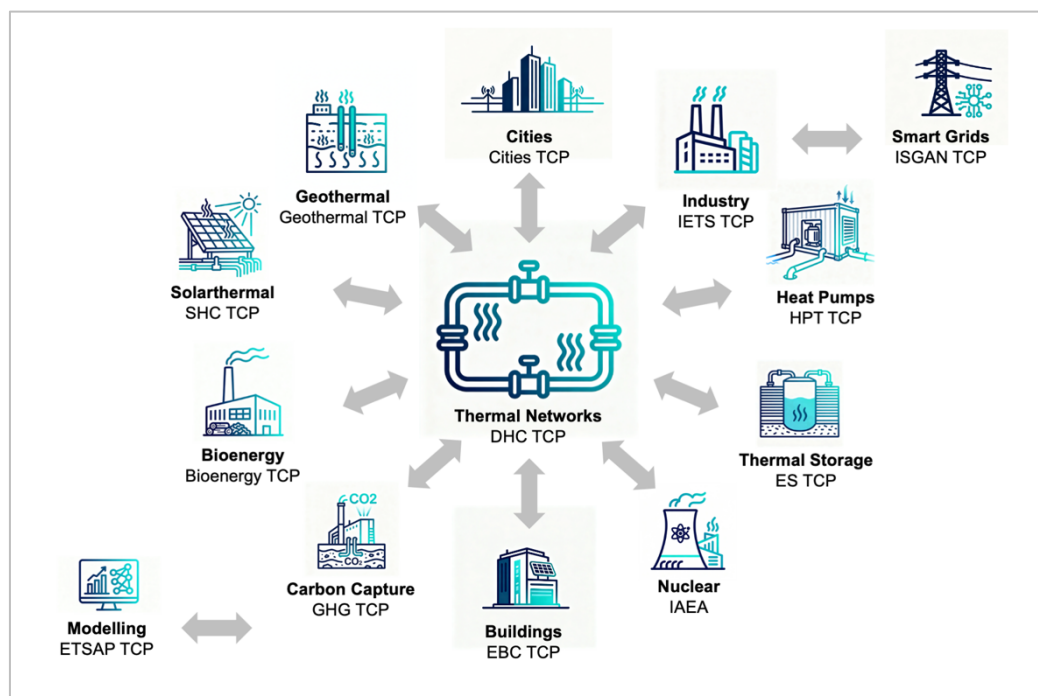




INTERNATIONAL ENERGY AGENCY

TECHNOLOGY COLLABORATION PROGRAMME ON

DISTRICT HEATING AND COOLING



A JOINT REPORT FROM THE PERSPECTIVE OF
11 INTERNATIONAL ENERGY AGENCY TECHNOLOGY
COLLABORATION PROGRAMMES (IEA TCPs)

THERMAL NETWORKS: EMPOWERING THE SMART TRANSITION TO NET-ZERO

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- **Bioenergy TCP** – focusing on sustainable bioenergy production and integration (ieabioenergy.com)
- **Cities TCP** – addressing city-scale implementation (cities-tcp.org)
- **Energy in Buildings and Communities TCP** – covering building-related aspects (iea-ebc.org)
- **Energy Storage TCP** – addressing thermal energy storage (www.iea-es.org)
- **Energy Technology Systems Analysis Programme (ETSAP TCP)** – providing systems analysis and modelling (iea-etsap.org/)
- **Geothermal TCP** – contributing geothermal heat integration expertise (iea-gia.org)
- **Greenhouse Gas R&D Programme** – covering carbon capture integration (ieaghg.org)
- **Heat Pumping Technologies TCP** – focusing on heat pump integration (heatpumpingtechnologies.org)
- **Industrial Energy-Related Technologies and Systems TCP** – covering industrial integration (iea-industry.org)
- **International Smart Grid Action Network TCP** – focusing on smarter, cleaner, and more flexible electricity grids (iea-isgan.org)
- **Solar Heating and Cooling TCP** – addressing solar thermal systems (iea-shc.org)

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EXECUTIVE SUMMARY:

THERMAL NETWORKS FOR NET-ZERO, SECURITY, AND JOBS

What are thermal networks?

Underground insulated pipes can deliver low- or zero-carbon heating and cooling to entire neighbourhoods, campuses, and industries using a mix of renewables, excess heat, and storage.

Why now?

- **Urgency:** To enable widespread well-being and prosperity, the world must stabilize the global climate by becoming carbon neutral. Heating and cooling are responsible for a substantial portion of global greenhouse gas (GHG) emissions.
- **Momentum:** District heating and cooling systems are growing in Europe, Asia and America. The share of district heating and cooling supply from renewable and waste heat sources is growing.
- **Resilience:** Networks absorb and store surplus wind and solar, buffer electricity peaks, diversify supply and keep cities resilient during crisis or extreme weather.

Key benefits

- **Decarbonization:** Replace fossil fuels at city and industry scale, with more than 90% greenhouse gas reductions possible despite embedded carbon emissions and fossil fuels in electricity generation.
- **Jobs:** Investments create local, skilled jobs in construction, operations, digital infrastructure, and supply chains.
- **Security:** Aggregating multiple diverse energy sources reduces reliance on fossil and renewable imports and buffers price shocks.
- **Affordability:** Economies of scale lower long-term costs, stabilize bills, and reduce exposure to price volatility.
- **Clean air:** Centralizing generation and minimizing in-building combustion sharply reduces urban air pollution and health risks.
- **Flexibility:** Compatibility with solar, geothermal, biomass, waste/ambient heat, heat pumps, nuclear and future-ready for Power-to-X and Carbon Capture Storage.



HIGH-LEVEL EXECUTIVE SUMMARY FOR GLOBAL POLICYMAKERS

Heating and cooling account for more than half of global final energy use and represent a major share of greenhouse gas emissions and local air pollution. Without a rapid transformation of thermal systems, global climate, energy security, and development goals cannot be achieved.

Thermal networks – modern district heating and cooling systems with integrated storage and smart controls – offer a proven pathway to deep, scalable, and socially just decarbonisation of the thermal sector. By aggregating demand across buildings and industries and connecting multiple sources – renewables, waste heat, and efficient heat pumps – they turn fragmented infrastructure into a flexible, resilient backbone for net-zero systems.

Evidence from Europe and China shows that existing district heating already contributes massively to decarbonization with up to 94% lower greenhouse gas emissions.

To capture this opportunity, **the global policy community should prioritise:**

- **Explicit thermal decarbonisation strategies:** Place heating and cooling – and thermal networks in particular – at the centre of national energy and climate strategies, NDCs, long-term strategies, and just transition plans.
- **Mandatory, well-resourced local heating and cooling plans:** Require cities and regions to map demand, identify renewable and waste-heat potentials, assess network zones and building-scale options, and translate plans into concrete investment pipelines, with the required technical and financial support.
- **Acceleration of clean thermal infrastructure:** Streamline permitting for thermal networks, large-scale storage, and renewable and waste-heat connections; phase out fossil subsidies; and align market rules with efficient, low-carbon operation.
- **Integrated system planning and sector coupling:** Coordinate electricity, gas, and thermal planning so that thermal networks absorb surplus renewables, reduce peak electricity demand, and enable smart electrification rather than grid stress.
- **People-centred design and local value creation:** Embed citizen participation, consumer protection, and local job strategies into every major thermal network investment to ensure public acceptance, fair distributional impacts, and long-term political durability.

If these actions are taken this decade, **thermal networks can become a cornerstone of net-zero pathways**, delivering climate mitigation, energy security, clean air, and local jobs at scale.



DETAILED SUMMARY (KEY MESSAGES)

- **Thermal networks (district heating and cooling) are essential for a stable climate and global well-being.**
 - Heating and cooling represent over half of global final energy use and are a major source of global emissions.
 - District heating already contributes significantly to decreased greenhouse gas emissions and resource efficiency. In some countries it already achieves almost carbon neutral heat supply.

Table 1: Savings from District Heating in Europe and China in 2022 in Comparison to a Hypothetical Heat Supply from Natural Gas Condensing Boilers (Jentsch, 2025)

GHG Emissions Avoided	Resource Exergy ¹ Savings
More than 69 Million Tonnes CO₂ equivalents saved in 2022 vs. natural gas boilers = 27 Million Cars Off the Road	More than 635 TWh Resource Exergy saved in 2022 vs. natural gas boilers = 73 000 Large Wind Turbines
Up to 94% GHG emissions avoided by district heating vs. natural gas boilers in 2022	Up to 37% resources saved by district heating vs. natural gas boilers in 2022

- In addition to their already impressive sustainability performance in comparison to fossil boiler technologies, district heating and cooling systems consistently move toward carbon neutrality as fast as local conditions allow.

¹ Resource exergy is a physically consistent extension of primary energy that accounts for both quantity and quality of energy resources. It is particularly suitable for thermal networks, as it properly reflects temperature levels, storability and losses along the chain from resource to useful heat, enabling a fair comparison of fossil, nuclear, renewable, waste heat and electrified solutions. The applied Resource Exergy Analysis (REA) method is explained transparently in Jentsch, 2023.



- **Thermal networks support energy security and resilience.**
 - By using a multitude of energy sources efficiently the demand for energy imports can be decreased thus promoting supply independence and energy security.
 - Combined heat and power plants can provide heating and cooling during power outages thus improving resilience of the connected communities.
- **Thermal networks enable smart electrification.**
 - Electrification of many sectors – including transport, industry and part of the heating and cooling sector – challenges the stability of electricity grids. Thermal networks minimize the need for excessive electricity grid upgrades.
 - They ensure that thermal sources that would be lost instead help to minimize need for additional electricity production.
- **Thermal networks promote equitable cost-sharing and broader access to clean heating and cooling.**
 - By pooling infrastructure investments across many users, thermal networks can lower individual financial burdens and enable fair distribution of capital and operational costs.
 - This collective approach supports inclusive participation—from large industrial users to low-income households—enabling energy affordability while maximizing social benefits and reducing energy poverty.
- **Smart infrastructure investments deliver rapid, lasting benefits.**
 - Every investment in thermal networks supports skilled local jobs, protects public health by reducing combustion emissions, and can provide stable, predictable energy bills.
 - Centralized systems are able to unlock efficiencies in heating and cooling production and distribution that are not possible with individual building solutions.



- **Flexibility makes net-zero and energy security feasible.**
 - Thermal networks allow cities and industries to use a mix of sustainable sources—solar, geothermal, industrial waste heat, and heat pumps—maximizing renewable integration and minimizing vulnerability to price shocks.
 - Large-scale thermal storage lets cities “bank” cheap or surplus energy, stabilizing supply during weather or market disruptions while minimizing the need for peak load production capacity.
- **Sector coupling and digital management multiply impact.**
 - Modern district systems link electricity, heating, and cooling, absorbing excess renewables and buffering demand, helping balance local and national energy grids.
 - Digital controls and planned upgrades are key to unlocking these benefits.
- **Barriers remain, but solutions exist.**
 - The biggest challenges are upfront investment costs, fragmented regulation, and legacy incentives for fossil boiler systems.
 - Proven approaches include targeted public/private funding, streamlined permitting, and fossil phase-out policies.
- **Immediate policy actions can drive rapid change and spread benefits.**
 - Mandate city-level heating/cooling plans, accelerate investment and permitting process for large thermal storage and renewable heat connections.
 - Integrate energy justice and job creation into every heat network project for maximum social and economic benefit.

- **Thermal networks enable net negative GHG emissions**
 - Carbon Capture and Storage (CCS) is only possible at comparably large plants. Thermal networks enable heat generation from biomass in combination with CCS which leads to negative greenhouse gas (GHG) emissions.
 - Thermal networks furthermore enable use of the extra heat generated by the CCS and thereby economically support the option to capture carbon from biomass-based heat and power generation or liquid fuel production.
- **Thermal networks are unique enablers that multiply the value of all clean energy and heating technologies.**
 - By connecting and integrating solutions like solar thermal, geothermal, large-scale heat pumps, carbon capture, bioenergy, industrial waste heat, energy storage, and nuclear, thermal networks create synergies, maximize system efficiency, and ensure every technology can contribute to climate, energy, and community goals.
 - This systemic approach turns what would be isolated projects into a cost-effective, resilient, and sustainable energy backbone—making the whole greater than the sum of its parts.

