximately 41–77°F / 5–25°C),** networks serve as a shared thermal source and sink rather than delivering directly usable heating and cooling. Each building requires heat pumps to satisfy heating and cooling needs. This enables bidirectional operation; buildings can inject or extract heat, which allows both heating and cooling to be served from a common pipe network. Pipes may be uninsulated since operating temperatures are close to ground temperature. A significant advantage of this configuration is that, where overlapping heating and cooling loads exist, they can directly offset one another; Rejected heat from cooling processes serves heating loads, while the cooled return flow serves cooling loads, potentially reducing the need for external heat sources.

Others have labelled the lowest end of the temperature spectrum (ambient-temperature networks with fully decentralized heat pumps) as "5th generation" (5G), which suggests a sequential improvement over 4G (IEA DHC, 2024). However, the IEA DHC Executive Committee recommends against using this term, instead classifying these systems as a subclass within the 4G family (Wiltshire et. al. 2024). IEA DHC and other leading researchers (Lund et al., 2021; Sulzer et al., 2021) note that ambient-temperature networks represent a parallel and complementary development to other 4G configurations, not a successor. The 4G label was formalized in 2014 (Lund et al. 2014), while the 5G classification emerged around 2015 among practitioners and industry first and only gained wider currency following Buffa et al.'s 2019 review, though it has never achieved the same consensus (Wiltshire et al. 2024). Both configurations have existed since the early 2000s, before the 4G and 5G labels began being used, and they continue to evolve concurrently. Recent comprehensive reviews confirm that both configurations continue to advance in parallel, with growing deployment of both across Europe and elsewhere (Yao et al. 2024; Dang et al. 2024).

For the purposes of this report, “moderate-temperature” refers to networks in the upper and middle ranges of modern low-temperature systems, where centralized semi-centralized heat production delivers usable heat to buildings. “Ambient-temperature” refers to networks that provide a low-temperature source for decentralized building-level heat pumps. The boundary between these categories is not sharp; networks in the lower portion of the middle range share characteristics of both, with centralized production but building-level supplementary equipment. “Mixed-temperature” refers to systems that combine moderate-temperature and ambient-temperature sub-networks within a single district, which are increasingly common in practice. Figure 1 illustrates this continuum.

Figure 1. Continuum of Thermal Energy Network Configurations



The position of a network along this temperature continuum does have direct implications for system architecture, building integration, and operational strategy. This report examines these implications across the following topics:

- Network configurations and characteristics, including building integration, pipe sizing, available heat sources, cooling provision, and load diversity (Section 2).
- Peaking technologies, thermal energy storage, and strategies for phased emissions reduction, including how the role and scale of storage and the options for reducing peaking emissions differ between configurations (Section 3).
- Implications for the electric grid and gas network, including how TENs can reduce grid strain relative to building-by-building electrification (Section 4).
- Implications for policy and regulation (Section 5).

The optimal point on the temperature continuum depends on site-specific factors including heating and cooling demand balance, building stock characteristics, available thermal resources and their temperatures, electric grid capacity, gas infrastructure transition strategy, rights-of-way constraints, and local policy goals.[3] Appendix A provides detailed case studies; Table 1 summarizes their relevance to the topics discussed in this report.

Table 1. Case Study Overview (refer to Appendix A for details)

Case Study	Network Type	Phased Emissions Reduction	Heat Sources & Storage	Mixed-Temperature Evolution
Biberach, Germany	Moderate-temperature	Phased fuel switching: gas to biomass to heat pump	Geoexchange, biomass, gas, CHP; central thermal storage	—
Dollnstein, Germany	Mixed (seasonal)	Not originally designed around an emissions reduction target (focus on renewable integration), but now subject to Germany's district energy emission reduction benchmarks (refer to Section 3.4)	Solar thermal, geoexchange HP, CHP; central and distributed buffer storage	Seasonal mode switching: moderate-temperature in winter, ambient in summer
False Creek, Vancouver, Canada	Moderate-temperature	70% renewable at outset; 100% target before 2030; decarbonization roadmap underway	Sewage heat recovery (baseload); gas boilers (transitional peaking)	—
Mijnwater, Heerlen, Netherlands	Initially ambient; transitioned to mixed-temperature network	Not designed around a phased emissions reduction target; low-carbon from outset using mine water geothermal and renewable sources	Mine water geothermal, solar thermal, biomass-CHP; mine water seasonal storage; Initial development included building-level gas backup	Ambient backbone with moderate-temp heating/cooling clusters added over time

2. Network Configurations and Characteristics

2.1 Moderate-Temperature Networks

Moderate-temperature networks represent the most widely deployed form of modern low-temperature district heating globally (Averfalk et al. 2021). These networks typically feature centralized or semi-distributed heat production, with the potential to integrate diverse thermal resources. Heat sources may include waste heat (e.g., from industrial processes, data centers, hydrogen production, sewer systems, and wastewater treatment plants), geothermal, air, solar, and biomass. Where source temperatures are insufficient for direct use, centralized heat pumps (including ground-source, water-source, and air-source heat pumps) can upgrade lower-grade heat to network supply temperatures, a common practice in Scandinavia and elsewhere. Electric boilers can provide supplementary heat and absorb surplus renewable electricity. Systems are often designed to meet baseload demand without the use of fossil fuels.

The network delivers heat to buildings via heat exchangers that transfer thermal energy from the network to the building’s internal hydronic distribution system. Where buildings already have hydronic heating, integration is low-cost, technically straightforward, and requires less floor area for in-building equipment than configurations requiring on-site heat pumps. The network typically consists of pre-insulated bonded pipes at relatively small diameters, enabled by the higher temperature differential (ΔT) between supply and return. Temperatures can be varied in response to weather using outdoor temperature reset controls, reducing distribution heat losses during milder conditions (refer to endnote 1).

A key advantage of moderate-temperature networks is load diversity. Because individual buildings typically do not peak simultaneously, centralized plant(s) can be sized well below the sum of individual building peaks, improving capital efficiency and equipment utilization. Thermal energy storage can be readily integrated at the network level to further reduce peak capacity requirements and absorb surplus renewable electricity.

Where cooling is required, moderate-temperature networks typically provide it through a separate chilled water distribution loop or through individual building-level cooling systems.

These networks have an extensive operational track record, with decades of experience across Scandinavia, continental Europe, Canada, and increasingly the United States (Averfalk et al. 2021).

2.2 Ambient Temperature Networks

Ambient temperature networks represent a complementary approach to moderate-temperature networks. In these networks, water circulates at or near ground temperature. Distributed heat pumps at each building connect to the ambient network to extract and upgrade heat to meet the temperatures required by the building's heating distribution system (in heating mode) or to inject heat to meet cooling requirements (in cooling mode). Building-level heat pumps may be owned, operated, and/or maintained by either the building owner or the network operator.[4] Building-level heat pumps must generally be sized to meet the full non-diversified peak of each building, as the network delivers energy at temperatures too low for direct use.

Unlike moderate-temperature networks, ambient-temperature networks serve both heating and cooling from a single piping system (which may consist of a single pipe or two separate supply and return pipes). This combined heating and cooling infrastructure enables bidirectional energy flow and allows buildings to act as "prosumers,"[5] wherein rejected heat from cooling becomes a resource for heating elsewhere. If there is overlap in demand from concurrent heating and cooling, measured as the Demand Overlap Coefficient or DOC, it can reduce the need for additional heating and cooling supply resources on the network, as buildings can balance one another's usage (Wirtz et al. 2020). This is a significant advantage where cooling demand is substantial or where buildings with complementary load profiles (e.g., offices and residential) can be clustered together.

