2024 TECHNICAL UPDATE

Mapping Heating and Cooling Loads to Assess the Potential of Thermal Energy Networks

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3002029431

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ACKNOWLEDGMENTS

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner: *Mapping Heating and Cooling Loads to Assess the Potential of Thermal Energy Networks.* EPRI, Palo Alto, CA: 2024. 3002029431.

ABSTRACT

Thermal energy networks offer a neighborhood-scale decarbonization strategy, using shared infrastructure to efficiently transfer thermal energy among interconnected buildings and shifting the focus from individual building-level solutions. While pilot projects have demonstrated localized benefits, the broader impacts of scaling thermal energy networks in the U.S. have not been explored. Assessing the full potential of these systems requires a systematic approach to identifying feasible deployment sites, assessing their technical and economic potential, and their integration into long-term energy system models. This report addresses the first step by (1) establishing key criteria for assessing the feasibility of thermal energy networks and (2) developing a geospatial methodology to map thermal energy sinks. The analysis presents a case study in Framingham, Massachusetts using scalable tools and publicly available geodata to characterize building stocks, calculate heating and cooling loads, and identify high-density load centers. Building-level heating and cooling load profiles are calculated using a gray-box model, aggregated into a thermal energy demand density map, and used to identify and characterize thermal sinks within the study area. The identified thermal sink aligns with sites selected for a potential thermal energy network pilot project, validating the methodology. Finally, the report provides guidelines to expand the analysis and advance the assessment of the system-wide value of large-scale deployment of thermal energy networks.

Keywords

Thermal energy networks
Heating and cooling
Energy density
Buildings
Decarbonization

ACRONYMS AND ABBREVIATIONS

CDD	cooling degree days
CHP	combined heat and power
DOC	demand overlap coefficient
GIS	geographic information systems
HDD	heating degree days
IRA	Inflation Reduction Act
LBI	load balance index
TEN	thermal energy networks
US-REGEN	U.S. Regional Economy, Greenhouse Gas, and Energy
1R1C	one resistance, one capacitance
5GDHC	5th Generation District Heating and Cooling

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1 INTRODUCTION

Motivation

Buildings account for approximately 28% of total energy consumption in the U.S. (EIA, 2024), with more than half of that energy used for heating and cooling (EIA, 2020). Addressing this significant energy demand is critical for meeting national climate goals, particularly as the U.S. aims to achieve net-zero emissions by 2050 (EPRI, 2022). Current approaches to decarbonizing buildings primarily involve electrification and efficiency improvements of heating and cooling systems at the building level, such as replacing gas furnaces with heat pumps (Molar-Cruz, Venkatesh, & Zhu, 2024). However, such building-by-building approach risks exacerbating grid challenges, increasing costs, and creating inequities for low-income households unable to afford upgrades (Camargo, Silber-Byrne, Schulman, & Magavi, 2024).

Thermal energy networks (TEN) offer an alternative decarbonization strategy by shifting the focus from individual buildings solutions to neighborhood-scale approaches. These networks use shared water-based infrastructure to transfer thermal energy among interconnected buildings, delivering heating and cooling services with higher efficiency and lower emissions (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). By harnessing renewable energy sources, nuclear energy, and waste heat, TEN can significantly contribute to reduce the carbon footprint of buildings (Boesten, Ivens, Dekker, & Eijdems, 2019). Moreover, TEN can provide technical and economic benefits, including cost savings through economies of scale and reduced electric peak and annual building loads, which can enhance grid reliability. TEN also can promote equitable access to low-carbon energy by distributing infrastructure costs among connected buildings, potentially making clean energy solutions accessible to a broader range of households. This is particularly relevant in disadvantaged communities, where increasing access to affordable, clean resources can alleviate energy burdens while supporting environmental justice (Camargo, Silber-Byrne, Schulman, & Magavi, 2024).