Bottom line:

Thermal networks are a backbone of the just energy transition, bringing climate and cost benefits to millions—if cities and governments act quickly with clear direction and support.



Barriers and solutions

- **Upfront cost:** Targeted public/private finance, streamlined permitting procedures, and phasing out fossil subsidies.
- **Efficiency and energy sources:** Thermal losses from thermal networks could have an impact on overall efficiency of the system. Lack of low carbon and low-cost energy sources could be another barrier.
- **Legacy systems:** Gradual, staged upgrades, digital metering, and integration of new storage solutions.
- **Policy:** Strong city-led mandates, clear targets, reliable policy frameworks, sector integration, and active citizen engagement.

Priority actions

- **Mandate** city/local heating and cooling plans for all urban centres.
- **Accelerate** renewable and waste heat connection, and investment in large thermal storage.
- **Digitize** and empower flexibility across heating, cooling, and electricity sectors.
- **Prioritize** energy communities, just transition, and local value creation in all projects.

Conclusion:

Thermal networks are the “hidden champion” behind net-zero, local jobs, and energy security—turning complex system integration into visible comfort, stable bills, clean air, and strategic resilience. All funding invested in thermal networks where they are economically feasible delivers lasting economic, climate, and social returns to communities across the globe.

Recommendation: Conserve, Connect, Convert!

1. **Conserve** by cutting demand through efficient buildings, smart controls, and lower temperature operation in networks.
2. **Connect** more buildings and waste-heat sources to district heating and cooling grids to improve economic viability and flexibility.
3. **Convert** existing systems from fossil fuels to efficient use of renewables, waste heat, and heat pumps to decarbonize supply.



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GLOSSARY

The glossary provides brief explanations of key concepts and terms used throughout this report to support readers from diverse backgrounds. It is alphabetically ordered to make it easy to quickly locate unfamiliar expressions while reading. Together with the executive and detailed summaries, it is intended to help decision makers, practitioners, and researchers navigate the technical content with confidence. Citations in this glossary without years refer to the general work of an International Energy Agency Technology Collaboration Programme (IEA TCP).

Bioenergy

Renewable energy obtained from biomass such as wood chips, biogas, and organic residues. When used in modern, well-controlled plants, bioenergy can provide dispatchable low-carbon heat and electricity to thermal networks, especially when combined with advanced emission controls and sustainable sourcing frameworks (Source: IEA Bioenergy).

Carbon Capture and Storage (CCS)

A set of technologies that capture CO₂ from large point sources (such as power plants or industrial facilities) and store it in geological formations. In combination with biomass (BECCS), CCS can enable net negative emissions, and thermal networks can utilise the additional heat generated in capture processes (Source: IEA GHG).

Combined Heat and Power (CHP)

Highly efficient plants that generate electricity and useful heat at the same time. When connected to thermal networks, CHP plants increase overall energy efficiency and can support both heat supply and power system stability, especially when integrated with storage and flexible operation strategies (Source: IEA DHC).

Geothermal Heat

Heat extracted from underground reservoirs of hot water or rock. Geothermal sources can provide stable, low-carbon heat to thermal networks, particularly when combined with lower network temperatures and appropriate drilling and integration strategies (Source: IEA Geothermal).



Heating and Cooling Plans (Thermal Energy Planning)

Strategic, spatially explicit plans that map current and future heating and cooling demand, identify areas best served by district systems versus individual solutions, and define pathways for decarbonisation. Such plans are a key instrument for aligning local infrastructure development with climate and energy goals (Source: IEA DHC).

IEA Technology Collaboration Programmes (IEA TCPs)

IEA Technology Collaboration Programmes are long-term, international research and cooperation frameworks under the auspices of the International Energy Agency that bring together governments, industry, and research organisations to advance specific energy technologies. Each TCP focuses on a particular domain (such as district heating and cooling, bioenergy, heat pumps, energy storage, buildings, cities, or smart grids), coordinating joint projects, knowledge exchange, and dissemination of best practices to accelerate innovation and support evidence-based policymaking (Source: IEA).

Large-Scale Heat Pumps

Electricity-driven devices that upgrade low-temperature heat (e.g. from rivers, lakes, wastewater, or ambient air) to useful temperature levels for heating and cooling. In thermal networks they enable efficient use of renewable and waste heat sources and help integrate variable renewable electricity (Source: IEA HPT).

Negative Emissions / BECCS

Net removal of CO₂ from the atmosphere achieved by combining sustainably sourced bioenergy with carbon capture and storage (BECCS). Thermal networks can use the heat from BECCS facilities, improving the economic feasibility of large-scale negative emission projects (Source: IEA Bioenergy).

Resource Exergy

An energy metric that accounts for both the quantity and the quality (temperature and usability) of energy resources. It provides a more physically consistent comparison of different heating options than primary energy alone and is particularly suitable for analysing thermal networks (Jentsch, 2023).

Sector Coupling

The coordinated planning and operation of electricity, gas, and thermal systems to increase efficiency, flexibility, and renewable integration. Thermal networks play a central role in sector coupling by connecting heat, power, and sometimes industry and transport through technologies like CHP and power-to-heat (Sources: IEA DHC, IEA HPT, IEA ISE).



Smart Electrification of Heat

Electrification strategies that use flexible technologies, storage, and thermal networks to minimise stress on the power grid. Smart electrification allows thermal networks and heat pumps to absorb surplus renewable electricity and reduce peak demand, instead of driving grid congestion and costly reinforcements (Source: IEA ISGAN).

Solar Thermal

Technologies that convert solar radiation directly into heat, typically using collectors and storage. When integrated into thermal networks, solar thermal fields can supply significant shares of low-carbon heat, especially in combination with seasonal storage (Source: IEA SHC).

Thermal Energy Storage (TES)

Systems that store heat or cold for later use, including large hot-water tanks, pits, and underground formations. TES combined with thermal networks enables daily, weekly and seasonal shifting of heat production, higher renewable shares, and reduced peak load requirements (Source: IEA ES).

Thermal Networks (District Heating and Cooling)

Insulated pipe systems that deliver heating and/or cooling from one or more central sources to multiple buildings or industrial users. Modern thermal networks integrate a wide range of renewable, waste-heat, and efficient technologies and are increasingly designed for lower operating temperatures (Source: IEA DHC).

Thermal Source Network

Thermal source networks are interconnected systems that collect, manage, and distribute multiple low-temperature and low-carbon heat and cold sources to one or more thermal grids or users through shared infrastructure and control. They link diverse sources such as ambient heat, wastewater, rivers, lakes, geothermal reservoirs, industrial waste heat, and renewable heat plants, and make them accessible to district heating and cooling systems or building-scale heat pumps under coordinated operation. By pooling and optimising these sources, thermal source networks increase flexibility, raise the share of renewables and waste heat in thermal supply, and reduce dependence on fossil fuels, while enabling smart integration with electricity and other energy sectors (IEA DHC, 2024)



Waste Heat

Heat that would otherwise be released to the environment from industrial processes, data centres, power plants, wastewater systems, or other sources. Thermal networks make it possible to capture and re-use this heat for buildings and industry, reducing fuel consumption, emissions, and cooling needs (Source: IEA DHC).



1 INTRODUCTION

Cities and industries face unprecedented challenges in decarbonizing their heating and cooling systems, which today account for more than half of total energy use and a major share of local air pollution and carbon emissions. With global climate targets tightening, energy security gaining urgency, and electrification and renewables reshaping energy markets, the question is no longer if, but how communities should overhaul the systems keeping their buildings comfortable, their businesses running, and their communities resilient.

Thermal networks—also known as district heating and cooling (DHC) or district energy—use a system of insulated pipes to deliver heating and cooling to multiple buildings from one or more centrally managed sources. They are a key element of a successful global transformation towards sustainability.

By aggregating the needs and strengths of thousands of buildings and diverse energy sources, thermal networks make possible what isolated systems cannot: the large-scale, efficient use of renewables; deep recovery of industrial and digital waste heat; cost-effective storage of seasonal energy surpluses; and the flexible coupling of heat, power, and green industry.

Modern thermal networks can:

- Deliver **clean, affordable heating and cooling** to millions of homes, schools, offices, hospitals, and industries worldwide.
- Enable deep integration of solar, geothermal, biomass, large-scale heat pumps, carbon capture, and waste heat—**raising renewables' share** in heating/cooling to more than 60% in leading cities.
- **Support** energy justice, reliable supply, and **local economic development** by offering stable prices, job creation, and improved urban air quality.
- **Provide** critical infrastructure for **net-zero** transitions, acting as a system buffer, “energy sponge,” and reliability backbone during energy market shocks and climate-driven extremes.

This document draws on technology expertise from IEA's Technology Collaboration Programmes (TCPs) and on leading European and global case studies to highlight the benefits that thermal networks bring to society. It translates this expert input into actionable advice for leaders across government, utilities, industry, and the public sector.



2 BENEFITS OF THERMAL NETWORKS

2.1 ENVIRONMENTAL BENEFITS

Thermal networks (district heating and cooling) can significantly reduce pollution and greenhouse gas emissions (JRC, 2023; Euroheat & Power, 2023).

A recent study found that **69 million tonnes of GHG emissions** (equivalent to **27 million cars** off the road)² and **635 TWh of resource exergy**³ (equivalent to avoiding the need for installation of **73 000 large windmills**) were **saved in 2022** in 10 European countries and China by district heating in comparison to natural gas condensing boilers (Jentsch, 2025).

All technologies presented in this played a role in achieving this impact. With increased focus on decarbonisation and more thermal networks being deployed, the savings thermal networks and their connected technologies bring to sustainability are set to increase.

How is this achieved?

- **Highly efficient technologies:** District heating already saves millions of tons of greenhouse gas emissions and hundreds of terawatt hours (TWh) of resource exergy consumption. In addition to the use of low-carbon fuel sources, this is largely achieved through application of fossil and renewable cogeneration and recovery of waste heat from fossil fired processes.
- **Economies of scale:** Centralized generation enables the use of large, highly efficient boilers, CHP plants, or renewable technologies that are much more effective than smaller, building-level solutions. Economies of scale means bigger plants or

² Jentsch, 2025 (see full reference in the “References” section) provides all details to transparently support these numbers.

³ Resource exergy can be considered an advanced primary energy metric. In addition to accounting for all energy used to provide a supply it considers the temperature-dependent energy quality of heat. This enables a more comprehensive and scientifically accurate accounting of the benefits of heating and cooling systems than a primary energy analysis can provide. The applied Resource Exergy Analysis (REA) method is documented transparently in Jentsch, 2023.



- **Aggregated and diverse demand:** By supplying many types of buildings at once—residential, commercial, industrial—a thermal network smooths the combined pattern of demand, resulting in fewer peaks and greater efficiency. This makes system operation more predictable and allows more stable use of all production assets (VCTN, 2024).
- **Load shifting and flexibility:** When paired with thermal storage and heat pumps, district energy operators can shift heat generation to off-peak hours or align it with periods of excess renewable electricity supply. This provides flexibility for both the heat and power systems, supporting integration of more variable renewables and stabilizing the grid (JRC, 2023).
- **Any available thermal source:** Networks can flexibly use sources that are difficult to tap at the building scale, such as waste heat from factories, sewage, data centres, and power plants, or large geothermal plants and solar-thermal arrays—all of which produce heat at a lower or zero-carbon level (Graff et al., 2023). Even heat pumps can be integrated into thermal networks using energy sources such as rivers, lakes, the sea or low-temperature waste heat that would otherwise be unavailable to individual buildings, and instead been rejected to the surroundings.

2.2 ECONOMIC BENEFITS

Thermal networks deliver substantial economic benefits to providers, consumers, and the local economy (JRC, 2023).

- **Reduced initial and maintenance costs:** Centralized generation and distribution means fewer and larger plants to maintain, which can result in lower repair costs, and no need for each building to have or maintain its own boiler, furnace, or air conditioning system (Euroheat & Power, 2023).
- **Long-term operational savings:** By tapping into waste heat, renewable sources, and efficient technologies, such as heat pumps, heat supply costs fall relative to fuel based decentralized systems. These savings also provide flexibility services for the broader energy system, enabling thermal networks to act as “energy sinks” at times of excess electricity and as a “source” when electricity is scarce or expensive.
- **Support for local jobs and economic growth:** Investments in district energy infrastructure create construction, operation, and engineering jobs and keep more of the money spent on heating local (IEA DHC, 2024).