Uninsulated pipes may be feasible for buried sections, reducing insulation cost and distribution heat losses. However, pipe diameters are typically larger than moderate-temperature networks due to the lower ΔT between supply and return, which increases civil works costs and may be challenging in constrained rights-of-way. The lower ΔT also means higher flow rates are required to deliver the same thermal capacity, resulting in larger pipe diameters and potentially increased pumping energy (nPro n.d.). These larger pipe diameters can partially offset the cost savings from eliminating pipe insulation, and the net infrastructure cost comparison depends on site-specific factors including trench constraints and pipe routing (Gudmundsson et al. 2022). A review of implementation experience identifies additional barriers for ambient-temperature networks, including more complex hydraulic design, higher planning costs, and the need for new business models to manage distributed heat pump ownership and operation (Gjoka et al. 2023).

Ambient-temperature networks are typically anchored by geoexchange (borehole or aquifer thermal energy storage systems) but can also incorporate waste heat recovery, surface water sources, sewage heat, boilers on the loop, and centralized boost heat pumps. Based on these characteristics, these systems may be particularly well suited to modern buildings with high-efficiency envelopes and space for on-site heat pumps, and in areas with balanced heating and cooling loads. A survey of 53 ambient-temperature networks in Germany confirms that geoexchange is the dominant thermal source configuration for these systems (Wirtz et al. 2022).

2.3 Mixed Networks

There are a growing number of mixed-temperature systems that combine elements of both approaches, emphasizing that moderate- and ambient-temperature configurations can be complementary. There are several different types of mixed configurations:

Ambient backbone with moderate-temperature sub-networks: A low-temperature trunk collects low-temperature waste heat or geothermal energy for upgrading at a central point, while moderate-temperature sub-networks distribute heat to specific clusters of buildings from centralized plants within each node (e.g., University of British Columbia Okanagan evolution, Amazon Campus Seattle).[6]

Mixed configurations by building type: Within a single development, new-build offices may connect to an ambient loop while retrofitted residential buildings receive moderate-temperature supply (e.g., Zibi Ottawa-Gatineau).

Phased evolution: Systems initially deployed at one temperature may evolve over time as building stock turns over, heat sources change, or technology improves. Operational experience frequently leads to pragmatic mixed configurations that were not part of the original design (e.g., University of California Davis, Duke University, Cornell University).

Seasonal variation: A network can operate in winter as a heating network with moderate supply temperatures — delivering heat directly to buildings via heat exchangers, with no building-level heat pumps required — and in summertime lower network temperatures to the ambient range, at which point building-level heat pumps provide domestic hot water and, where applicable, cooling (e.g., Dollnstein, Germany (Werner 2023); Berlin-Tegel, Germany; Bedburg, Germany).[7] Depending on the load profile and cooling technology employed, this approach may allow for reductions in heat pump capacity, and resulting decreases in equipment footprints and costs.

2.4 Network Configuration Comparison

Table 2 summarizes the key characteristics of moderate-temperature, ambient-temperature, and mixed-temperature networks.

Table 2. Key Characteristics of Different Network Configurations

Factor	Moderate-Temperature	Ambient-Temperature	Mixed
Supply temperature	86-158°F (30-70°C)	41–77°F (5–25°C)	Varies by sub-network
Building integration	Simple integration into existing buildings with low-temperature hydronic distribution systems; At lower end of temperature range, requires in-building equipment to boost DHW temperatures	Requires a heat pump at each building, sized to meet full building peak; May be challenging in space-constrained and retrofit contexts	Varies by sub-network
Cooling provision	Network cooling requires a separate set of supply/return pipes or on-site cooling equipment	Heating and cooling use the same set of pipes	Varies by sub-network
Pipe specifications	Insulated 2- or 4-pipe systems with smaller pipe diameters (higher ΔT); Smaller diameters may take up less space in rights-of-way and reduce trenching costs	Uninsulated 1- or 2-pipe systems with larger pipe diameters (lower ΔT); May require additional pumping due to higher flow rates; Larger pipe diameters may constrain dense urban routes	Mixed, route-dependent
Load diversity	Centralized plant(s) sized below the sum of peaks	Each heat pump sized to meet individual building peak, but networks with a significant amount of concurrent heating and cooling may allow for reduction in other thermal resources	Varies by sub-network[8]
Scalability / track record	Many examples at city-scale; Expansion may require augmentation of central plant capacity	Emerging model mostly <100 buildings; Expansion may require additional thermal resources along the loop	Emerging model; Highly scalable, as system expansion can adapt to site-specific contexts
Common use case	Heating-dominated loads, dense urban areas, seasonal heating and cooling demand	Significant amounts of concurrent heating and cooling; Office/mixed-use areas; New buildings with efficient envelopes	Mixed stock (e.g., new construction and retrofits) and/or phased development

2.5 Thermal Resources

A central finding of this analysis is that both moderate-temperature and ambient-temperature TENs can achieve low-carbon performance through different pathways and mixes of resources. Advanced modeling performed by Lédée and Evins (2024) confirms that both can achieve comparable emissions performance when optimized for local conditions. Both network configurations can employ the same thermal resources, though in different ways and with varying benefits.

2.5.1 Heat Pumps

Both configurations employ large-scale heat pumps as core technologies, leveraging waste heat, water bodies, geothermal, or the air to extract (or inject) heat.

Moderate-temperature networks typically employ centralized large-scale heat pumps to enable delivery of directly usable heating and/or cooling. Load diversity can allow a heat pump to be sized below the sum of each individual building’s peak. As mentioned, the lower temperature range of moderate-temperature networks may require in-building heat pumps for DHW.

Ambient networks deploy individual heat pumps at the building level to deliver usable heating and cooling to building systems. Each building’s heat pump is sized to meet the peak load of that building. Some systems may employ centralized heat pumps to temper the loop to ensure operating temperatures fall within the intended range.

2.5.2 Boilers

Boilers are also used in both configurations, though employed differently. Boilers can be fueled by electricity, natural gas, heating oil, propane, renewable natural gas, renewable diesel/biodiesel, hydrogen, or biomass.

In moderate-temperature networks, boilers are a common choice for peaking as they can substantially reduce capital costs compared to meeting 100% of the peak load with heat pumps. In ambient-temperature networks, it is possible for electric or gas boilers to connect at the network level for balancing, but they tend to be connected at the building level for backup or redundancy. More information on peaking strategies can be found in Section 3.

Renewable natural gas (RNG or biomethane) can serve as a drop-in replacement for natural gas in peaking boilers, and renewable diesel can serve as a drop-in replacement for heating oil. In moderate-temperature networks, a single centralized conversion point simplifies the fuel-switching logistics. In ambient-temperature networks with distributed gas backup, RNG would need to be delivered to each building's gas connection, requiring the gas distribution infrastructure to remain in place. Alternatively, buildings could use renewable diesel (or a renewable diesel/biodiesel blend) for distributed peaking boilers. Supply availability and cost remain constraints on the use of alternative fuels.