Despite the potential of TEN, energy systems at the district scale in the U.S. remains largely confined to university and college campuses, hospital or research institutions, military bases and airports, and central business districts with legacy steam and hot water systems (U.S. Department of Energy, 2021). Expanding efficient low-temperature networked systems into urban neighborhoods and mixed-use areas presents an untapped opportunity to decarbonize the building sector at scale. Utility TEN pilot projects in the U.S. (e.g. Massachusetts (Eversource, 2024) and New York (Con Edison, 2024; National Grid, 2024)), currently under different development stages, are showcasing the feasibility of such systems, offering insights into the operational, economic, and regulatory considerations for scaling TEN nationwide.

While pilot projects demonstrate localized benefits, the system-wide impacts and economic competitiveness of TEN as part of a U.S. net-zero energy future remain underexplored. Unlocking their potential requires a systematic approach to identifying viable TEN deployment sites, assessing their technical and economic feasibility, and their integration into long-term energy system models. These analyses are critical for assessing the value of community- or district-scale solutions and understanding their cross-sectoral implications.

This project lays the groundwork for scaling TEN by conducting a concise literature review of TEN applications in the U.S. and globally, along with a literature-based synthesis of criteria for assessing their feasibility. Additionally, it introduces a systematic methodology to identify high-potential deployment sites through thermal energy density mapping. While this work represents an initial step, it provides a basis for evaluating TEN's role in a net-zero future.

Objectives and Scope

This project is the initial phase of assessing the system-level impacts of large-scale TEN deployment across the U.S. The main objectives of this report are:

- **to provide a concise overview of the state-of-the-art in TEN,** including a clear definition of these networks and the identification of criteria for determining their feasibility.
- **to develop a geospatial methodology to map heating and cooling loads and identify potential thermal sinks**, leveraging geographic information systems (GIS) tools and publicly available datasets to support its application at scale. To validate the proposed methodology, it is applied to a selected case study, demonstrating its practicality and effectiveness in identifying high-potential sites for TEN deployments.
- **to offer recommendations for advancing the evaluation of TEN's potential role in the broader energy system**.

2 OVERVIEW OF THERMAL ENERGY NETWORKS

Definition

Thermal Energy Networks (TEN)[1] are systems designed to efficiently distribute thermal energy among interconnected buildings to meet their heating and cooling demands. These networks leverage shared infrastructure for the bidirectional exchange of thermal energy, optimizing energy use and balancing heating and cooling loads across the system as depicted in Figure 1.

Unlike traditional district heating and cooling systems, which typically rely on centralized thermal power plants supplying thermal energy to all connected buildings via high-temperature supply and return pipes, TEN operate at lower temperatures, closer to ambient conditions. In a typical TEN, there are two separate pipe loops, warm and a cold, operating at relatively low temperatures but with a temperature differential of 5–10 K (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). In some TEN configurations, with thermally balanced loads, a single pipe loop may be sufficient (see Figure 1 in (Camargo, Silber-Byrne, Schulman, & Magavi, 2024).