- **Protection from fuel imports and price swings:** By using a mix of energy sources with a strong emphasis on local resources, cities and countries reduce their need for imported, often price-volatile fossil and renewable fuels (Green Energy Association, 2018).
- **Regional reinvestment:** The operational costs (labour, materials, upkeep) of thermal networks are typically sourced locally, ensuring a significant portion of revenue from heat sales circulates within the area.
- **Reduced energy poverty:** Frequently lower, more stable heating and cooling life cycle costs from efficient networks support inclusion and make reliable comfort available to all income levels (Energy Cities, 2022).

2.3 SOCIAL BENEFITS

- **Energy security and reliability:** Thermal networks allow for diversified energy supply, cutting reliance on singular fuel types, and improve reliability. If one source fails, others can be ramped up, decreasing the likelihood and impact of supply interruptions (Gudmundsson et al., 2020).
- **Public health and comfort:** Central systems eliminate in-building combustion without need for considering local electricity grid upgrades. This removes local air emissions and associated health risks, making urban air cleaner and buildings quieter, safer, and more comfortable (C40, 2022a; C40, 2022b).
- **Reduced risk and maintenance burden:** Building owners enjoy lower insurance costs, reduced fire risk, and less maintenance versus managing on-site combustion and fuel storage.

2.4 TECHNOLOGICAL SYNERGIES

- **Combine many technologies:** Networks can pair traditional efficient generation, such as CHP, with new solutions. Large-scale heat pumps, for example, allow the use of low-temperature heat sources (such as rivers or wastewater) to deliver heat at scale (IEA HPT TCP, 2024).
- **Buffer with storage:** Thermal energy storage—often in the form of large hot water tanks, pit thermal energy storage or underground caverns—lets cities store renewable or cheap heat for later use, smoothing peaks, storing solar heat for winter, or providing backup during outages.



- **Moderate grid loads:** Well-integrated district energy systems can help the power grid during periods of extreme demand, acting as controllable “sponges” for surplus electricity or letting stored heat be used to replace electric heating during electricity demand peaks (Schmidt & Lygnerud, 2021).
 - *A regional analysis carried out in Ontario, Canada demonstrates the importance of an overall strategic approach: an all-electric scenario with air-source heat pumps supplying every home indicates a future electricity peak demand of 80 GW in Ontario, Canada whereas the use of 70% district energy and 30% air-source heat pumps can limit this to 30 GW (Green, 2024).*

2.5 RESILIENCE

- **Robust and redundant infrastructure:** Modern networks are laid out with loops and backup plants, making them highly resilient to outages or extreme weather. Service reliability often exceeds 99.99%, and emergency backup systems can be deployed to ensure critical supply is never interrupted (Gudmundsson et al., 2020).
- **Urban quality:** Replacing building boilers, chimneys, fans and cooling towers with low- or no-emission central sources frees up valuable building space in cities and makes for cleaner, quieter, and safer urban environments.

2.6 THERMAL NETWORK OR INDIVIDUAL BUILDING HEATING?

- The cost benefit of district heating over decentralized solutions strongly depends on the systems compared, the relation of heating and cooling needs, national regulations, capital investments and energy prices, so that individual life cycle cost comparisons are always required for an informed decision on the most economically sensible heating system.
- In densely populated urban environments district heating in many cases provides a more cost-effective solution than using individual heat pumps when full costs for building heating are considered for both electrification and thermal network solutions (generation, transmission, distribution, building conversion), especially if there are heating needs only (no cooling need).



- *In some countries, such as Denmark, district heating is generally the most economical solution, as was demonstrated (Gudmundsson, 2020). For 4 900 MWh/a the cost of district heating was a total of 1 100 €/a while heat from individual air-to-water heat pumps cost 2 000 €/a. This shows that the economic viability of district heating largely depends on the political boundary conditions rather than on technology costs itself.*
- In low heat demand density areas, such as villages or suburbs, decentralized solutions, such as using individual heat pumps, are likely to be more cost-effective. Which means that district heating and cooling can well synergize with efficient decentralized solutions such as heat pumps.

Of great importance is the fact that, while all electricity sources can be used for thermal generation via heat pumps or direct electrical heating, thermal networks can also include renewable heat from solar or geothermal sources as well as waste heat from industry, waste incineration and electricity production – all lower quality sources that usually are not useable for electricity production. Not connecting those low-grade sources to thermal networks therefore often means significantly increased load on the electricity grid, which in turn leads to higher electricity prices, higher greenhouse gas emissions and more resource consumption.



3 THE BENEFITS OF THERMAL NETWORKS TO OTHER IEA TCPs

In the following, the benefits of thermal networks to the technologies covered by IEA Technology Collaboration Programmes (TCPs) are listed. Figure 1 shows the TCPs considered.

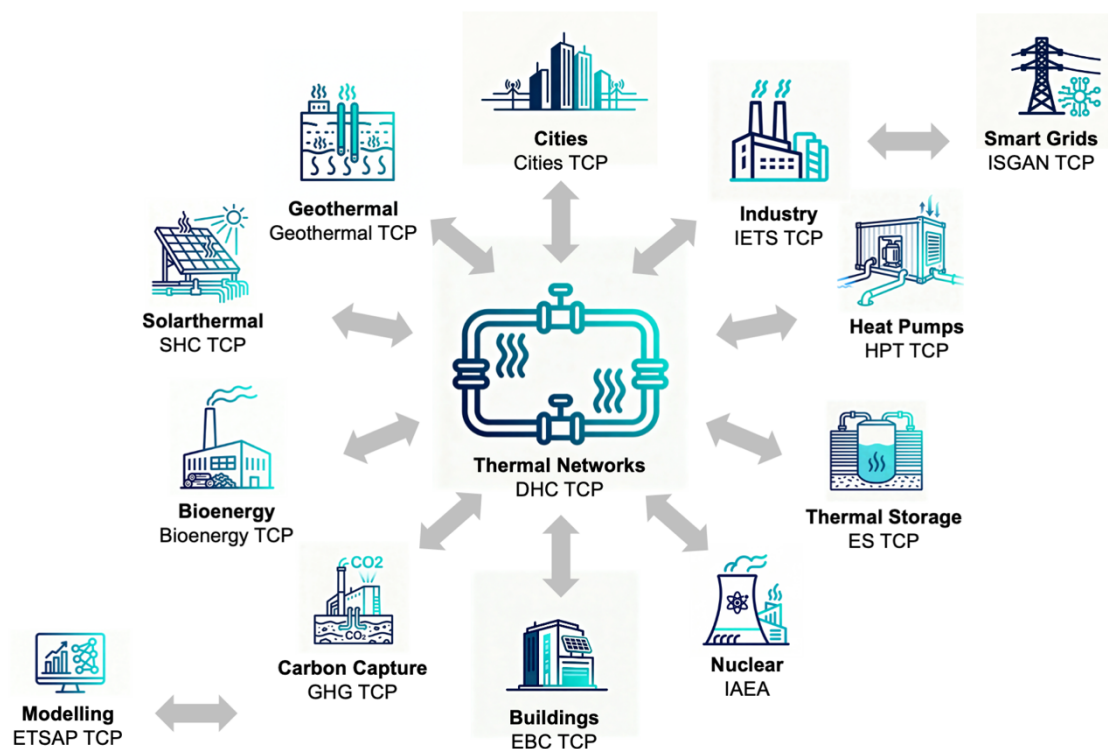


Figure 1: Overview over technologies and the involved IEA Technology Collaboration Programmes (TCPs) and organisations that are empowered by thermal networks

This document is based on an initiative of IEA DHC (also DHC TCP) – the International Energy Agency Technology Collaboration Programme on District Heating and Cooling. While IEA DHC promotes international research with a focus on thermal networks and their connections to other technologies, the technology-centric TCPs enable in-depth research into specific technologies that can be connected to and integrated with thermal networks.

In the following subchapters the technologies are sorted alphabetically with the TCP acronym matching the topic in brackets. Some technologies are not the focus of IEA TCPs but have been covered in addition to provide a more complete overview. In this case, the acronym of the organization responsible for that technology is given in brackets after the title. IEA DHC is only listed in brackets, if no other TCP covers this technology too.



3.1 BUILDINGS (EBC TCP)

Buildings and communities play a central role in the energy transition. While traditionally viewed only as energy consumers, their aggregated flexibility and interaction with thermal networks make them key assets for system efficiency and decarbonisation. By connecting buildings through district heating and cooling networks, their energy demand can be coordinated, optimized, and balanced at scale—turning them into active contributors to system reliability and low-carbon transformation.

Key benefits

- **Energy flexibility and load shifting:**

Connected buildings can adjust and shift heating and cooling loads according to system needs, reducing peak demand and enabling better integration of variable renewable sources.

- **Efficient demand management:**

Smart control systems and thermal storage in buildings help coordinate thousands of energy users collectively, stabilizing energy flows and improving overall system performance.

- **Digital coordination and automation:**

Advanced digitalisation enables predictive operation and automated control of flexible heat loads, maximizing efficiency in multi-building or neighbourhood-scale systems.

- **Equitable cost-sharing:**

Coordinated operation in district systems allows shared infrastructure costs and fair tariff structures that improve access and affordability for households and communities.

- **Rapid decarbonisation:**

District heating solutions offer a powerful pathway for the quick decarbonisation of buildings and neighbourhoods, combining renewable heat sources, waste heat utilization, and efficient collective infrastructure.



Thermal networks thus transform buildings and neighbourhoods into energy-flexible hubs that provide stability, accelerate decarbonisation, and enable inclusive participation in the clean energy transition.

3.2 BIOENERGY (BIOENERGY TCP)

Modern bioenergy uses sustainably sourced biomass fuels (such as wood chips, biogas, and organic residues) to provide renewable heat for buildings and industry, making it highly relevant for decarbonising district heating networks (IEA Bioenergy, 2024; IRENA, 2017). When converted in modern combined heat and power plants, bioenergy can efficiently feed thermal networks. In general, bioenergy can provide dispatchable, low-carbon heat that can complement variable renewables and waste heat sources (IEA Bioenergy Task 32, 2019; IEA Bioenergy Task 32, 2021). If biomass is sourced and governed sustainably, and advanced combustion and emission-control technologies are used, bioenergy can significantly cut fossil fuel use while maintaining low air pollutant emissions (IEA Bioenergy Task 32, 2021; Nussbaumer, 2024).



Figure 2: Brønderslev Biomass CHP plant and solar thermal field, Denmark
(Source: niras.com, Case study details in: IEA TNCG, 2025)

- **Thermal networks enable strategic, system-level use of biomass.**

They allow biomass to fill vital supply gaps that cannot be consistently met by other renewables, such as periods with little sunlight or wind, and to provide reliable backup for variable loads. Integrated with thermal storage, networks optimize the contribution of biomass and make it possible to maintain clean, uninterrupted energy services year-round (Hansen et al., 2019).

- **Thermal networks centralize combustion, unlocking higher efficiency and dramatically reducing air pollution.**

Old or poorly operated individual stoves, pellet stoves and boilers may be inefficient, emit more pollutants, and create greater local truck traffic for fuel delivery than larger, automated plants. By aggregating demand and combustion of biomass in large, combined heat and power (CHP) plants feeding a network, cities can deploy advanced combustion concepts as well as secondary measures (filters and flue gas cleaning systems that are often too expensive or cumbersome for single buildings, achieving much lower emissions and streamlined supply logistics (Nussbaumer, 2024).

- **Modern thermal networks empower ultra-low-emissions biomass use.**

Technical advances in large-scale combustion control and filtration allow centralized biomass plants to reach very high efficiency while slashing emissions of particulates and nitrogen oxides, even with inexpensive or lower-grade biomass. Such air quality is hard to attain with distributed home-scale units, making district energy systems uniquely suited for urban use of biomass (Nussbaumer, 2024).

- **Thermal networks recover and distribute valuable bio-conversion waste heat.**

By interconnecting industrial users and processes, thermal networks capture waste heat from complex bioenergy conversions—such as biofuel or synthetic gas production and use it to supply homes, businesses, or other industries, maximizing resource efficiency (IEA Bioenergy Task 32, 2021).