Green hydrogen is an emerging option as a fuel for centralized boilers or combined heat and power (CHP). While hydrogen distribution infrastructure faces challenges, a single central conversion point in a moderate-temperature network simplifies logistics. However, a more promising but indirect role for hydrogen in TENs is the recovery of waste heat from hydrogen production processes (e.g., electrolysis), even if the resulting hydrogen fuel is used for other applications such transportation and industrial processes. This also can also improve the economics and energy efficiency of hydrogen production.

2.5.3 Solar Thermal

Solar thermal energy can serve as a baseload or seasonal resource in both network configurations, though it is most commonly integrated into moderate-temperature networks. Large-scale solar collector fields paired with seasonal pit or borehole storage can provide a substantial share of annual heating demand, as demonstrated in Danish district heating systems such as Vojens (Solar Heat Europe, n.d.). In moderate-temperature networks, solar thermal output at 140–175°F (60–80°C) can be used directly or stored at network-compatible temperatures for seasonal dispatch. In ambient-temperature networks, solar thermal can contribute to ground recharging (injecting heat into boreholes during summer to maintain thermal balance), which is a critical operational requirement for systems relying on seasonal ground-source extraction. The Dollnstein case study illustrates effective solar thermal integration in a mixed-temperature system, where solar collectors contribute meaningfully during summer operation (Werner 2023).

2.5.4 Waste Heat

Waste heat from various sources, such as wastewater treatment, sewage, industrial processes, hydrogen electrolysis, refrigeration, or data centers can be integrated into either network configuration. The key consideration is the temperature of the waste heat being produced. Ambient-temperature networks can more readily integrate low-grade waste heat. Moderate-temperature networks require low-grade waste heat to be upgraded, typically via heat pumps, to directly useable temperatures.

The integration of data center waste heat in particular highlights the distinct technical benefits of different network configurations for different waste heat resources. Yuan et al. (2025) categorize integration strategies for data center waste heat according to the data center's cooling technology, which influences the recoverable heat temperature. Air-cooled data centers typically produce low-grade waste heat (80–95°F / 25–35°C), which aligns well with ambient-temperature networks without temperature upgrading. This allows for direct heat rejection into the network, improving the data center's cooling efficiency while balancing the network's thermal load. For moderate-temperature networks requiring supply temperatures of 140–160°F (60–70°C), this low-grade heat requires upgrading via centralized industrial heat pumps. Liquid-cooled data centers, however, can produce outlet temperatures up to approximately 150°F (65°C), which can be more directly utilized in a moderate-temperature network without necessarily requiring heat pumps.

2.5.5 Electric Grid Decarbonization

Electricity-based components in both network configurations may continue to have indirect emissions from electricity production. As the electricity grid incorporates more renewable generation, these indirect emissions will decline proportionally. Grid decarbonization benefits both network configurations, but the magnitude of benefit is greater for configurations with a higher share of electricity in the energy mix.

3. Peaking, Backup, and Thermal Storage

3.1 Peaking Challenge

Peak demand is a critical design consideration that can influence the financial viability, reliability, safety, and performance of TENs. In cold climates, peak heating loads during extreme weather events may represent only 10–30% of annual energy delivery but determine 100% of system capacity requirements. Across utility types, the marginal cost of peaking capacity is high relative to the marginal energy it delivers, and the emissions benefit of decarbonizing peaking loads may be modest relative to the cost.

Moderate- and ambient-temperature networks address peaks in fundamentally different ways, though they may employ some of the same technologies. In general, moderate-temperature networks can employ centralized peak reduction strategies, such as large-scale thermal storage, centralized electric boilers, chillers, or centralized gas boilers, which directly reduce or shift the peak demand that needs to be met by the network's heat production plant. Ambient-temperature networks, by contrast, address peaks primarily at the building level (e.g., via thermal storage, boilers, or electric resistance heating), since each building's heat pump must independently meet its own peak. Centralized equipment on an ambient loop (e.g., boilers or heat pumps) can temper the loop temperature to improve building-level heat pump performance, but this is not traditional peak shaving; It manages long-term thermal drift concerns and supports efficiency rather than directly reducing the building-level peak.

3.2 Thermal Storage: A Key Differentiator

Thermal storage is among the most cost-effective strategies for managing peak heating and cooling demand while reducing emissions and peak electricity use from TENs. However, the type, scale, and duration of storage that can be effectively deployed differ by network configuration. The appropriate mix of storage durations, ranging from minutes (buffer tanks) to hours (hot water tanks) to seasons (borehole thermal energy storage, BTES; aquifer thermal energy storage, ATES; pit storage), depends on network configuration, climate, energy sources, and load profiles. The network temperature also affects which storage media are practical.

3.2.1 Heating Storage

Moderate-temperature networks can integrate thermal storage at the network level for both short-term peak shaving and longer-term seasonal balancing. They can directly integrate a wider range of centralized high-temperature storage media, including hot water tanks and pit thermal storage[9] to emerging technologies like sand, brick, and phase change materials (PCMs) with higher melting points. This is because the stored heat can be dispatched at temperatures compatible with direct building use. Some of these technologies provide short-duration storage (hours to days) that charge at times of lower electricity costs and high renewable electricity generation, which can shift loads away from peak periods, support grid system efficiency, and provide grid-balancing revenue to the network. Solar thermal collectors paired with seasonal pit or borehole storage can provide a substantial share of annual heating demand.

Ambient-temperature networks benefit most from ground-based storage (BTES/ATES), which provides seasonal balancing.[10] Heat extracted in winter must be replenished in summer through waste heat injection, solar recharging, or cooling rejection from connected buildings. This seasonal recharging is both a storage mechanism and a critical operational requirement, as failure to maintain ground thermal balance degrades system performance over time. High-temperature centralized storage can still feed an ambient network but requires intermediate heat exchange, adding cost and complexity. Building-level hot water buffer tanks can supplement with short-duration storage (minutes to hours) for peak shaving and load shifting, though at a much smaller scale than centralized alternatives. A design consideration for ambient networks is whether higher-grade waste heat can be efficiently stored in very low temperature networks, or whether intermediate heat exchange and separate storage loops may be needed.

3.2.2 Cooling Storage

Thermal storage for cooling serves different functions depending on network configuration. In moderate-temperature networks that include a chilled water loop, chilled water tanks or ice storage can shave cooling peaks and shift compressor electricity consumption away from high-cost periods. Ice storage, which stores cooling energy at higher density than chilled water, is a mature technology for peak demand reduction that is widely deployed in district cooling and large commercial building systems.

In ambient-temperature networks, cooling storage operates differently. Buildings rejecting heat into the loop during the cooling season effectively use the ground (via BTES/ATES) as a seasonal cooling resource; Rejected heat is stored for winter extraction, simultaneously addressing the cooling load and recharging the ground for the heating season. At the building level, chilled water buffer tanks can provide short-duration cooling peak shaving, analogous to their heating-side counterparts.

These differences further underscore that storage strategy, like peaking strategy generally, should be tailored to the network configuration and local conditions rather than prescribed universally.[11]

3.3 Peaking Options by Network Type

Table 3 summarizes the peaking and backup options available to each network configuration. An important distinction is that for moderate-temperature networks, the technologies listed provide centralized peak reduction, directly reducing the peak demand on the network's heat production plant(s). For ambient-temperature networks, centralized technologies primarily provide loop tempering, which is maintaining the loop's operating temperature within its design range by managing the balance of heat injections and extractions across the network; Peak demand is ultimately met at the building level by each building's heat pump.