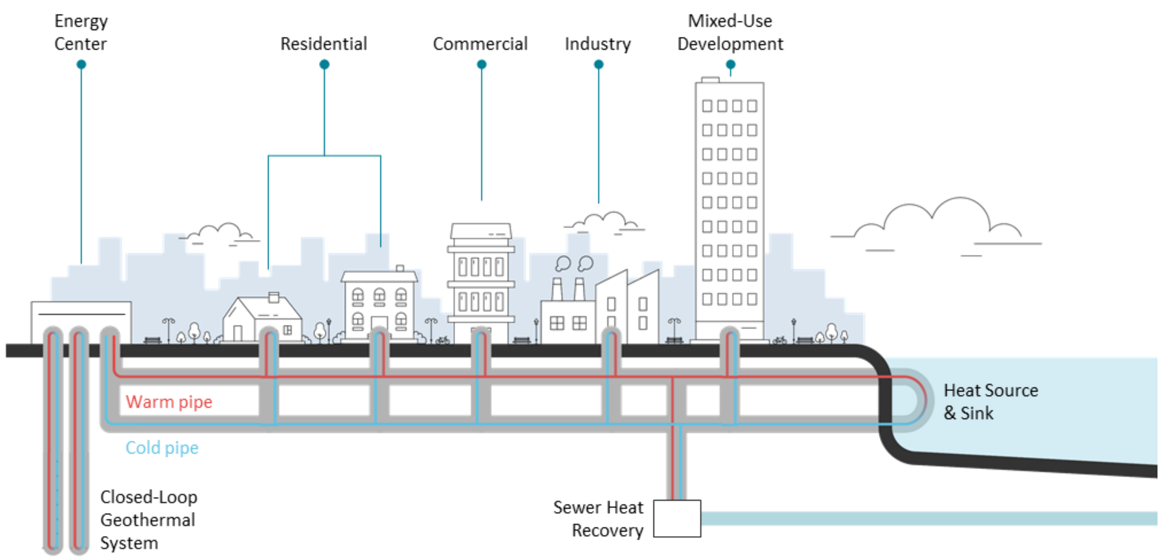


Figure 1. Two-pipe loop thermal energy network with multiple heat sources and heat sinks.

[1] Thermal energy networks are referred to by various names in literature, reflecting their technological and operational characteristics. Common terms include 5th Generation District Heating and Cooling (5GDHC) (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; Dang, et al., 2024), bidirectional low-temperature networks (Bünning, Wetter, Fuchs, & Müller, 2018), balanced energy networks (Song, Wang, Gillich, Ford, & Hewitt, 2019), ultra-low temperature district heating and cooling (Messenburg, Ommen, Thorse, & Elmegaard, 2020), and cold district heating (Pellegrini & Bianchini, 2018). When integrated with geothermal energy, they are often referred to as geothermal energy networks, community geothermal or district geothermal (Camargo, Silber-Byrne, Schulman, & Magavi, 2024). This work utilizes the term *thermal energy networks* to denote the full diversity of technologies and applications described in literature, consistent with its growing usage in the U.S. energy sector.

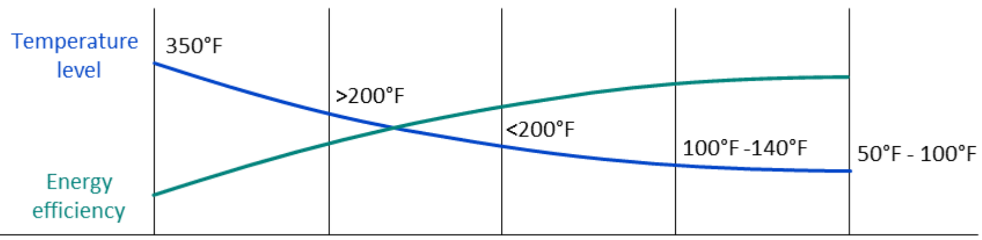
Individual buildings connected to the network are equipped with heat pumps, which deliver the required temperature to meet the building specific heating or cooling requirements. In heating mode, a building's heat pump extracts heat from the warm pipe loop, raising its temperature to the level needed for the building's heating system, and discharges the cooled water into the cold pipe. Conversely, in cooling mode, the heat pump removes heat from the building and transfers it to the warm pipe, with the cold pipe providing the necessary cooling medium.

A key advantage of TEN is their ability to utilize both thermal sources and sinks, optimizing local energy flows to enhance efficiency and flexibility. Thermal sources include, for example, geothermal energy, waste heat from industrial processes, data centers, and combined heat and power (CHP) plants, as well as thermal energy extracted from water bodies or solar thermal systems (Wirtz, Kivilip, Remmen, & Müller, 2020). Thermal sinks are primarily the heating or cooling demands of the buildings within the network. TEN's bidirectionality enables waste heat from cooling processes in one building to be reused to meet the heating needs of another, reducing thermal imbalances. When internal balancing is insufficient, excess heat can be dissipated to external sinks such as water bodies or ambient air, and external thermal sources are incorporated to ensure consistent energy availability. This dynamic integration of thermal sources and sinks allows TEN to align local energy supply with demand, maintain reliable performance, and adapt to seasonal variations in heating and cooling loads.