- **Thermal networks with modern bioenergy enable net negative GHG emissions.**

Application of carbon capture and storage (CCS) on bioenergy plants typically entails a substantial flow of low temperature heat that is suitable for district heating supply. Thermal networks enable use of the extra heat generated by the CCS system and thereby economically support the option to capture and store carbon from biomass-based heat and power generation or liquid fuel production.

- **Connecting biomass plants to thermal networks maximizes the value delivered to urban areas.**

Proximity to dense districts ensures all useful energy from biomass plants—including low-temperature waste heat—can be economically delivered where it is most needed. This approach allows city dwellers to benefit from biomass resources without hosting the fuel storage, delivery trucks, or emissions at their doorstep (IEA Bioenergy Task 32, 2019).

- **Use of Biomass-based energy in thermal networks requires supportive policy and planning.**

Recognizing the broader grid and societal benefits in regulation (emissions, jobs, efficiency, resilience) and urban development planning is essential, as markets and emissions accounting focused only on individual buildings could undervalue or block such integrated, efficient solutions (Hansen et al., 2019).

- **Demonstrated results: Thermal networks leveraging biomass deliver clean, stable, and affordable heat.**

Reported operational experience and case studies confirm modern networked bioenergy projects are helping cities achieve air quality and climate targets—while maintaining affordability and reliability for consumers (Hansen et al., 2024; IEA Bioenergy Task 32, 2019).



3.3 CARBON CAPTURE INTEGRATION (IEA GHG)

Carbon Capture projects offer significant emission reduction potential for stationary industries, but decision makers must weigh substantial risks and uncertainties. Leakage from CO₂ storage or pipelines could undermine environmental benefits and pose health hazards, especially in the long term (Parliament of Australia, 2007). High costs, complex project coordination, energy penalties, and frequent underachievement in capture targets threaten financial and operational viability (CIEL, 2023; IEEFA, 2024). While CCS can reduce emissions up to 90% or even make biomass combustion carbon negative, these gains depend on rigorous site monitoring, regulatory standards, and public acceptance initiatives to mitigate risks and maximize climate value (IPCC, 2005; Parliament of Australia, 2007).

Assuming that CCS systems are implemented in a way that fulfils very high standards and reliably contributes to greenhouse gas emission mitigation, its integration with thermal networks can bring significant additional advantages.

- **Thermal networks allow efficient recovery and utilization of waste heat from carbon capture processes.**

Carbon capture and storage (CCS) creates substantial amounts of surplus heat—often up to 20–25% of the input energy at a capture plant. By connecting these facilities to a district energy system, this excess heat is recovered and distributed as zero- or very-low-carbon heat to thousands of homes and businesses—instead of being lost to the air. The result: improved system efficiency, lower carbon footprint, and new revenue streams for CCS operators (DBDH, 2024; Buhl, 2024; Eliasson et al., 2022).

- **District heating networks create new financial and operational incentives for carbon capture adoption.**

Selling surplus heat improves overall project economics and can help make carbon capture investments financially viable—even in applications where carbon prices alone are insufficient. In Denmark, integrated projects between district energy companies and CCS providers are already turning this theory into reality, with real-world collaborations supplying thousands of homes and reducing the total societal cost of decarbonisation (DBDH, 2024; Buhl, 2024).



- **Thermal networks support sector integration and future flexibility.**

As more CCS, hydrogen, and synthetic fuel projects scale up, their heat outputs and optimal locations will diversify. Connecting these varied sources via thermal networks maximizes system flexibility—allowing cities and industries to reap the benefits of emerging climate technologies, to shift between different fuels and energy vectors as economics evolve, and to decarbonize “hard-to-abate” sectors more quickly (Buhl, 2024; JRC, 2023).

- **System integration with district energy increases overall CO₂ reduction and negative emissions potential.**

CHP plants and waste-to-energy facilities equipped with CCS (including Bio Energy Carbon Capture and Storage (BECCS) for negative emissions) often cut their main product (electricity or steam) output, but with network integration, this energy can be mostly recovered and used for district heating—a win for both plant economics and the urban energy transition (Beiron et al., 2023; Ahlmén et al., 2023).

- **Design and operation must consider heat grades, geography, and evolving energy mixes.**

To maximize recovery, careful planning is needed: routes, temperatures, backup capacity, and market structures all impact integration’s effectiveness. Utilities, planners, and investors increasingly account for these factors—ensuring that CCS systems don’t just reduce emissions at point-of-capture, but directly drive urban decarbonization, resilience, and cost control (Beiron et al., 2023; Eliasson et al., 2022).

3.4 CITIES (CITIES TCP)

Thermal networks are pivotal for city-scale decarbonization because they allow entire neighbourhoods to rapidly shift away from fossil-based boiler heating systems. By distributing heat among buildings, these networks increase efficiency and lower greenhouse gas and other emissions, directly addressing urban climate and health challenges (Bagdanov et al., 2023; EU Mayors, 2025; Malcher et al., 2025).



- **Thermal networks greatly expand sustainable energy choices in cities.**

By connecting buildings to a shared infrastructure, cities can use not only renewably generated electricity for heat but also tap into heat sources unavailable to standalone buildings—such as industrial waste heat, geothermal energy, and large-scale solar thermal. This opens the door to a much broader and more sustainable energy mix for urban centres (Köhler et al., 2021; Graff et al., 2023).

- **Thermal networks help cities plan coordinated, cost-effective heating transitions.**

Urban energy planning guided by thermal network potential ensures that areas best suited for district energy—those with higher building density and heat demand—are prioritized for network expansion, while less dense regions can use decentralized systems like individual heat pumps. Coordinated planning also addresses noise, space, and logistic constraints that often limit other renewable options in urban environments (Braungardt et al., 2021).

- **District energy networks optimize investments and promote urban resilience.**

Investments in shared network infrastructure drive job creation and keep spending within the local economy, while reducing the need for every building to manage its own aging heating system. Centralized maintenance and upgrades yield cost savings, reliability, and improved adaptation to future low-carbon requirements. By sharing resources, cities are also better able to withstand extreme weather, energy price shocks, and supply disruptions, keeping citizens comfortable and secure (Euroheat & Power, 2023; Gudmundsson et al., 2020).

- **Thermal networks reduce electricity grid upgrade needs and costs for cities.**

By shifting a large share of heating and cooling demand from individual electric solutions to shared thermal networks, cities can avoid or significantly defer expensive electricity distribution and substation reinforcements, while still integrating more heat pumps and renewables in a grid-friendly way (Green, 2024).



- **Integrated urban planning enables area-wide decarbonisation.**

By mapping local energy demand, supply lines, and waste/recovery heat possibilities, cities can systematically deploy district heating and cooling to achieve emissions reductions that simply are not feasible through piecemeal, building-by-building interventions. This also ensures that required investments in storage, distribution, and renewable heat supply are allocated where they provide the largest shared impact (Schardinger et al., 2019; Köhler et al., 2021).

- **Cities leveraging thermal networks actively shape cleaner, more liveable environments.**

Reducing combustion on-site in homes and businesses significantly cuts urban air pollution and noise, supports public health, and frees up space normally used for boilers and fuel storage. The result: safer, healthier, more valuable buildings, and cleaner city streets for all (C40, 2022a; C40, 2022b; Energy Cities, 2022).

- **Flexible policy tools help maximize the benefits of thermal networks.**

Cities can use information campaigns, planning incentives, and both “soft” (e.g., voluntary district heating zones) and “hard” (e.g., development requirements or building codes) instruments to accelerate network deployment and unlock its full value. Integrated urban policy is crucial for sustained transformation and effective climate action (Braungardt et al., 2021).

3.5 ENERGY STORAGE (ES TCP)

Energy storage is fundamental to the climate transition because it ensures that renewable energy supply matches demand, allowing integration of variable generation and promoting grid reliability. Storage technologies provide resilience against energy supply disruptions, accelerate the phase-out of carbon-based sources, and facilitate deep decarbonisation by supporting stable, renewable-powered urban systems (Lund et al., 2025; Tosatto et al., 2024; Mussawar et al., 2024).

Thermal networks make large-scale and seasonal thermal energy storage (TES) possible. They enable the collection and redistribution of heat from and to different locations, increasing system flexibility and supporting renewable energy integration.

Thermal energy storage is much cheaper than electricity storage and facilitates the use of a large variety of technologies such as large-heat pumps, cogeneration units and electrical boilers using excess solar and wind power.



This capability allows cities to balance supply and demand fluctuations in the heating sector and thus reduce reliance on fossil fuels. In the following, the key benefits of thermal networks to thermal storage are listed.



Figure 3: Pit thermal energy storage in Denmark

(Source: Ioannis Sifnaios, DTU, Case study details in: IEA TNCG, 2025)

- **Thermal networks turn energy storage into a city-scale tool for flexibility, resilience, and deep decarbonisation.**

When integrated into a district energy system, thermal energy storage (TES) enables entire neighbourhoods or cities to absorb excess renewable generation—such as solar or wind—by storing surplus heat or cold when it is abundant and delivering it during times of peak demand or price volatility. This makes urban energy supply both cleaner and more reliable, transforming thermal storage from a niche add-on into a critical infrastructure for net-zero transitions (DBDH, 2025; Kalavasta, 2023).

- *In Denmark's climate neutral 2045 scenario, thermal energy storage emerges as a cornerstone for enabling the entire energy system to fully utilize renewable energy at a manageable cost. Analyses show that the optimal mix includes 110 GWh of thermal energy storage, working alongside 160 GWh of storage capacity from electric vehicle batteries and 340 GWh from hydrogen storage. This integrated strategy supports not only domestic energy demand but also the substantial needs of international shipping, aviation, and materials industries, highlighting the indispensable role of affordable thermal storage across all sectors (Lund et al., 2025).*
- **Centralized storage in networks cuts energy costs and improves both operating efficiency and reliability.**

Centralized TES is only possible with thermal networks. It allows pooling heat from various heat sources and provides essential balancing services efficiently to the building stock. By reducing the need for expensive, peak-time boiler operation and optimizing when and how energy is produced, TES makes the best use of both low-carbon local heat sources and the grid.

Well-designed storage can slash annual fuel costs, flatten demand peaks, and allow combined heat and power plants to run in the most efficient mode—often generating millions in annual savings for large cities. TES can also be used as a back-up heat source, supplying heating or cooling through the thermal network, in case of shut-down of a production unit or during its maintenance, making the system more reliable (Kalavasta, 2023).

- *Large thermal energy storage ((L)TES) decreases national primary energy consumption and significantly reduces the total energy system costs. This has been clearly demonstrated in Task 35 of the IEA Energy Storage TCP, where modelling of a German decarbonized energy system in 2050 showed that using thermal storage for district heating inside sector-coupled systems (such as heating, cooling and power) provides crucial system flexibility, which enables lower overall costs by allowing renewable electricity to be stored as heat when supply exceeds demand. These benefits position (L)TES as a key enabler in the transformation to a cost-effective, low-carbon national energy system (Botzov et al., 2024).*



- **District networks make seasonal, large-scale storage achievable and cost-effective.**

Unlike small battery units, city-scale pit, tank, or aquifer storage systems—serving thousands of customers—are much cheaper per unit of stored energy. This means excess energy from summer solar, waste heat, or CHP can be kept for months and used in colder periods, covering a high percentage of annual heating needs with low marginal costs (DBDH, 2025; Lund, 2019).

- *An example from Denmark demonstrates that increasing national thermal energy storage (TES) capacity to approximately 200 GWh yields substantial benefits for the energy system. In scenarios for 2020 and 2030, expanding TES notably lowers both overall system costs and fuel consumption. For the projected 2045 energy landscape, a higher TES capacity also leads to significant reductions in critical excess electricity production—helping balance renewables and minimize waste, while supporting a more efficient and resilient energy system (Yuan et al., 2024).*
- **Thermal networks use storage as a “virtual battery” supporting electricity grid stability.**

When connected with large-scale electric heat pumps or power-to-heat systems, TES can act as a huge sink for renewable oversupply. Cities can heat up storage when wind is strong or the sun is shining, then discharge to meet heat needs when electricity is scarce—or use reverse flows for district cooling. This stabilizes both the heating and electric grid, reduces reliance on imported fuels, and supports rapid growth in renewables. TES also gives the opportunity to store surplus heat from CHP plant when the grid needs it, and use the heat later during increased heat demand periods (DBDH, 2025; Sihvonon et al., 2024).