Table 3. Peaking and Backup Options by Network Configuration

Option	Moderate-Temperature	Ambient-Temperature
Electric boilers	Low capital cost; Large, centralized units that can be installed and dispatched quickly; Proven at scale; Can absorb surplus renewable electricity	Less common at network scale; A centralized electric boiler can boost loop temperatures but serves a tempering role rather than meeting building peaks directly; Individual building electric resistance heating is still required for peaking and backup
Thermal energy storage (TES)	Highly applicable at network level; Large, insulated tanks store heat at network temperature; Proven technology providing hours to days of peak capacity and grid-balancing services	Limited applicability at the network level due to low temperatures; Building-level hot water buffer tanks can provide short-duration peak shaving and load shifting, but the aggregate impact is smaller than centralized thermal storage serving an equivalent number of buildings
Ground thermal storage (BTES/ATES)	Feasible for seasonal storage; Pit storage proven in Denmark (Vojens); Higher temperatures require insulation	Ground acts as seasonal thermal reservoir; Mine water (Mijnwater) is a large-scale example; Lower losses at ambient temperature; Thermal balance management is critical
Transitional gas boilers (Refer to Section 4.2 for gas network transition implications)	Centralized gas boilers for peaking are proven and low-cost; Single point for future fuel-switching (e.g., RNG); Enables pruning of gas distribution to individual buildings from the outset	Can be centralized (on the loop) for tempering or distributed at individual buildings for peak backup; Distributed gas backup requires maintaining or installing gas infrastructure to each building, which potentially complicates or delays gas network pruning

Table 3. (continued)

Option	Moderate-Temperature	Ambient-Temperature
RNG or renewable diesel/blends	Single central conversion point; RNG is a drop-in replacement for gas or renewable diesel is a drop-in replacement for fuel oil in a peaking boiler; Biodiesel is not a drop-in replacement but can be blended with renewable diesel at a potentially lower cost and greater availability; Potential supply and cost constraints for these alternative fuels	Can be used to temper loop temperatures but RNG still requires gas infrastructure to each building for use as a peaking and backup resource; Renewable diesel/biodiesel blend can be delivered by truck and stored on-site
Green hydrogen	Emerging option for centralized boilers/CHP; Distribution infrastructure for H2 faces challenges, but a single central conversion point simplifies logistics; Waste heat from H2 production (electrolysis or other processes) can be directly integrated into moderate-temperature networks as a heat source and not just as a fuel	Could be used centrally to temper the loop, but H2 distribution to the building level for peaking and backup poses safety and infrastructure challenges; Integration of waste heat from H2 production into ambient loops is feasible for loop tempering but remains limited in practice
Biomass	Proven for centralized peaking/baseload; Common in Scandinavian systems given availability of wood waste and favorable emissions accounting treatment in local protocols; Supply chain, air quality, emissions considerations	May be used to loop tempering (less common); Not practical for distributed building-level use

3.4 Implications for Phased Carbon Reductions

As described above, both ambient- and moderate-temperature networks can have zero- or very low-emission baseload. Using capital-intensive clean energy technologies to meet peak heat demand, however, may be cost-prohibitive in the near term, impacting project bankability and affordability for customers. To ensure that fossil fuel peaking is used on an interim basis and does not become permanent, policy, regulation, and private contracts can require emission reduction goals to be met on cost-efficient schedules.

While phased decarbonization is feasible for both ambient- and moderate-temperature configurations, the available technical decarbonization pathways and associated investment sequences may differ:

Moderate-temperature networks offer a straightforward centralized pathway, as central plants simplify fuel-switching decisions. A system may begin with efficient heat pump baseload and limited gas peaking, progressively add thermal storage to reduce peak reliance, and eventually replace gas with electric boilers, RNG, or hydrogen. Centralized gas use during transition enables rationalization of downstream gas distribution (i.e., pruning of the gas distribution networks to individual buildings).

Ambient-temperature networks reduce peaking emissions through different mechanisms. One common mechanism is to optimize thermal resource balance on the loop such as by maximizing summer heat injection from waste heat sources or cooling rejection in geoexchange systems to maintain borefield temperatures, which improves heat pump performance during peak winter extraction and reduces the need for supplementary boost. Other mechanisms include deploying smart network controls to manage coincident demand and scaling central plant boost capacity over time. Where building-level gas peaking and backup exists, fuel switching involves many distributed points rather than one central plant, though the transition may be simplified if the network owner also owns distributed, in-building equipment (as in Mijnwater). If building-level gas backup is used during transition, the timeline for gas network pruning may be longer than under centralized approaches.[12]

Both network types benefit significantly from grid decarbonization over time. As noted previously, electricity-based peaking and backup in either network configuration can still have indirect emissions associated with electricity production. As the electricity grid incorporates more renewables, indirect emissions decline proportionally, offering a pathway to further emissions reduction without changes to TEN infrastructure. The higher share of electricity in a network's energy mix, the greater the emissions benefit from grid decarbonization.

A resource-efficient phased approach to emissions reduction offers practical and economic advantages, including:

- Allowing projects to deploy cost-effective, low-carbon baseload immediately while managing the higher cost of fully decarbonizing peaking loads
- Addressing both perceived and legitimate early-stage reliability and energy security concerns (new systems need operational track records before eliminating all backup capacity)
- Allowing alternative technology options for peaking (renewable gases, advanced storage, next-generation heat pumps) to mature and decrease in cost
- Providing clear regulatory certainty to developers and investors while preserving flexibility in compliance pathways

- Enabling alignment with differentiated emissions standards for new buildings vs. retrofits, so new buildings can meet more stringent energy codes while existing buildings can reduce emissions over time in line with the requirements of building performance standards and similar policies

As an example, Germany has implemented country-wide benchmarks for emissions reduction in district energy networks that do not prescribe network type (German Bundestag 2023):

- **From 2025:** New district energy systems are required to have a 65% share of renewable energy or waste heat
- **By 2030:** Existing district energy systems are required to have a 30% share of renewable energy or waste heat
- **By 2040:** Existing district energy systems are required to have an 80% share of renewable energy or waste heat
- **By 2045:** All district energy systems are required to have a 100% share of renewable energy or waste heat

At the project level, the City of Vancouver's False Creek Neighbourhood Energy Utility (NEU) illustrates a phased approach led by municipal policy. The NEU began operations in 2010 with sewage heat recovery providing low-carbon baseload and centralized natural gas boilers for peaking, achieving approximately 70% renewable energy from the outset. Under the City's Climate Emergency Response (City of Vancouver 2019), the NEU has set a target of 100% renewable energy before 2030. A decarbonization roadmap completed in 2024 identified options for fully transitioning peaking loads away from fossil fuels, and detailed feasibility analysis is now underway (City of Vancouver 2026). The NEU demonstrates that a phased approach, deploying proven low-carbon baseload first, then systematically addressing peaking, can deliver substantial early emissions reductions while preserving a credible and cost-effective pathway to zero emissions within a defined timeline.

Ideally, network-level emissions reduction timelines should reflect the requirements of individual buildings connected to the network. New construction typically faces higher energy performance standards (and higher avoided costs compared to conventional systems), justifying lower carbon emissions from the outset. Existing buildings may have lower or no standards that are phased in over time. In networks serving a mix of new and existing buildings, green heat tariffs or differentiated carbon allocations may be required. Regardless of the approach, actual energy sources and emissions on the network can be allocated according to the requirements of individual connected buildings, and network-level reduction targets can be coordinated with building-level regulations to prevent mismatches that could create commercial risks for TEN operators.