The low-temperature operation of TEN minimizes thermal losses and allows for the integration of renewable energy sources, making them highly efficient and environmentally sustainable (Boesten, Ivens, Dekker, & Eijdems, 2019). Moreover, the decentralized nature of TEN offers greater flexibility compared to traditional district heating and cooling systems, enabling the adaptation of network configurations to suit diverse urban contexts and building clusters. TEN can be configured to provide heating, cooling, or both, depending on the needs of the connected buildings and available resources. By emphasizing localized energy exchange, resource efficiency, and operational flexibility, TEN can play a critical role in the decarbonization of the buildings sector.

Evolution of Heating and Cooling Networks

The evolution of district energy networks showcases a progressive shift toward meeting heating and cooling demands with increased efficiency and integration of sustainable energy systems. This progression is depicted in Figure 1 adapted from Lund et al. (2014) and Wirtz et al. (2020). The first generation was introduced in the late 19th century and relied on high-temperature steam from coal-fired boilers, leading to substantial heat losses and safety risks. The second generation transitioned to pressurized hot water above 200°F, primarily supplied by fossil fuel-based CHP plants driven by fuel savings and reduced costs. By the 1970s, the third generation emerged, with reduced temperatures below 200°F and the adoption of pre-insulated pipes. Motivated by increasing the security of supply and short-term marginal costs, these innovations enabled the integration of local energy sources like biomass and industrial waste heat. The fourth generation lowered supply temperatures further, to the hot water supply temperature (100-140°F), and expanded the use of renewable sources, such as geothermal and solar thermal, while increasing compatibility with energy-efficient buildings. The latest and the focus of this study, the fifth generation, operates at near-ambient temperatures and uses bidirectional networks to balance heating and cooling demands, and integrates shallow geothermal, low-grade waste heat, and other low-temperature renewable sources.



	1st Generation 1880-1930	2nd Generation 1930-1980	3rd Generation 1980-2020	4th Generation >2020	5th Generation >2020
Heat carrier	Steam system	Pressurized hot water system	Pressurized hot water system	Low-temperature water system	Very low-temperature water system
Thermal power generation	Centralized coal steam boilers and some CHP	Centralized fossil CHP and some heat-only boiler	Centralized fossil CHP, biomass and waste heat	Decentralized waste heat, renewable sources	Decentralized waste heat, renewable sources
Service demand	Heating	Heating	Heating	Heating **or** Cooling	Heating **and** cooling
Urban energy density in GWh/km²/year [~bn. BTU/mi²/year]	>300 [>2600]	200-300 [1700-2600]	100-200 [800-1700]	50-150 [400-1300]	50-150 [400-1300]

Figure 2. Evolution of district energy systems adapted from (Lund et al., 2014) and (Wirtz et al., 2020). Thermal Energy Networks (TEN) are the 5th and latest stage in the evolution of community-level heating and cooling systems.

For a comprehensive overview of the different generations of district energy systems and a detailed comparison of their features, Dang et al. (2024) provide a thorough summary of literature reviews on district heating and cooling systems, tracing the ongoing evolution of these technologies. It is worth noting that the concept of *fifth generation district heating and cooling* (5GDHC) remains ambiguous, as many definitions emphasize the temperature level of the distribution medium or specific applications, leading to confusion among different technologies (Yao, Wu, & Qadrdan, 2024; Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). This study adopts the term *thermal energy networks* as it captures the broad diversity of technologies and applications while aligning with terminology increasingly used in the U.S. energy sector.