- **Storage in thermal networks directly reduces carbon emissions and gas use.**

Large studies show that adding thermal storage to a district heating network can cut fossil fuel and gas consumption by 20–50%, depending on design, and enables higher renewable penetration while keeping costs stable for end users (Kalavasta, 2023; DBDH, 2025).



- **TES in networks is mature, customizable, and already scaling up in cities around the world.**

From Copenhagen's multiday hot water pit to Netherlands' aquifer storage and North America's university- and hospital-scale systems, district energy systems successfully deploy short-term and seasonal storage tailored to the local energy mix, climate, and market structure—maximizing societal and economic value (DBDH, 2025).

3.6 ENERGY SYSTEMS ANALYSIS (IEA ETSAP)

Thermal networks greatly increase the need for advanced software and digital analysis tools by adding layers of complexity to urban energy systems. To optimize flows, match variable sources with demand, balance pressures, and unlock their full flexibility and efficiency, sophisticated modelling, simulation, and predictive control algorithms are essential. As a result, the growth of thermal networks directly stimulates innovation and demand in energy systems analysis, driving the evolution of software platforms and boosting the entire digital ecosystem for planning, operation, and optimization (Zoschke et al., 2025; Diabatix, 2025).

- **Thermal networks drive demand for advanced software and analytical modelling, synergizing with energy systems analysis.**

The integration and operation of complex, multi-source thermal networks require digital platforms that can optimize flows, balance diverse energy sources, and plan investments—stimulating demand for sophisticated tools like TIMES and MARKAL from IEA ETSAP (IEA-ETSAP, 2024; Diabatix, 2025; Synapse Energy Economics, 2024).

- *An example from Copenhagen shows the how modelling and thermal networks benefit each other. Since January 2008, three major district heating operators in Greater Copenhagen—VEKS, CTR, and HOFOR—have jointly operated "Varmelast," coordinating heat production across a network serving over one million households. The system dispatches production across CHP plants, heat pumps, and storage using economic optimization that integrates fuel prices, CO₂ costs, and electricity market revenues. This Balmorel model-based approach, presented in IEA ETSAP workshops, demonstrates how thermal networks enable sector-coupled optimization that validates national energy system planning (Hedegaard, 2014).*



- **IEA ETSAP's TIMES and MARKAL or other models are foundational for network analysis and strategic planning.**

These technology-rich, least-cost optimization models capture energy flows from resources to end-use, support sector coupling, model policy impacts, and enable planners to test diverse expansion and decarbonization scenarios, making them essential for evidence-based investment and policy at the city, national, or regional level (IEA-ETSAP, 2024; Pfenninger et al., 2014).

- **Digital analysis with TIMES/MARKAL/Balmorel and other models unlocks optimal integration of renewables, waste heat, and storage.**

These models support the identification of the lowest-cost mix of technologies, flexible operations, and paths to climate neutrality—enabling robust, future-ready thermal networks and guiding targeted infrastructure investments (IEA-ETSAP, 2024).

- **Best practice: transparent stakeholder engagement, scenario analysis, and participatory planning.**

Clear modelling and user-friendly outputs from platforms like TIMES and THERMOS have been shown to increase social acceptance, inform regulatory frameworks, and speed up large-scale adoption of affordable, low-carbon heating and cooling (THERMOS, 2020; European Commission, 2021).

3.7 ELECTRICITY GRID (ISGAN TCP)

The electrical grid is the energy backbone of modern societies. Most households are connected and the function of society largely depends on an operational electrical grid. As energy systems increasingly integrate variable renewable sources and electrify heating, industry and transport, the interaction between electricity grids and thermal networks becomes critical for system stability, efficiency, and decarbonisation (ISGAN, 2020; Hillberg et al., 2019).

As renewable electricity shares increase and heating electrification accelerates, the flexibility services provided by district energy systems will become increasingly valuable. ISGAN's ongoing work on TSO-DSO interaction, flexibility harvesting, and sector coupling directly supports the development of regulatory frameworks and market designs that enable thermal networks to contribute fully to electricity system stability and decarbonisation (ISGAN, 2022; Hillberg et al., 2019).



- **Thermal networks provide essential flexibility services to electricity grids.**

District heating and cooling systems equipped with power-to-heat technologies, large-scale heat pumps, and thermal storage act as controllable loads that can absorb surplus renewable electricity during periods of oversupply and reduce demand during electricity grid stress. Combined heat and power units in combination with thermal storage can generate electricity at times where more electricity is needed while making use of the unavoidable waste heat of thermal power generation for heat supply. This flexibility supports grid frequency regulation, congestion management, and voltage stability—core challenges addressed by ISGAN's work on power transmission and distribution systems (ISGAN, 2022; ISGAN Annex 6, 2020).

- **Sector coupling through thermal networks reduces peak electricity demand, grid congestion and infrastructure costs.**

Electrification of heating without strategic integration risks overwhelming electricity grids with unprecedented peak demands. ISGAN research demonstrates that coordinated deployment of district energy with heat pumps dramatically limits required grid reinforcement.

- *A study in Ontario, Canada, project that combining 70% district energy with 30% ground-source heat pumps could limit peak electricity demand to 30 GW—compared to 80 GW under full electrification with individual heat pumps alone (ISGAN Annex 6, 2017; Green, 2024).*

- **Power-to-heat in thermal networks enables participation in electricity balancing markets.**

Electric boilers and heat pumps connected to district heating networks can respond to grid operator signals within seconds, providing ancillary services such as secondary and tertiary frequency regulation. This creates new revenue streams for district heating operators while supporting grid stability in systems with high shares of variable renewables (ISGAN, 2019).

- *Electric boilers are suitable for very fast response times—achieving full load from standby in less than 30 seconds—but convert electricity to heat with a ratio close to 1:1 (ISGAN, 2019). Heat pumps, on the other hand, use electricity to upgrade external heat sources, typically providing 2.5 to 4 times more heat than the electricity they consume (IEA HPT TCP, 2024; Lund et al., 2014). A combination of electric boilers and heat pumps promises the best of both worlds: high efficiency from heat pumps during longer periods of low electricity prices, and response within seconds from electric boilers for short-term grid balancing and frequency regulation (ISGAN, 2019; IEA HPT TCP, 2024).*
- *Salzburg AG operates two 15 MW electric electrode boilers connected to the city's district heating network since 2015–2016. These power-to-heat plants convert excess electricity into heat, participating in Austria's secondary balancing market. The plants respond to automatic generation control signals, providing grid flexibility while supplying CO₂-free heat. Operational experience confirms that power-to-heat in district heating is technically mature and economically viable when integrated with balancing markets (ISGAN, 2019).*
- **Thermal energy storage provides cost-effective electricity buffering.**

Thermal storage is approximately 100 times more economical than electricity storage per unit of energy capacity. When integrated with district heating networks, thermal storage enables cities to "bank" surplus renewable electricity as heat, releasing it during periods of high demand or low renewable generation. This capability is essential for managing the variability inherent in wind and solar power systems (ISGAN, 2019; ISGAN Annex 6, 2020).

- **Digital coordination between thermal and electricity networks enhances overall system efficiency.**

Smart grid technologies—including advanced metering and real-time communication protocols—enable fine-grained coordination between district heating operators and electricity system operators. This allows dynamic throttling of power-to-heat assets based on grid conditions, maximizing the value of flexibility while ensuring reliable heat supply (ISGAN Annex 6, 2017).



- *Denmark pioneered a regulatory framework allowing electric boilers in district heating systems to connect to the grid with minimal connection fees, provided they operate only when excess network capacity is available. This policy incentivizes CHP plants to produce heat from electricity during periods of high renewable surplus, improving the balance between electricity production and demand. The Danish CHPCOM project developed standardized IEC 61850-based communication solutions enabling distribution system operators to dynamically control boiler output, demonstrating successful real-time coordination between electricity and thermal sectors (ISGAN Annex 6, 2017).*

3.8 GEOTHERMAL (GEOTHERMAL TCP)

Geothermal energy is a baseload energy source with the possibility to produce close to 24/7, 365 days a year. It can be used to decarbonize the power sector as well as the heat/cold demand of the built environment. The footprint and visual impact at the surface is small. The same geothermal technologies can also be used for high-capacity seasonal storage of surplus heat/cold underground for times of high demand. Geothermal energy district heating exploits a local energy source and creates local jobs in green energy.



Figure 4: Geothermal plant Sauerlach, Germany (Source: SWM, Case study details in: IEA TNCG, 2025)



- **Thermal networks allow geothermal energy to supply cities reliably and at large scale.**

By channelling geothermal heat via extensive thermal networks, entire neighbourhoods or regions can access clean, renewable warmth—even in dense areas lacking the space or resource for individual wells.

- *Geothermal energy is a reliable and established renewable heat source for large-scale thermal networks, known as geothermal networks. These networks can incorporate various geothermal technologies, ranging from traditional high-temperature to advanced low-temperature Grids (SAPHEA Project, 2023). Today, geothermal networks supply significant portions of the heating needs in major cities—such as Paris (1.6 TWh_{th} annually), Munich (200 MW_{th} installed capacity with an 800 MW_{th} target), and entire countries like Iceland, where over 90% of household heating comes from geothermal (10 GWh_{th} annually) (Graff et al., 2023; IEA Geothermal, 2023; Ragnarsson et al., 2023). Beyond heating, geothermal can also be an efficient and cost-effective solution for cooling—an advantage often overlooked. (EGEC Geothermal, 2024; IEA Geothermal, 2024).*
 - **Thermal networks leverage the use of heat from large-scale geothermal sources as baseload.**
- Geothermal energy is not dependent on weather or daylight. Linking this resource to a thermal network allows round-the-clock and year-round heat delivery to homes, businesses, and industries—stabilizing energy supply and insulating communities from weather and energy market volatility (EC Geothermal, 2022).
- **Thermal networks make the most of both high- and low-temperature geothermal, thanks to large heat pumps and advanced system design.**

Thermal networks can combine direct use of high-temperature geothermal (direct injection) with electric heat pumps to lift lower-grade geothermal temperatures, widening the range of exploitable resources. This synergy supports both low-temperature networks and conventional systems, improving total system efficiency and carbon savings (SAPHEA, 2023).



- **Integration with thermal networks dramatically increases the capacity factor, economic returns and lifespan of geothermal investments.**

Geothermal systems are designed for long-term operation and can require high capital investment, but operating expenses are low, especially in the case of direct use without heat pumps. Thermal networks enable maximum use of each geothermal well, avoiding stranded resources and making deep drilling more economically viable. They also allow hybridization with other sources, such as waste heat or biomass, for back-up during maintenance or rare supply dips—ensuring reliable service and return on long-term investments (GeoDH project, 2015; Graff et al., 2023).

- **Thermal networks help cities safely manage geothermal exploration, scaling up only in proven areas and sharing risks.**
- Geothermal energy is dependent on underground properties. It is therefore not possible to exploit geothermal energy without knowledge of local conditions and often requires an exploration phase prior to its implementation in thermal networks. But thanks to a wide range of exploitation technologies (with or without heat pumps, open systems using aquifers or closed loop systems in dry rock) geothermal energy can be produced in most geological settings in one way or another. Because the infrastructure connects broad geographic areas, city planners can bring new wells online progressively (even connecting several fields), share the benefit of early successes, and minimize service disruption as the system expands or is upgraded (IEA Geothermal, 2023; interregeurope.eu, 2004).

3.9 HEAT PUMPS (HPT TCP)

Heat pumps are a flexible and highly efficient technology that synergizes exceptionally well with thermal networks. On the one hand small, building-scale heat pumps can supply low-carbon heat efficiently to areas that are not economically feasible for thermal networks, such as many villages and single-family house areas, to buildings with combined heating and cooling needs or where no large scale heat source for a thermal network is available. On the other hand, large heat pumps connected to thermal networks can supply dense urban areas by extracting renewable heat from air, water, or waste sources and amplifying it for distribution. Thus, large heat pumps enable thermal networks to deliver electricity-based, efficient and low-carbon heating and cooling at scale, while supporting the integration of diverse renewable and waste heat streams. Heat pumps distributed in different buildings can also extract heat from thermal source networks and supply the heat to the buildings.