A phased approach can accelerate deployment, manage costs, address early-stage reliability concerns, and allow technology options for peaking (renewable gases, advanced storage, grid evolution) to mature before large-scale investment is required.

4. Electric and Gas System Implications

4.1 Electric Grid Context

Electric grids face growing challenges from climate impacts such as wildfires and storms, retirement of aging infrastructure, load growth driven by new large loads (e.g., data center proliferation, manufacturing facilities), and electrification of heating and transport. These trends combine to increase reliability risks and the need for large-scale electric infrastructure investment. TENs can help mitigate some of these challenges by reducing overall electric demand compared to building-by-building electrification, and particularly by managing costly electric peaks. Oak Ridge National Laboratory (ORNL) research on mass deployment of geothermal heat pumps found that deploying ground-source heat pumps in approximately 70% of US buildings could reduce electric power system generation and capacity needs by up to 11% and 13% respectively, while avoiding approximately 24,500 miles of new transmission lines (Liu et al. 2023). These findings were based on individual building installations; district-scale networked deployment, which enables shared ground loops, leveraging of waste heat, coordinated controls, and network-level thermal storage, would be expected to yield additional benefits. Research on heating electrification in cold climates further confirms that grid flexibility investments, including thermal storage and coordinated load management at-scale of the kind enabled by TENs, are essential to managing electric system costs as heating loads shift to the electric grid (Knittel et al. 2024).

Both moderate- and ambient-temperature TENs have the potential to offer significant grid benefits. Both configurations benefit from shared infrastructure and thermal diversity to reduce aggregate coincident peak demand. Centralized or network-level non-electric peaking technologies and thermal storage enable demand response, load shifting, and grid services that individual building heat pumps cannot provide. This benefit is strongest for moderate-temperature networks with centralized production and storage. Ambient-temperature networks may capture some of this benefit through smart network controls and coordinated heat pump operation, but the opportunity is complex and limited given the distributed nature of heat pumps.[13]

4.2 Supporting the Gas Network Transition

Both network types can support a managed gas network transition by enabling coordinated, neighborhood-scale pruning of gas customers. This has several important benefits:

- **Strategic pruning:** Gas distribution segments serving TEN areas can be decommissioned, avoiding costly renewal of aging pipe and reducing ongoing maintenance costs
- **Stranded cost reduction:** Coordinated transition reduces the risk of stranded gas assets and associated rate impacts on remaining customers
- **Workforce transition:** Gas utility workers can transition to TEN construction, operation, and maintenance, preserving skilled employment while shifting to lower-carbon infrastructure
- **Business model evolution:** Gas and electric utilities are among the entities that can develop and operate TENs, as enabled by New York's Utility Thermal Energy Network and Jobs Act (UTENJA) framework, but it is important to note other entities could also own and operate TENs

However, the timeline and mechanics of gas network rationalization may differ between network types. Moderate-temperature networks with centralized gas peaking can enable building-level gas disconnection from the outset, since the TEN replaces all building-level gas consumption (assuming electrification of cooking and other gas-fired appliances). Ambient-temperature networks that rely on distributed building-level gas backup during transition may require a longer timeline before individual gas connections can be decommissioned, which is a factor that should be considered in gas utility transition planning, cost-benefit analysis, and stranded asset management.

4.3 Grid Implications by Network Type

Table 4 compares the electric grid and gas network implications of each TENs configuration.

Table 4. Grid Implications by Network Configuration

Grid Factor	Moderate-Temperature	Ambient-Temperature
Electric peak demand	Centralized electric load management; Large heat pumps and electric boilers can be dispatched, curtailed, or shifted; Thermal storage provides buffer	Distributed heat pump load is less controllable individually, but ground-source efficiency reduces per-unit electric demand; Smart network controls emerging
Electric grid upgrade avoidance	Centralized connection reduces electric distribution upgrades; Thermal storage shifts load away from electric grid peaks	Distributed heat pumps still require building-level electrical capacity, though less than resistance heating; Network diversity can mitigate electric peaks
Renewable electricity integration	Electric boilers can absorb surplus wind/solar, proven in Aarhus, Denmark (Kortegaard Støchkel 2024)[14]	Building-level heat pump scheduling can shift some electricity consumption to periods of surplus renewable generation, but the distributed nature of heat pumps limits the scale and responsiveness of this capability compared to centralized alternatives
Gas network pruning	Enables neighborhood-scale disconnection from gas and reduction of stranded assets; Building-level gas connections can be decommissioned; Central plant is single switch point for alternative fuels	Enables neighborhood-scale disconnection from gas and reduction of stranded assets; However, if distributed gas backup is used during transition, building-level gas infrastructure must be maintained, potentially delaying pruning timeline
Renewable fuels	Single central boiler/CHP can switch to alternative fuels; Simplified logistics; H2 production can result in directly usable waste heat	Distributed gas backup is more complex to transition; H2 waste heat integration may require intermediate exchange

5. Policy and Regulatory Considerations

The evidence in this report supports a regulatory approach built on several core principles:

1. **Set performance outcomes,** not technology mandates. Regulations can focus on objectives, including for GHG intensity and electric peak management, but should not prescribe network temperatures, technologies, or configurations.
2. **Require site-specific feasibility analysis**. Each project should demonstrate that the selected configuration is appropriate for local conditions relative to other options, using a transparent decision framework grounded in least-cost and least-risk resource planning principles.
3. **Enable the full range of low-temperature TEN configurations,** including moderate-temperature, ambient-temperature, and mixed-temperature networks, under a single regulatory and incentive framework.
4. **Identify mechanisms, programs,** and initiatives to support TENs to reduce emissions over time, while managing near-term costs and reliability.
5. **Recognize and compensate grid benefits,** including avoided electric grid upgrades, renewable electricity integration, and managed gas network transition, through incentive design and tariff structures that reflect the full value TENs provide to both electric and gas networks. These benefits may be site-specific and also differ across network configurations, but incentive designs and tariff structures that generally reward off-peak electricity use, incent use of surplus renewable generation, and reflect the value of avoided or decommissioned gas infrastructure may improve the value proposition of TENs.

6. Conclusions

Effective TENs policy and strategy involve identifying the right solution for each site, optimizing a resource-efficient pathway to low-carbon performance, and enabling a managed energy transition that delivers reliable, affordable, low-carbon heating and cooling.

This report supports the following conclusions:

1. **Moderate-temperature and ambient-temperature networks are complementary configurations** along a continuous temperature spectrum. The "generation" terminology should not be construed as implying that successive generations are inherently superior, and policy should not reinforce this framing.
2. **The optimal configuration depends on site-specific contexts,** including thermal density, building stock, heating/cooling demand overlap, available heat sources, rights-of-way constraints, electric and gas network conditions, and expansion plans.
3. **Both configurations can achieve deep emissions reductions through different resource mixes and timelines.** Both support phased emissions reductions coordinated with building-level requirements.
4. **Both provide benefits to electric and gas networks by reducing electric consumption and peaks and allowing for strategic pruning of gas distribution networks.** Configurations may differ as to the extent of flexibility enabled in the electric system and the timeline and mechanics of gas infrastructure rationalization.
5. **A technology-neutral policy framework with a resource-efficient phased approach to carbon reduction delivers superior outcomes:** expeditious deployment, lower costs, appropriate technology matching, and clear accountability for emissions performance.