Global Perspectives on Thermal Energy Networks

District energy systems have been central to urban energy infrastructure, with district heating systems operating in Europe and the U.S. for over a century. According to Muncán et al. (2024), there are more than 17,000 operational district heating systems in Europe, serving around 70 million citizens and supplying over 450 TWh (1.5 quadrillion BTU) of heat. In countries such as Denmark, Estonia, Lithuania, and Sweden, district heating meets more than 50% of residential heating demand. District energy systems in Europe rely on diverse heat sources including CHP plants, waste heat, geothermal energy, biomass, and solar thermal systems. District cooling in Europe remains underdeveloped, primarily serving commercial buildings in warmer regions, such as France, or in countries with advanced district heating infrastructure, such as Sweden. European district energy systems range from first to fifth generation technologies, with Europe leading in fifth-generation adoption, particularly in Germany and Switzerland, where over 40 operational TENs existed by 2019 (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019).

In the U.S., over 660 district energy systems operate across all states, serving 5.5 billion square feet of heated space, mainly in commercial and institutional buildings such as universities, hospitals, and military bases (U.S. Department of Energy, 2021). Most of these systems are first generation legacy networks that use steam distribution systems to provide thermal energy for space heating and hot water needs of connected buildings. They predominantly rely on fossil fuels, particularly natural gas, often in CHP plants. Additionally, district energy systems meet cooling demands for 1.9 billion square feet through electric and hybrid chiller plants, frequently coupled with thermal storage. Modern TENs (fifth generation systems) are in the early stages of adoption in the U.S., primarily concentrated on university and college campuses, and private residential developments (Camargo, Silber-Byrne, Schulman, & Magavi, 2024).

The expansion of TEN is strongly influenced by regulatory and policy frameworks. In Europe, directives under the European Green Deal and the Clean Energy for All Europeans package, provide a comprehensive framework for decarbonizing the buildings sector, including the expansion of thermal energy networks (European Comission, 2023). The Renewable Energy Directive sets renewable targets for heating and cooling, while the Energy Efficiency Directive promotes local heating and cooling plans and aims for fully decarbonized systems by 2050. The Energy Performance of Buildings Directive enhances building efficiency and supports clean heating and cooling.

In the U.S., the federal goal of achieving net-zero emissions by 2050, coupled with state-level commitments, drives innovation in decarbonizing the building sector. Specific to TEN, initiatives such as the Community Geothermal (Department of Energy (DOE), 2023) support feasibility studies for geothermal-based networks nationwide. The Inflation Reduction Act (IRA) further incentivizes adoption by offering a tax credit of up to 50% for geothermal network investments. At the state level, legislation in Massachusetts, Minnesota, New York, Colorado, Washington, Maryland, and Vermont allows utilities to install and operate TEN pilot projects, with a focus on transitioning from natural gas to geothermal systems. Nationally, 19 utility-led pilots are in various stages, from feasibility studies to construction, with significant activity concentrated in Massachusetts, Minnesota, and New York. (Camargo, Silber-Byrne, Schulman, & Magavi, 2024)

3 ASSESSING THE FEASIBILITY OF THERMAL ENERGY NETWORKS

The feasibility of TEN depends on a diverse set of factors that influence their technical, economic, environmental, regulatory, and participatory dimensions as summarized in Table 1. These factors were identified through a comprehensive review of pilot project feasibility studies (HEET and BuroHappold Engineering, 2023; NSTAR Gas Company, d/b/a Eversource Energy and CDM SMith, 2022), site selection guidelines (HEET, 2021), and related literature (Zach, Erker, & Stoeglehner, 2019; Spirito, et al., 2024; Novosel, Grozdek, Domac, & Duić, 2021). Together, they provide a high-level framework for systematically characterizing the TEN deployment potential for large geographies. By assessing regions against these factors, the framework pinpoints areas that are favorable for TEN implementations across all relevant dimensions. However, while effective for broad-scale assessments, these factors represent a preliminary step; more detailed, site-specific analyses will be required to address the complexities of project planning and execution.