This solution can reduce system emissions and operational costs, and maximize flexibility by matching supply and demand efficiently (Rehman et al., 2024).





Figure 5: Large river-water heat pump in Mannheim, Germany (Source: GKM, Case study details in: IEA TNCG, 2025)

The following benefits are brought to the heat pump technology by its integration into thermal networks:

- **Thermal networks enable efficient, large-scale use of both renewable and waste heat through heat pumps.**

Large-scale heat pumps integrated into district heating systems extract and upgrade heat from sources such as rivers, lakes, ambient air, seawater, industrial processes, or wastewater. This allows city-scale recovery of low-grade heat that would otherwise be lost, transforming it into a backbone of cost-effective, low-carbon heating (IEA HPT TCP, 2024; Euroheat & Power, 2023).

- *Large-scale heat pumps can efficiently replace traditional fossil fuel-based boilers in thermal networks. For example, in Stockholm, Sweden, heat pumps totalling 660 MW have operated flexibly alongside other heat sources since 1986, supplying reliable district heating at scale (IEA HPT Annex 57, Stockholm, 2023).*

- **Thermal networks magnify energy efficiency and carbon savings from heat pumps.**

Grid-connected heat pumps in thermal networks can achieve high coefficients of performance (COPs) even when supplying existing building stock with legacy in-house heating systems. They can provide the efficiency benefits of heat pump technology to areas not feasible for individual heat pumps. When powered by renewables or surplus grid electricity, they can deliver affordable, near-zero emission heating and cooling to whole districts (IEA HPT TCP, 2024).

- **Sector coupling: Thermal networks facilitate the efficient use of renewable electricity and grid stability via heat pumps.**

Heat pumps in district networks act as a buffer for the electric grid: they can absorb excess wind or solar electricity (for example, at times of high production and low demand), convert it efficiently to heat for storage or immediate use, and with thermal storage reduce load when the grid is strained. This flexibility advances renewables integration and grid decarbonisation on a mass scale (IEA HPT TCP, 2024).

- *Large-scale heat pumps can also utilize renewable sources (such as air, ground, or seawater). In Esbjerg, Denmark, DinForsyning built Denmark's largest seawater heat pump and the world's largest CO₂ heat pump (as of 2023), with a nominal capacity of 70 MW and district heating output of 60 °C to 90 °C (IEA HPT Annex 57, Esbjerg, 2023).*
- *Integration of heat pumps with thermal storage unlocks grid flexibility and cost efficiency. In Burgenland, Austria, a direct line from a wind park, coupled with large thermal and electric storage and four high-performance heat pumps, has reduced gas consumption by 1,250 GWh/a, emissions by 300 t/a, and biomass consumption by 1,200 t/a (IEA HPT Annex 57, Burgenland, 2023).*
- *Large-scale heat pumps can deliver grid flexibility, even participating in ancillary services markets. In Sdr. Felding, Denmark, the district heating provider uses a large heat pump, buffer tank, and a 10 MW electric boiler to absorb and store renewable electricity, supporting the grid's aFRR and mFRR markets as approved by the Danish TSO (IEA HPT Annex 57, Sdr. Felding, 2023).*



- **Thermal networks expand the usable range of heat pump sources and applications.**

Networks make it feasible to use very low-temperature or distributed sources (e.g., data centres, sewage) and to integrate multiple heat pump types (absorption, electric, hybrid) in a coordinated way. This enables tailor-made designs for specific urban, industrial, or neighbourhood contexts—including combined heating and cooling, or simultaneous operation for district cooling and heating (IEA HPT TCP, 2024).

- *Heat pumps are essential in a post-fossil era, as many renewable and waste heat sources are at temperatures too low for direct use. Modern 4th generation district heating networks now employ heat pumps to upgrade these sources, bridging the temperature gap between supply and demand. The performance (COP) of heat pumps increases as this temperature difference narrows (IEA HPT Annex 57, Stockholm, 2023).*
- *In Hallein, Austria, an absorption heat pump in the district heating system taps the flue gas from biomass cogeneration, saving approximately 10,100 t CO₂ annually by increasing waste heat utilization at the AustroCel cellulose plant (IEA HPT Annex 57, Hallein, 2023).*
- *Industrial and societal waste heat sources, such as wastewater, can be upgraded by heat pumps for practical heating. In Vienna, Austria, “Spa Vienna” uses thermal wastewater and heat pumps to deliver 2.2 MW to the district heating network at max supply temperatures of 84 °C, producing about 11 GWh of heat annually (IEA HPT Annex 57, Vienna, 2023).*
- **Low-temperature thermal networks support heat pumps for maximum efficiency and minimal losses.**

Thermal networks operating at lower temperatures or thermal source networks combined with distributed heat pumps, minimize heat pump electricity consumption and also heat losses from thermal networks. This can cut network operating costs, and further boost heat pump emissions performance. This next-generation approach is already being demonstrated across Europe and Asia (Euroheat & Power, 2023).

- *Low temperature thermal networks use heat pumps to recover and boost waste heat just enough to meet building heating needs and optimize energy flows. In Lund, Sweden, the E.ON ectogridTM system links 15 buildings to efficiently balance annual heating and cooling needs, reducing supplied energy from 14 GWh to a target of 3 GWh annually (IEA HPT Annex 47, Lund, 2019).*



- **District heating with heat pumps fosters reliable, resilient, and fuel-independent local energy.**

By accessing multiple geographically distributed or backup heat sources, district energy with heat pumps greatly reduces reliance on local combustion, imported fuels, or weather-dependent renewables, leading to a more stable, self-reliant system (Euroheat & Power, 2023; IEA HPT TCP, 2024).

- **Thermal networks for cooling require chillers – which are a specific type of heat pump – whenever no free cooling source is available.**

Chillers – a type of heat pump dedicated to cooling – are essential in thermal cooling networks when natural cold sources like deep water or ambient air cannot meet cooling demand. By upgrading and distributing cooling from various renewable and waste sources, heat pumps ensure reliable, efficient, and resilient urban cooling even under rising temperatures and fluctuating grid conditions (Euroheat & Power, 2023; Sustainable Energy Week, 2025).

- *Heat pumps also provide both heating and cooling in networks. At the IKEA site in Aalborg, Denmark, an electric heat pump supplies nearly 1 MW of district cooling for the store, while excess heat is recaptured and used for district heating (IEA HPT Annex 57, Aalborg, 2023).*

3.10 INDUSTRIAL INTEGRATION (IEA IETS)

Industrial integration with thermal networks enables cities and regions to tap into vast sources of waste heat from manufacturing, data centres, and other industrial processes—transforming a previously underutilized resource into a pillar of low-carbon, efficient district energy. By linking industrial facilities to district heating and cooling networks, ideally in combination with large-scale thermal energy storage, thermal networks not only reduce emissions and energy waste but also diversify local energy supplies while enhancing economic competitiveness and resilience. This synergy is essential for accelerating the decarbonization of both industrial operations and city infrastructure (IEA SHC, 2024).



- **Thermal networks maximize efficient use of industrial heat and power resources.**

By integrating industry into a district energy system, both process heat and byproduct (waste) heat from manufacturing, chemical, or power facilities can be efficiently delivered to urban or other industrial neighbours, rather than vented or cooled as waste. This system-level approach dramatically raises resource utilization rates and enables businesses to monetize previously discarded energy (Kleinertz, 2019; JRC, 2023).

- **Centralized networks lower both operational and capital costs for industries.**

When multiple plants or companies connect to a shared network, they benefit from economies of scale: central boilers, CHP units, storage, and emission controls cost less per user, while maintenance is easier and supply security is higher than with many isolated, smaller units. This is crucial in areas with limited free space for on-site generation or storage, or high demand for supply reliability (Kleinertz, 2019; JRC, 2023).

- **Sector coupling and power-to-heat raise industrial flexibility and savings.**

With thermal networks, industries can both supply and draw energy from the system, leveraging “power-to-heat” when electricity prices are low or renewables are abundant, and switching to fuel-based CHP during grid scarcity. Industrial operators using combined thermal batteries and flexible CHP can thus minimize electricity and gas bills, optimize process timing, and reduce emissions with no loss of supply reliability (JRC, 2023).

- **Thermal integration optimizes energy flows between companies and communities.**

Modern software tools and detailed system planning enable designers to view surplus heat as a shared regional resource, mapping, exchanging, and optimizing flows between disparate industries, municipal users, and heat/cold demand. This regional integration delivers energy savings and allows businesses to sell heat or cold, driving new business models and economic development (JRC, 2023; TNO, 2025).



- **Shared networks allow gradual, flexible decarbonization of industrial process heat.**

Companies can electrify processes, integrate new renewables, or use green fuels in central facilities in stages, while still benefiting from secure, backup heat flow. This “future proofing” reduces technology risk and unlocks climate compliance pathways—especially valuable for sites with changing production lines or long investment cycles (Kleinertz, 2019).

- **Thermal networks support resilience, backup, and security for critical operations.**

Centralized heating and cooling raise industrial supply security, with backup units efficiently pooled and easier to maintain, safeguard, and restart after outages, as compared to fragmented, single-site systems. For critical infrastructure and high-output plants, this is often a regulatory or insurance requirement (Kleinertz, 2019; JRC, 2023).

3.11 NUCLEAR INTEGRATION (IAEA)

Nuclear plants, when operated in combined heat and power (CHP) mode, provide an enormous opportunity for low-carbon district energy by utilizing their large quantities of unavoidable waste heat. Integrating this waste heat into thermal networks can dramatically increase system efficiency and supply stable, resilient, and secure local heat over long timeframes. Importantly, studies and operational experience confirm that the risks and operational costs of nuclear power are only minimally affected by the addition of heat recovery for district energy, as heat is extracted using robust, secondary circuits that maintain high safety standards. The scale and reliability of nuclear plants make them uniquely capable of supplying high shares of local and regional heating demand—several reactors worldwide currently supply district heating, and a single modern nuclear plant can provide thousands of megawatts of continuous thermal output for large metropolitan areas or industries, making nuclear power generation one of the world’s largest, most reliable low-carbon waste heat sources (IAEA, 2021; Power Magazine, 2022; EPRI, 2022; NEA OECD, 2022).



- **Thermal networks let cities tap nuclear heat—turning what’s now waste into low-carbon urban supply.**

Most nuclear plants release about two-thirds of their generated heat to the environment. By connecting nuclear power generators to district heating networks, this previously wasted thermal energy can be delivered to cities as clean heat—dramatically boosting overall plant efficiency to as high as 80% and providing reliable, carbon-free heating for urban areas (PowerMag, 2022; Mašata et al., 2022; IAEA, 1997).

- *Currently, at least 51 nuclear combined heat and power (CHP) plants provide district heating globally. These examples demonstrate that nuclear CHP is already a significant, proven provider of robust, low-carbon thermal energy for district networks worldwide (Opadokun et al., 2024).*

- **District heating networks make nuclear energy’s decarbonization impact far greater, replacing fossil fuels at scale.**

Nuclear-based district heating offers a solution for urban decarbonization, particularly where electrification or renewables are constrained. Several Eastern European and Nordic countries already use this approach to avoid coal or gas heating in major cities, showing that heating from nuclear, delivered via networks, is technically mature (PowerMag, 2022; IAEA, 1997; Mašata et al., 2022).

- **Central networks unlock new opportunities for small modular reactors (SMRs) and advanced technologies.**

Advanced nuclear designs provide more flexible heat output and enhanced safety, allowing plants to be sited closer to cities and directly connected to district heating grids. SMRs can serve smaller or mid-size urban areas, replace retiring fossil plants, or anchor new regional “energy parks” integrating multiple resources—including renewables, storage, and sector coupling (Abushamah et al., 2024; RISE, 2024).

- **Thermal storage in district networks complements nuclear’s constant output.**

Because nuclear plants operate most efficiently at steady power, connecting them to large thermal energy storages through thermal networks allows excess heat to be buffered at night or during low demand and released when cities need it most. This balancing helps adapt to variable seasonal demand and makes nuclear-based heating more responsive and economic for customers (Mašata et al., 2022; PowerMag, 2022).