The report suggests the following future directions for regulators and policymakers:

- Define TENs broadly and technology-neutrally in enabling regulations.
- Promote site-specific feasibility analysis using an evidence-based decision framework grounded in least-cost resource planning.
- Allow transitional peaking resources with declining GHG emissions over time and a defined low-carbon endpoint.
- Recognize grid benefits (electric and gas) in utility cost recovery and incentive design, including tariff structures that reflect avoided infrastructure costs.

- Enable consolidated ownership of both network and distributed equipment to ensure the network performs optimally and/or to aggregate load shifting to manage electric peaks where appropriate.
- Build engineering and workforce capacity for all network configurations.

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Appendix A. Case Studies

The following case studies illustrate how thermal energy networks operate across the low-temperature continuum. They demonstrate that moderate-temperature, ambient-temperature, and mixed configurations are not competing generations but context-specific system architectures. Each example highlights different technical, operational, and governance characteristics that inform site-appropriate design decisions. The case studies also provide evidence of phased emissions reduction strategies and grid integration benefits discussed in the body of this report.

A.1 Biberach an der Riß, Germany — Moderate-Temperature Network

Biberach an der Riß, located in southern Germany, is a moderate-temperature district heating system that has served an existing, dense residential neighborhood since 2022. The system is anchored by a centralized heat pump and three energy centers with a mix of heating technologies.

A.1.1 System Characteristics

- **Network type:** Moderate-temperature district heating
- **Supply temperature:** >140°F (60°C), with weather-compensated (outdoor temperature reset) control (refer to endnote 1)
- **Primary network heat sources:** Geoexchange, wood, wood pellets, and natural gas
- **Heat production:** Centralized heat pump, wood pellet furnace, natural gas furnace, and CHP
- **Distribution:** Insulated two-pipe network (heating only)
- **Storage:** 264,000-gallon (1,000 m^3) and 26,400-gallon (100 m^3) central thermal energy storage
- **Building integration:** Direct connection via heat exchangers (no building-level heat pumps required)
- **Building stock:** Existing buildings (retrofit)
- **Governance:** Strong municipal involvement

The system serves an existing residential district and was designed to allow phased expansion in network size and generation type, starting with natural gas and phasing into biomass and a central heat pump. It is an example of a retrofit-oriented neighborhood-scale deployment rather than a greenfield development. Biberach exemplifies the strengths of moderate-temperature networks in retrofit contexts. Existing buildings connect directly to the network, minimizing in-building equipment complexity and electrical capacity upgrades. The centralized plant benefits from non-coincident building peaks, reducing installed capacity relative to distributed systems. The architecture supported four incremental network extensions.

Biberach demonstrates that moderate-temperature networks are particularly effective for retrofit and high-density contexts with only heating needs, minimizing building-level complexity.

A.2 Dollnstein, Germany — Mixed-Temperature Network

The municipality of Dollnstein in Germany has operated a mixed-temperature TEN since 2014, with operational modes shifting seasonally. In winter, the system functions as a moderate-temperature heating network. In summer, it transitions toward ambient-temperature operation, allowing flexible integration of renewable heat sources.

A.2.1 System Characteristics

- **Network type:** Mixed-temperature (seasonally adaptive)
- **Winter supply temperature:** 150–165°F (65–75°C) (moderate-temperature heating)
- **Summer supply temperature:** 68–95°F (20–35°C) (ambient-temperature operation)
- **Primary network heat sources:** Geoexchange heat pump, solar thermal, backup natural gas, and CHP
- **Heat production:** Centralized and building-level booster heat pumps with seasonal control strategies
- **Storage:** 7,100-gallon central buffer, 4,000-gallon low-temperature storage, and 80-gallon buffer tank at each of the 24 end-users
- **Distribution:** Insulated network with seasonal control strategy
- **Scale:** 24 end-users, including public buildings and private homes
- **Building stock:** Existing buildings (retrofit)

The summer operation enables effective integration of solar thermal energy during appropriate periods. Rather than choosing between moderate-temperature and ambient-temperature configurations, Dollnstein incorporates both principles in a coordinated manner. The system directly supports the argument that temperature configurations exist on a continuum. Mixed-temperature systems are not theoretical; they are operational and increasingly common.

A.3 Vancouver, Canada — Moderate-Temperature Network

The False Creek Neighbourhood Energy Utility in Vancouver, BC, is a publicly owned district energy system serving the Olympic Village neighborhood and surrounding developments. It began operations in 2010 as part of the Vancouver Winter Olympics, initially serving the Athletes' Village (new construction). It is one of North America's most prominent examples of municipally led low-carbon district heating.

A.3.1 System Characteristics

- **Network type:** Moderate-temperature district energy (heating only)
- **Supply temperature:** Summer: 150°F (65°C); Winter: 150–195°F (65–90°C), weather-compensated based on outside temperature
- **Primary network heat source:** Sewage heat recovery
- **Heat production:** Centralized heat pumps located in a large central energy center
- **Peaking and backup:** Natural gas boilers (transitional)
- **Building stock:** New construction (original); ongoing extension to mixed new and existing buildings
- **Building integration:** Direct connection via heat exchangers (no building-level heat pumps required)
- **Ownership model:** City-owned utility
- **Expansion:** Ongoing extension to additional neighborhoods

The network serves residential and commercial units in a high-density urban redevelopment area. The system was designed for long-term expansion and has already undergone capacity upgrades (City of Vancouver 2020; 2022; 2023). The City of Vancouver acts as planner, investor, and operator, demonstrating the feasibility of municipal leadership in district energy. A large central energy center upgrades sewage heat and distributes it efficiently.

The False Creek Neighbourhood Energy Utility illustrates a phased approach to emissions reduction led by municipal policy. The system began operations in 2010 with sewage heat recovery providing low-carbon baseload and natural gas boilers for peaking, achieving approximately 70% renewable energy from the outset. Under the City's Climate Emergency Response (City of Vancouver 2019), the utility has set a target of 100% renewable energy before 2030. A decarbonization roadmap completed in 2024 identified options for fully transitioning peaking loads away from fossil fuels, and detailed feasibility analysis is now underway (City of Vancouver 2026). The centralized architecture enables staged fuel switching without requiring modifications at each connected building.

The False Creek Neighbourhood Energy Utility demonstrates that moderate-temperature systems can scale in dense urban contexts in North America and serve as long-term decarbonization pathway. It also shows that a phased approach—deploying proven low-carbon baseload first, then systematically addressing peaking—can deliver substantial early emissions reductions while preserving a credible pathway to zero emissions within a defined timeline.

A.4 Heerlen, The Netherlands — Ambient- to Mixed-Temperature Network

The Mijnwater district energy system in Heerlen, the Netherlands, is one of the most widely cited operational examples of an ambient-temperature network. The system distributes thermal energy at near-ambient temperatures through a shared loop and relies on decentralized heat pumps at each building connection to provide usable heating and cooling. Originally developed to repurpose flooded abandoned coal mines as a geothermal resource, the flooded mines now act as the system's thermal backbone. The system demonstrates how low-grade thermal energy can be integrated into a neighborhood-scale network architecture. Since its original development, new heating and cooling clusters have been added that are operated as a moderate-temperature four-pipe heating and cooling system, making the overall system a mixed-temperature configuration.

A.4.1 System Characteristics

- **Network type:** Originally ambient-temperature; now mixed-temperature (ambient backbone with moderate-temperature heating and cooling clusters)
- **Operating temperature (ambient sections):** Approximately 50–75°F (10–25°C)
- **Operating temperature (moderate-temperature sections):** Cold: 40–65°F (5–18°C); Heat: 85–120°F (30–50°C)

- **Primary network heat source:** Flooded mine water (low-grade geothermal resource) with supporting solar thermal and biomass-CHP
- **Energy transfer:** Bidirectional thermal exchange among buildings and storage reservoirs
- **Heat production:** Building-level booster heat pumps at each ambient connection and cluster heat pumps connecting ambient- and moderate-temperature sections
- **Building integration:** Heat exchangers plus booster heat pumps for ambient sections
- **Heating and cooling:** Integrated with a single distribution network backbone and direct heating and cooling clusters or sub-networks
- **Scale:** Approximately 250,000 m^2 (2.7 million sf) of connected floor area across four cluster grids, delivering roughly 20 TJ per year each of heating and cooling (Mijnwater B.V. 2020)
- **Building stock:** Mixed (new construction and retrofit)

The Mijnwater system serves a mixed urban district in Heerlen, connecting residential, commercial, and institutional buildings. By using mine water as a stable thermal reservoir, the system leverages local legacy infrastructure to create a long-term low-carbon energy asset.

In the original ambient-loop sections, the network circulates water close to ground temperature, minimizing distribution heat losses relative to higher-temperature systems. Building-level heat pumps upgrade thermal energy to usable heating temperatures (though initially buildings also retained their gas-fired boilers for backup). This contrasts with the added moderate-temperature clusters, where upgrading occurs centrally. The same infrastructure supports both heating and cooling: buildings requiring cooling reject heat into the loop, where it may be utilized by buildings with heating demand. Connected buildings act as both thermal consumers and suppliers, enabling bidirectional energy flows across the network. The connected building mix includes offices, a data center, educational facilities, and residential buildings, providing a diversity of heating and cooling loads with overlapping demand profiles. For example, waste heat rejected by the APG data center is recovered and used to heat the nearby Arcus College campus (Mijnwater B.V. 2020).

Mijnwater demonstrates the technical viability of ambient-temperature architecture in urban contexts where suitable low-grade thermal resources and overlapping heating and cooling demands exist, while also illustrating the versatility of mixed-temperature configurations when expanding the network. It also demonstrates that ambient networks may require gas distribution to buildings to support initial peaking needs, though such infrastructure may be phased out over time.

Together with the moderate-temperature and mixed-temperature case studies presented above, Mijnwater reinforces the central conclusion of this report: that optimal system configuration depends on local context rather than adherence to a specific "generation" label.

Table A-1. Case Study Summary

Feature	Biberach an der Riß, Germany	Dollnstein, Germany	Vancouver, Canada (False Creek NEU)	Heerlen, The Netherlands (Mijnwater)
Network Type	Moderate-temperature; heating only	Mixed-temperature (seasonally adaptive)	Moderate-temperature; heating only	Originally ambient-temperature, now mixed-temperature
Retrofit / New Build	Retrofit	Retrofit	New Build	Mixed (new construction and retrofit)
Heating / Cooling	Heating	Both	Heating	Both
Operating / Supply Temperature	>140°F (60°C), with weather-compensated (outdoor temperature reset) control	Winter: 150–165°F (65–75°C); Summer: 68–95°F (20–35°C)	Summer: 150°F (65°C); Winter: 150–195°F (65–90°C)	Ambient sections: ~50–75°F (10–25°C); Moderate-temp sections: Cold 40–65°F (5–18°C); Heat 85–120°F (30–50°C)
Primary Network Heat Source(s)	Geoexchange, wood, wood pellets, and natural gas	Geoexchange heat pump, solar thermal, backup natural gas, and CHP	Sewage heat recovery	Flooded mine water (low-grade geothermal) with solar thermal and biomass-CHP
Heat Production	Centralized heat pump, furnaces, and CHP	Centralized and building-level booster heat pumps with seasonal control strategies	Centralized heat pumps in a large central energy center	Building-level booster heat pumps at each ambient connection and cluster heat pumps connecting ambient and moderate-temperature sections

Table A-1. (continued)

Feature	Biberach an der Riß, Germany	Dollnstein, Germany	Vancouver, Canada (False Creek NEU)	Heerlen, The Netherlands (Mijnwater)
Building Integration	Heat exchangers	Building-level booster heat pumps activated in summer for DHW production when network temperatures are below direct-use thresholds	Heat exchangers	Heat exchangers plus booster heat pumps for ambient sections
Storage	264,000-gal and 26,400-gal central thermal energy storage	7,100-gal central buffer, 4,000-gal low-temp storage, and 80-gal tanks at each end-user	None	Repurposed abandoned coal mines as backbone storage
Key Context	Dense, heating-only retrofits with phased expansion	Small moderately dense village; existing buildings (retrofit)	High-density urban redevelopment; city-owned utility; phased emissions reduction pathway	Mixed urban district (new construction and retrofit); residential, commercial, and institutional

Appendix B. Site Selection Decision Framework

The following factors often inform technology selection for each TEN project. This report only discusses the trade-offs between low-temperature TENs configurations. It does not address selection criteria to determine if a site is more suited to a TEN rather than stand-alone, building-level heating/cooling provision. No single factor is determinative; the optimal configuration emerges from the balance of local conditions.

Table B-1. Site Selection Decision Framework

Factor	Favors Moderate-Temp	Favors Ambient
Heating & cooling balance	Heating-dominated or seasonally dominant heating and cooling	Overlapping/concurrent heating and cooling loads
Building stock	Existing hydronic buildings, retrofits, limited in-building space	New construction, modern envelopes, ample in-building space
Thermal density	High density, compact urban	Moderate density, campus-style
Available heat sources[a]	A few medium/high-grade waste heat sources	**Large number of low-grade sources, ground/water bodies, balanced prosumer loads**
Central plant space	Available	Constrained (distributed approach)
Electric grid capacity	Constrained (centralized load easier to manage and shift)	Less constrained (distributed heat pump load manageable)
Rights-of-way	Constrained (smaller pipe diameters)	Less constrained (larger diameters feasible)
Gas transition strategy	Centralized fuel-switch point; early building-level gas disconnection	Neighborhood gas disconnection timing depends on distributed backup strategy
Building types	Areas with mix of older and newer buildings	Areas with mostly new buildings
Future expansion	Large area, diverse phasing	Well-defined campus or development

[a] While both configurations can accommodate different heat sources, the location/balance of heat sources may affect optimal network configuration as discussed elsewhere in this report.

Mixed configurations may be advantageous when:

- the development includes diverse building type clusters
- multiple heat source temperatures are available
- heat sources are more distant from target buildings
- phased buildout spans many years
- different clusters have different heating/cooling profiles, or
- rights-of-way constraints vary across the service area

Endnotes

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[1] The 70°C (158°F) threshold refers to the general design intent and average operating temperature of the network, not an absolute operational ceiling. Many moderate-temperature networks use weather-compensated (outdoor temperature reset) control strategies that dynamically adjust supply temperature based on outdoor conditions. During typical conditions—which represent the vast majority of operating hours—supply temperatures may be well below 70°C (e.g., 50–55°C / 122–131°F). During peak cold events, supply temperatures may temporarily be raised above 70°C to deliver additional capacity through existing pipe infrastructure and to serve older buildings with higher-temperature distribution systems. This flexible operation is consistent with the 4G concept as originally defined by Lund et al. (2014), which identifies variable supply temperatures as a distinguishing feature of modern low-temperature networks. See also Rønneseth et al. (2019) for an empirical demonstration of weather-compensated operation.