- **Thermal networks overcome siting, backup, and energy system constraints—if there’s policy support and forward planning.**

While local regulations, siting, and investment cycles remain barriers, the experience in Sweden, Czech Republic, Russia, and China shows that careful integration—paired with supplementary boilers (biomass, gas, or waste heat) and strategic storage—can reliably deliver nuclear heat to city centres up to 100 km from the plant. Accelerating this integration will require policy coordination, clear land use plans, and public engagement but provides unique potential for rapid, low-carbon urban transition (PowerMag, 2022; Mašata et al., 2022; RISE, 2024; IAEA, 1997).

- **Thermal networks stand to benefit from emerging heat-only reactor designs**

While traditional nuclear CHP plants achieve significant efficiency gains by capturing waste heat from electricity generation for heat supply, heat-only SMRs optimize for pure thermal output, eliminating the complexity and risk associated with nuclear electricity generation. Heat-only reactors operating below 100–150°C are inherently safer, simpler to operate, potentially require no refuelling for up to 15 years, and can be sited closer to urban centres.

- *Heat-only reactors with a heat output of 50 MW have been found a potentially profitable option for Helsinki’s future decarbonized district heating system (Ikonen, 2025).*

3.12 SOLAR THERMAL (IEA SHC)

Solar thermal technology, when integrated with thermal networks, transforms abundant sunlight into a reliable, emission-free heat supply for cities and industries. Thermal networks enable solar plants—using flat-plate, evacuated tube, or concentrating collectors—to efficiently provide both high and low-temperature heat, directly covering large portions of district heating demand or preheating return flows for greater system efficiency. These systems can deliver cost-effective, scalable, and highly decarbonized heat, with large-scale solar thermal plants already supplying up to 20% or more of district heating demand in some European cities and offering further gains when paired with seasonal storage (IEA SHC Task 68, 2024; Winterscheid, 2017).





Figure 6: Silkeborg Solar District Heating system as seen from above. (Source: stateofgreen.com, Case study details in: IEA TNCG, 2025)

- **Thermal networks unlock the true economic potential of large-scale solar heat.**

Integrating solar thermal plants with district heating networks allows solar energy to be collected in central, carefully chosen locations—such as open fields, park spaces, or rooftops—and delivered to thousands of buildings. This approach achieves much greater cost-effectiveness per installed square meter compared to individual rooftop solar panels, while enabling the use of high-performance, utility-grade collectors and economies of scale in system construction and maintenance (Solar Heat Europe, 2025; EU-MAYORS, 2024).

- *In 2025, the solar heat produced reaches costs from 30-50 €/MWh without subsidies. These costs are stable over the 25 years of operation of the plant since no fuel price influences the expenses, i.e., solar heating provides de-risking of heating costs independent of future fuel or electricity prices (and government policy changes).*

- **District networks make year-round solar heating practical using thermal storage.**

When paired with large-scale hot water tanks or underground heat storage, solar thermal plants can store heat produced in the summer for use in colder months. This “seasonal shifting” means solar energy can reliably supply a high fraction of space heating needs—even during the winter—reducing the need for backup fossil fuel boilers or electric heaters. In advanced systems, solar can reach up to 60% of a district’s annual heat demand, rather than the 5-20% coverage typical of individual systems, with lower total fuel use and emissions (EU-MAYORS, 2024; Gao et al., 2024, IEA SHC Task 55, 2020).

- **Thermal networks enable flexible, low-carbon system operation and decarbonisation.**

By using solar thermal as a “first option,” networks allow backup sources (such as biomass or heat pumps) to be used only when the sun isn’t shining, extending their lifespan, reducing operating hours, and cutting emissions even further.

- *Municipalities like Salaspils, Latvia and Härnösand, Sweden have shown that combining solar with biomass, thermal storage, and efficiency upgrades enables renewable shares of over 90%, deep local job creation, and reliable, low-cost heat through persistent energy crises (Nguyen et al., 2024; EU-MAYORS, 2024).*

- **District networks boost technological performance and reliability.**

Centralized control, professional maintenance, remote monitoring, and advanced metering in district networks maximize the performance and operational uptime of large solar thermal plants. This ensures predictably high solar fractions year after year, with low operating and maintenance costs per building. Larger plants make it feasible to use bigger, more efficient collectors and sophisticated automation—capabilities out of reach for most decentralized solar installations (Solar Heat Europe, 2025; Solid, 2025).

- More than 300 plants are in operation and more than 20 years of return on experience is available.



- **Solar in thermal networks secures stable, long-term heat prices.**

Since sunshine is free, and solar thermal plants have very low running costs after installation, districts with solar-integrated networks are protected from spikes in fossil fuel or electricity prices. Solar heat reliably delivers low, predictable prices for 20+ years, as has been demonstrated in Scandinavia and Central Europe—even through recent energy crises (Solar Heat Europe, 2025; EU-MAYORS, 2024).

- **Synergy with district cooling and decarbonized cities.**

District heating/cooling systems can also leverage solar heat for applications beyond space heating, such as absorption cooling, industrial process heat, and hot water for hospitals or swimming pools. These synergies allow cities to maximize climate mitigation benefits and transform the character of their energy system for future generations (Solar Heat Europe, 2025).

3.13 WASTE HEAT (INCLUDED IN IEA DHC)

The direct utilization of waste heat for heating and cooling nearly always requires thermal networks, as they are uniquely able to collect, transport, and deliver surplus heat from diverse sources—such as industry, data centres, and commercial buildings—to consumers across an entire district or city. By integrating this otherwise lost energy, thermal networks not only reduce fuel consumption and emissions, but also enhance local energy resilience, create cost savings, and support a more circular urban economy. With massive, accessible waste heat streams available in most urban centres, district energy systems leveraging waste heat are emerging as an essential pillar of decarbonization and energy efficiency (DBDH, 2024).



- **Thermal networks turn diverse waste heat streams into reliable, low-carbon heat for cities.**

By interconnecting many buildings and heat sources, district energy systems can capture surplus heat from industrial facilities, data centres, sewage treatment, supermarket refrigeration, and even metro tunnels. Instead of letting this recoverable energy go to waste, thermal networks collect, upgrade (where necessary), and redistribute it to cover large portions of urban heating demand—significantly reducing fossil fuel use and municipal carbon emissions (REWARDHeat, 2025; Yuan et al., 2025).

- **Networks allow use of both high- and low-temperature waste heat, even from distributed sources.**

Integration is possible whether heat comes from a major industrial plant or from smaller, scattered sources like data centres and refrigeration systems. Waste heat above 70°C can often be fed directly into a district heating network; for lower temperature sources, large heat pumps are used to upgrade heat to usable levels, further multiplying sources that can contribute to the grid (REWARDHeat, 2025; ENTRAIN, 2024; Monsalves et al., 2024).

- **District heating boosts the technical, economic, and climate value of waste heat compared to standalone recovery.**

By pooling demand and orchestrating thermal loads, thermal networks provide steady, year-round outlets for fluctuating waste heat—making use of energy that individual buildings or industries would often be forced to discard. This enhances overall system efficiency, grid resilience, and supports the business case for both energy service providers and industries seeking to decarbonize.

- **Thermal networks maximize energy efficiency and reduce consumer bills by leveraging otherwise discarded heat.**

Instead of building new, fossil-fuelled production capacity, capturing and using metropolitan waste heat can be cheaper, improves network efficiency, and can lower end-user prices by sharing operational costs and reducing fuel consumption (NetZeroCities, 2025; Kalavasta, 2023).



- **Smart systems and new markets bring waste heat into competitive district heating.**

Thermal networks with open-market models allow multiple sources—including prosumer buildings and private companies—to feed in heat, often using smart meters and dynamic pricing tailored to supply and demand. This can support grid flexibility, fairer cost sharing, and growth of resilient urban energy communities (REWARDHeat, 2025; ENTRAIN, 2024; GrowSmarter, 2025).

- **Policy and planning are essential to overcome hurdles for waste heat integration.**

Agreements on heat ownership, pricing, connection costs, and network access are needed. Incentives and supportive frameworks help industries and utility partners collaborate, monetize previously unused energy, and accelerate decarbonization at lower societal cost (Monsalves et al., 2024).



4 CONCLUSION

4.1 CHALLENGES AND OPPORTUNITIES

- **Thermal networks offer high-impact decarbonization and energy security—but adoption is uneven.**

While countries like Denmark, Sweden, and Finland lead Europe with high district heating shares and rapid decarbonization, many other regions have few or no networks. Adoption lags due to legacy gas systems, limited experience, regulatory inertia, and lack of integrated heat planning (JRC, 2023; EC, 2022).

- **Upfront investment and retrofit costs remain a primary barrier.**

Construction, pipe installation, and retrofitting of buildings or legacy networks for lower temperature operation require significant capital. This is compounded in dense urban areas and when existing infrastructure is old, making “business as usual” solutions more attractive in the short term, even if less efficient over the long term (JRC, 2023; DBDH, 2025).

- **Subsidies for fossil fuels and unpriced carbon distort competition and slow network deployment.**

In several member states, fossil-fuelled heating (such as gas boilers) is subsidized or fails to account for health and climate costs, giving an unfair advantage over more sustainable—but initially costlier—thermal networks (JRC, 2023; IRENA & IEA, 2020).

- **Aging infrastructure and the technical challenge of “smart” upgrades.**

Many older networks must transition from higher to lower operating temperatures to maximize renewable and waste heat integration (“4th generation” upgrades). This requires systematic investment, digital controls, and robust data for optimization—technologies that are proven but not yet universally deployed (JRC, 2023).



- **Policy fragmentation and inconsistent regulation cause investor uncertainty.**

Regulatory differences between regions, unclear market rules for network access and third-party feed-in, and lack of long-term signals all extend project lead times and can discourage municipalities and the private sector from pursuing thermal networks at scale (JRC, 2023).

- **Success factors: digitalization, integrated energy planning, social engagement, and bold leadership.**

Rapid progress has been made where cities combine smart metering, demand aggregation, sector coupling (electricity, gas, heat, cooling), and community participation, supported by long-term plans and stable policy. Data-driven planning tools and digital integration enable targeted investments, reliable balancing of renewables, and efficient operation (JRC, 2023).

- **Legal mandates and climate targets are driving change.**

New EU directives, national laws and climate roadmaps (such as Germany's GEG, the Energy Efficiency Directive, and the Green Deal) are mandating waste heat integration, renewable sourcing, and comprehensive urban energy plans—moving thermal networks into the mainstream as a strategic infrastructure for a net-zero future (EC, 2022; JRC, 2023; EUAgenda, 2024).

4.2 LIMITATIONS OF THERMAL NETWORKS

While thermal networks offer substantial benefits, their successful deployment requires awareness of inherent limitations that must be addressed through appropriate planning, regulation, and technology choices.



- **Infrastructure and Investment Characteristics**

Thermal networks are capital-intensive infrastructure with high upfront investment requirements and long payback periods, typically 20–40 years (Jiminez Navarro et al., 2022; Frontier Economics, 2015). This creates financing challenges, particularly for smaller municipalities or in markets without established public financing mechanisms. Unlike building-level solutions, network investments require long-term commitment and coordinated planning across multiple stakeholders.

- **Thermal Losses**

Distribution losses in thermal networks typically range from 8–15% of total heat delivered, depending on network age, temperature levels, and insulation quality (Jiminez Navarro et al., 2022; Lund et al., 2014). While modern low-temperature networks significantly reduce these losses, and while these losses are almost always significantly overcompensated by the choice of generation technologies, they represent an inherent characteristic that must be considered in system design and lifecycle assessments.

- **Natural Monopoly Characteristics**

Thermal networks exhibit natural monopoly characteristics due to their high fixed costs and local market structure (Frontier Economics, 2015; Egüez, 2021). Without appropriate regulation, this can lead to concerns regarding pricing transparency, consumer choice, and market power. Several jurisdictions have addressed this through price regulation or public ownership models, but regulatory frameworks remain inconsistent across countries (IEA DHC Annex TS5, 2024).

- **Geographic and Density Dependencies**

The economic viability of thermal networks is strongly dependent on heat demand density. In low-density areas such as rural villages or dispersed suburbs, decentralized solutions including individual heat pumps are typically more cost-effective (Gudmundsson et al., 2020). Thermal networks are most advantageous in urban environments, industrial clusters, and areas that can leverage their multiple benefits.