[2] The report currently uses approximately 50°C (122°F) as the DHW/Legionella threshold. While 50°C is commonly cited in the district heating literature as the point where Legionella begins to die, most codes and standards (including the German DVGW W 551) require DHW storage at 60°C or higher and distribution above 55°C to ensure safe conditions at the tap after accounting for heat losses through the heat exchanger and building piping.

[3] This report only concerns the different strategies, benefits, and tradeoffs between low-temperature TENs configurations. It does not address selection criteria to determine whether a TEN is optimal for a given site in lieu of stand-alone non-networked heating and cooling provision, which is an essential first step.

[4] Ownership, operation, and maintenance by building owners can introduce additional risks for network operators, including inconsistent maintenance standards that degrade heat pump performance over time, uncoordinated operation that affects the thermal balance of the shared loop, and reduced ability for the network operator to provide demand response or grid-balancing services. For these reasons, many ambient-temperature network operators retain control over building-level heat pumps regardless of ownership structure.

[5] The word "prosumer" is a portmanteau of "producer" and "consumers." In the context of TENs, a prosumer would both offtake heating/cooling from a network and supply thermal resources to a network.

[6] Both the ambient backbone and the moderate-temperature sub-networks can independently integrate geothermal and waste heat sources. The decision as to which network element serves as the integration point depends on several technical and spatial factors. Temperature grade is a primary consideration. Higher-grade sources (e.g., deep geothermal wells producing water above 122°F (50°C) or liquid-cooled data centers with outlet temperatures reaching 150°F (65°C)) can be integrated directly into a moderate-temperature sub-network without temperature upgrading. Lower-grade sources (e.g., shallow geoexchange, air-cooled data center waste heat at 80–95°F (25–35°C), sewage heat recovery, or low-temperature industrial process cooling) can be integrated directly into an ambient backbone at or near their native temperature, preserving their thermodynamic value without the cost and efficiency losses associated with upgrading the thermal resources with a heat pump. The physical location of the thermal resource relative to the network also matters. A high-grade waste heat source situated along the ambient backbone route may be most efficiently connected there, even if its temperature could support a moderate-temperature sub-network because routing a separate moderate-temperature pipe to the source would add cost and complexity. Conversely, a high-grade source located near a building cluster served by a moderate-temperature sub-network is most logically connected at that point. In mixed-temperature systems, the network designer has the flexibility to match each thermal resource to the most appropriate integration point based on temperature, location, scale, and temporal availability (e.g., whether the source is continuous or intermittent). This flexibility is itself an argument for mixed-temperature configurations in districts where multiple thermal resources of varying grades are available at different locations. The decision may also be driven by existing infrastructure and operational experience. For example, some networks may start as moderate-temperature systems but add ambient-temperature extensions to integrate new low-temperature energy sources that are further afield. In other cases, moderate-temperature sub-networks may be added to an existing ambient-temperature loop to address challenges such as

borefield thermal imbalance, peak capacity constraints at the building level, or the need to serve older buildings with higher temperature requirements, while also reducing the aggregate cost of building-level heat pumps.

[7] Seasonal switching also introduces operational complexity during shoulder seasons (spring and autumn), when heating and cooling demands may alternate in quick succession or co-exist across different buildings on the same network. The network operator must manage the timing and rate of the temperature transition, and buildings may experience brief periods where the network temperature is not optimally suited to either mode. Some systems manage this through gradual temperature ramps over several days, while others define fixed seasonal switchover dates based on historical weather data. In either case, buildings may require supplementary heating or cooling capacity (e.g., small buffer tanks, electric resistance backup, or short-duration thermal storage) to bridge the transition period. Experience from the Dollnstein network in Germany, one of the first temperature-variable systems serving 35 existing buildings including heritage structures, confirms that such systems require ongoing operational optimization (Werner 2023). At Dollnstein, building-level heat pumps are idle during the winter heating season (when the network operates at 65–75°C, sufficient for direct heating and DHW) and are used primarily for domestic hot water preparation during the summer (when the network drops to 20–35°C). The operational risks of shoulder-season switching are a factor in deciding whether a seasonally variable network is appropriate for a given application, versus a year-round moderate-temperature or year-round ambient-temperature configuration.

[8] Mixed-temperature networks can capture two complementary forms of load diversity. On moderate-temperature sub-networks, centralized plant(s) can be sized below the sum of individual building peaks, the same diversity benefit available to standalone moderate-temperature networks. On ambient sub-networks, diversity is captured through demand overlap. If there are simultaneous heating and cooling loads, they offset one another, reducing the net thermal resource required from the network. At the system level, the interaction between the two sub-networks may provide additional benefits. For example, waste heat rejected by building cooling systems on the ambient loop can serve as a thermal resource for the moderate-temperature sub-network, reducing central plant sizing further. The net diversity benefit depends on the relative proportion of buildings on each sub-network and the degree of heating/cooling overlap.

[9] Pit storage can be used for both peak shaving and seasonal storage, but the most prominent examples are seasonal. An example of pit thermal storage is in Vojens, Denmark, which has a storage capacity of 200,000 m^3 (Solar Heat Europe, n.d.).

[10] Mijnwater's abandoned mine workings provide an unusually large and effective storage medium. Additional detail is provided in Appendix A: Heerlen, The Netherlands.

[11] Water-based TES (e.g., tank and pit storage) is the most mature and widely deployed option for thermal network peaking. However, a growing range of storage media and technologies can serve similar functions. For heating, these include solid-state sensible heat storage using sand (e.g., Polar Night Energy, Finland), ceramic bricks or rock beds, and crusite or concrete modules — all of which store heat at moderate to high temperatures and can be charged with surplus renewable electricity. Latent heat storage using phase change materials (PCMs) such as salt hydrates offers higher energy density in a smaller footprint and is suited to both centralized and distributed applications. For cooling, ice storage remains widely used for peak shaving in district cooling and building-level systems. Chilled water tanks provide lower-cost alternatives where there is sufficient available space. Emerging thermochemical storage (sorption and chemical reaction systems) offers very high energy density and near-zero standby losses but remains largely at pilot scale.

[12] For example, buildings on the Mijnwater network retained their gas boilers during the first phase of network development. However, building-level boilers were eventually phased out of the system. Additional detail is provided in Appendix A: Heerlen, The Netherlands

[13] Grid services available from TENs vary by configuration. Moderate-temperature networks with centralized production can provide: demand response (curtailing or ramping electric boilers and heat pumps in response to grid signals), load shifting (using thermal storage to move electric consumption away from peak periods), frequency regulation (fast-response electric boilers), and renewable energy absorption (converting surplus wind or solar electricity to stored heat). Ambient-temperature networks can provide some of these services through coordinated heat pump scheduling, though the distributed nature of heat pumps makes aggregation more complex. The value

of these services depends on local electricity market structures, grid conditions, and the availability of thermal storage.

[14] In Aarhus, Denmark, the district heating system's 110 MW electric boiler and 60,000 m³ thermal storage tank absorb surplus wind energy, providing grid-balancing services worth millions of euros annually while decarbonizing heat supply (Kortegaard Støchkel 2024).