- **Transformation Complexity**

Converting and expanding thermal networks presents significant technical and organisational challenges. These include the need for building-side adaptations, integration with other urban infrastructures and development of new operational competencies (IEA DHC Annex TS5, 2024). A shortage of experienced personnel—from project managers to technicians skilled in district energy integration—can delay project implementation.

4.3 TRENDS AND OUTLOOK

- **Thermal networks are evolving toward hybrid, smart, and low-carbon systems—at the centre of net-zero policy.**

The district heating and cooling (DHC) market in Europe is seeing major acceleration towards renewables, advanced flexibility, and integration of heat pumps, large storage, and sector coupling solutions. By 2025, renewables and waste heat account for over 44% of the average DHC mix—a rapid increase thanks to targeted climate policy, cost declines, and regulatory pressure on fossil fuels (Euroheat & Power, 2025).

- **Expanded and densified networks deliver broader access and inclusivity.**

Network length and connections are rising in both large and medium cities, with year-on-year increases in connected buildings and effort to densify existing grids. Germany and France, for example, each connected thousands of new users in 2023 alone, marking not just growth but social momentum towards clean, district-scale energy (Euroheat & Power, 2025).

- **Harnessing urban, industrial, and data centre waste heat is a key trend for climate and resilience.**

Projects in urban cores (Stockholm, Berlin, Rotterdam), as well as suburban and industrial clusters, now routinely plan to capture and circulate heat from data centres, industrial parks, and even rivers—with major efficiency, emissions, and reliability gains (European Commission, 2021; eutech, 2025).



- **District cooling is expanding rapidly, paralleling climate-driven demand for resilience.**

Cooling networks, which grew another 3% in 2023, are being deployed everywhere from municipal buildings to business parks, often using river or aquifer sources plus large-scale thermal storage. Integrated “heating and cooling” strategies are emerging as standard city policy, with dedicated EU roadmaps due by 2026 (Euroheat & Power, 2025).

- **Digitalization and AI are reshaping network operation and investment.**

Next-generation networks deploy predictive analytics, digital twins, dynamic tariffs, and embedded sensors to optimize flows and maintenance, further reducing emissions and operational cost. AI-driven tools are being piloted for investment planning, demand aggregation, and resilience forecasting (Thermal Management Expo Europe, 2025; Euroheat & Power, 2025).

- **Extreme weather (heatwaves) and electrification loads underscore the importance of flexible, grid-integrated thermal networks.**

Record-breaking summer temperatures have increased the use of air conditioning, strained grids and doubling peak power prices in countries like France, Spain, and Germany. Thermal networks and their storage capabilities act as a buffer, using off-peak renewables for both hot and cold, supporting both grid stability and urban adaptation under climate stress (Ember, 2025; Eurostat, 2025).

- **Investment momentum is strong but needs regulatory and financial streamlining.**

The sector’s strong growth is still challenged by complex market rules, fragmented permitting, and up-front capital needs. Calls for an EU “Industrial Decarbonization Bank,” simpler state aid rules, and implementation of the “Affordable Energy” action plan are spotlighted as success factors for the coming years (Euroheat & Power, 2025).



4.4 POLICY RECOMMENDATIONS AND ACTIONS

THERMAL NETWORKS: POLICY ACTIONS FRAMEWORK

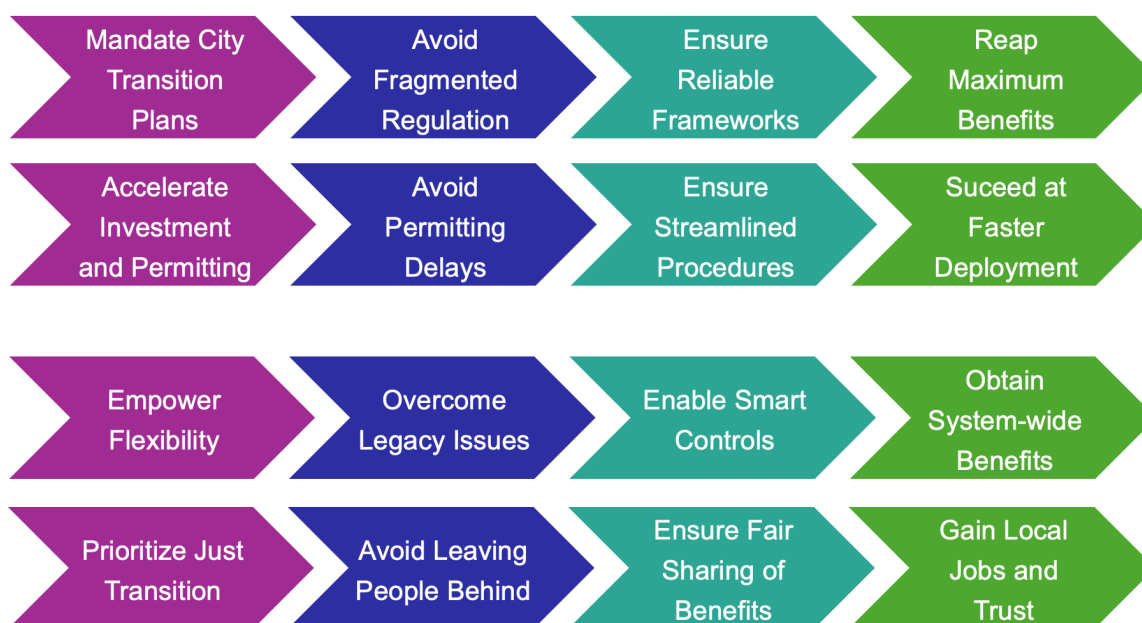


Figure 7: Thermal Networks Policy Actions Framework

The framework above identifies four critical policy priorities that address core barriers to thermal network deployment. By mandating city transition plans, accelerating investment and permitting, empowering system flexibility through digitalization, and ensuring equitable benefit-sharing, policymakers can remove the primary obstacles to rapid scaling.

These priorities translate into the following specific actions:



- **Mandate local heating and cooling plans and empower cities as energy transition leaders.**

Require all municipalities above a population threshold to develop and update integrated local heating and cooling strategies, mapping demand, supply, network zones, and waste heat opportunities. Provide financial and technical support (via national/EU funds and digital tools) so cities have the capacity to implement robust, future-proofed district energy plans (EU Energy Efficiency Directive, 2023; Energy Cities, 2024; CAN Europe, 2025).

- **Accelerate and streamline permitting, investment, and connection procedures for networks.**

Shorten administrative timelines for district energy projects, prioritize fast-track approvals for renewable and waste-heat connections, and enable “one-stop-shop” platforms for investors and operators. Reduce capital costs via guarantees, blended finance facilities, and clear procurement pipelines aligned with NECP (National Energy and Climate Plan) targets (EU Commission, 2025; DBDH, 2025).

- **Enforce fossil fuel phase-out and ensure strong carbon pricing to support clean heat investment.**

Rapidly phase out subsidies for fossil-based individual heating and ensure the cost of carbon is reflected in fuel prices for heat. Adopt binding targets for low-carbon heat shares in buildings, infrastructure, and industry, with timelines that allow for market development and just transition (CAN Europe, 2025; EU Commission, 2025).

- **Prioritize grid readiness, storage, and flexibility for thermal-electrical sector coupling.**

Align national and EU grid action plans, support heat/cold storage and cross-border infrastructure and promote Distribution System Operator (DSO) procurement of flexibility from district energy operators. Ensure legal frameworks recognize storage and district heating and cooling as integrated, strategic assets—crucial for renewable balancing and price stability (CAN Europe, 2025; EC, 2022).



- **Digitalize planning and operation for performance, resilience, and outreach.**

Mandate robust digital metering and integration in new and renovated networks, adopt predictive analytics and AI for operational efficiency, and create interactive platforms for transparency, public input, and cross-sectoral learning. Enhance data collection for monitoring climate, air quality, supply security, and user engagement (Euroheat & Power, 2025; DBDH, 2025).

- **Mainstream social engagement and local value creation in all network projects.**

Require and incentivize processes that actively involve citizens, local businesses, and energy communities in network planning, investment, and governance. Prioritize models that maximize local jobs, reinvestment, and user buy-in, building trust, ending energy poverty, and ensuring fair transition (Energy Cities, 2024; CAN Europe, 2025).

- **Ensure climate-proof implementation, accountability, and ambition ratcheting.**

Empower EU and national regulators to monitor implementation of National Energy and Climate Plans (NECPs), enforce phased renewables targets, and demand action from lagging member states. Activate cross-border project tools, enforce climate and air quality standards, and adjust ambition every five years based on science and progress (EC, 2022; CAN Europe, 2025; EU Commission, 2025).



4.5 SUMMARY FOR DECISION MAKERS

Thermal networks—also called district heating and cooling or district energy—are central to the energy transition, urban sustainability, and industrial decarbonization in Europe and globally. By integrating a diverse range of heat and cold sources (including solar, biomass, geothermal, large-scale heat pumps, waste heat from industry and data centres, and even nuclear), thermal networks reliably supply affordable, low-carbon energy to millions of buildings and entire communities (Euroheat & Power, 2025).

They amplify the system value of renewables, help cities leverage industrial and digital waste heat, and provide critical flexibility and resilience in the face of climate-driven extremes and electrification challenges. Storage and smart digital controls turn networks into powerful “energy sponges,” moderating grid loads and capturing value from variable electricity markets. Capital investments in networks create local jobs, lift air quality, and fortify urban resilience (JRC, 2023).

However, rapid expansion faces challenges—from upfront cost and regulatory fragmentation to old infrastructure and unfair fossil fuel subsidies. Overcoming these requires clear mandates for city and regional network planning, fossil fuel exit strategies, market access for new heat suppliers, and next-generation digitalization and incentives. Social engagement, equity, and local benefit sharing should be woven into every policy and financing action.

STRATEGIC RECOMMENDATIONS

- **Develop and implement clear national and local decarbonisation strategies for the thermal sector**, anchored in mandatory heating and cooling plans. These strategies must coordinate electricity, gas, and thermal systems to enable sector coupling and maximize the use of local renewable and waste heat sources.
- **Empower and require cities and regions to develop and implement local heating and cooling plans**, supported by robust financial, analytical, and regulatory frameworks. Planning should identify optimal zones for district energy versus individual solutions to ensure cost-effectiveness and energy efficiency.
- **Accelerate permitting and investment for thermal networks and storage** where renewable or waste heat sources are available. Policies should streamline approval processes for large-scale thermal storage and renewable connections, which are essential for buffering peak loads and integrating variable renewables.



- **Ensure that thermal energy planning is systematically followed by thermal energy action.** Frameworks must move beyond planning to execution, ensuring that identified potentials for waste heat recovery and renewable integration are realized through concrete investment pipelines.
- **Elevate social co-creation, community ownership, and regional job strategies.** Investments in thermal networks should be leveraged to create skilled local jobs in construction, operations, and digital infrastructure, while ensuring fair cost-sharing and tackling energy poverty.
- **Promote "Conserve, Connect, Convert" as a simple, actionable guiding principle:**
 - **Conserve:** Reduce demand through efficient buildings, smart controls, and lower-temperature operation.
 - **Connect:** Link more buildings and waste-heat sources to district heating and cooling grids to improve economic viability.
 - **Convert:** Switch existing systems from fossil fuels to efficient use of renewables, waste heat, and heat pumps.

Thermal networks are a critical enabler of net-zero, energy security, and social welfare.

Real-world experience shows that smart, ambitious, and inclusive thermal networks can deliver cleaner air, more stable bills, and higher public trust.

Over the coming decade, national governments, cities, regulators, investors, and international organizations must move from viewing heating and cooling as a residual challenge to treating thermal decarbonization as a strategic priority.

By adopting clear thermal decarbonization strategies, mandating and resourcing local heating and cooling plans, accelerating thermal networks, and placing people and jobs at the centre of every project, decision-makers can turn today's fragmented thermal systems into resilient, low-carbon backbones of prosperity.

The opportunity is clear, the solutions are available, and the next investment cycle will determine whether the full potential of thermal networks is realised.

Strong leadership and focused investment are needed to unlock thermal networks' full potential as a backbone of a smart, resilient and climate-safe future.



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