Table 1. Technical, economic, environmental, regulatory, and participatory factors for assessing the feasibility of thermal energy networks.

Category	Factor	Description
Technical	Thermal sink potential	Energy density, peak heating and cooling demand, seasonal variability, load diversity, full load hours, and thermal balance of energy demand centers or thermal sinks.
	Thermal source potential	Thermal capacity, capacity factor, and seasonal variability of thermal sources (e.g., geothermal, waste heat).
	Source-sink matching	Spatial and temporal alignment of supply (thermal sources) and demand (thermal sinks).
	Compatibility with building systems	Integration with existing buildings (e.g. heating and cooling systems, electric panel, thermal efficiency).
	Compatibility with infrastructure	Integration with existing infrastructure (e.g., street network, gas and water networks, rail corridors).

	Scalability and flexibility	System ability to expand and adapt to future demands or changes in energy usage.
	System reliability	Reliability and resilience to potential disruptions including availability of thermal sources and extreme weather events.
Economic	Capital investment	Initial capital investment for design, installation, and deployment, including necessary retrofits in the existing buildings and infrastructure.
	Operational costs	Operational and maintenance costs for the whole system
	Financial incentives	Availability of subsidies tax credits or other incentives to reduce the financial burden of the project.
	Payback period	Time required to recover the initial investment through revenue or cost savings.
	Risk assessment	Financial and operational risks (e.g. market changes, regulatory uncertainty, technology readiness)
	Competitiveness	Competitiveness with alternative heating and cooling technologies.
	Cross-sectoral impacts	Impacts on other sectors of the energy-economy system (e.g. power, gas)
Environmental	GHG reduction potential	Potential for reduction of GHG in the buildings sector.
	Environmental impact	Local and regional impacts on air quality, ecosystems, biodiversity, and land use.
Regulatory	Land-use regulations	Local and regional land-use and zoning regulations.

	Permitting requirements	Administrative processes and approvals for project implementation.
	Legal frameworks	Existing legal structures defining roles, responsibilities, and ownership within the project.
	Policy alignment	Local, state-level and national policies supporting project development.
Participatory	Stakeholder engagement and support	Stakeholder (e.g. community, utilities, government) engagement during planning, implementation, and operation.
	Equitable energy access	Equitable access to energy services for all community members.

Assessing the thermal sink and thermal source potential are key, as they directly influence the technical and economic viability of a TEN. The ability to identify and characterize thermal sinks ensures that the energy demand is sufficiently dense, diverse, and balanced to justify the investment and operational costs. Given its central role, the next section of this report is dedicated to presenting a methodology for effectively identifying and characterizing thermal sinks, thereby supporting informed decision-making in TEN planning and deployment.

4 MAPPING AND CHARACTERIZATION OF THERMAL ENERGY SINKS

General Workflow

Identifying thermal energy sinks is a key step in assessing the feasibility of TEN in any area. The workflow for their mapping and characterization, outlined in Figure 3, begins with the characterization of the building stock. Building-level attributes, essential for estimating heating and cooling load profiles, are sourced from publicly available datasets, calculated, or estimated using probabilistic approaches derived from aggregate statistics.

Heating and cooling demand profiles for individual buildings are calculated using a 1R1Cmodel[2], a practical and computationally efficient method. These demands are then aggregated at a higher spatial resolution to map the distribution of thermal loads and identify high-demand zones. Thermal energy sinks are defined as areas where aggregated demands exceed a specified threshold, with additional parameters like local thermal balance used to assess their suitability for TEN. This methodology, which is flexible and adaptable, can be applied to any geographic area to identify and characterize thermal energy sinks. Its application is demonstrated in a case study of Framingham, Massachusetts in Section 5.

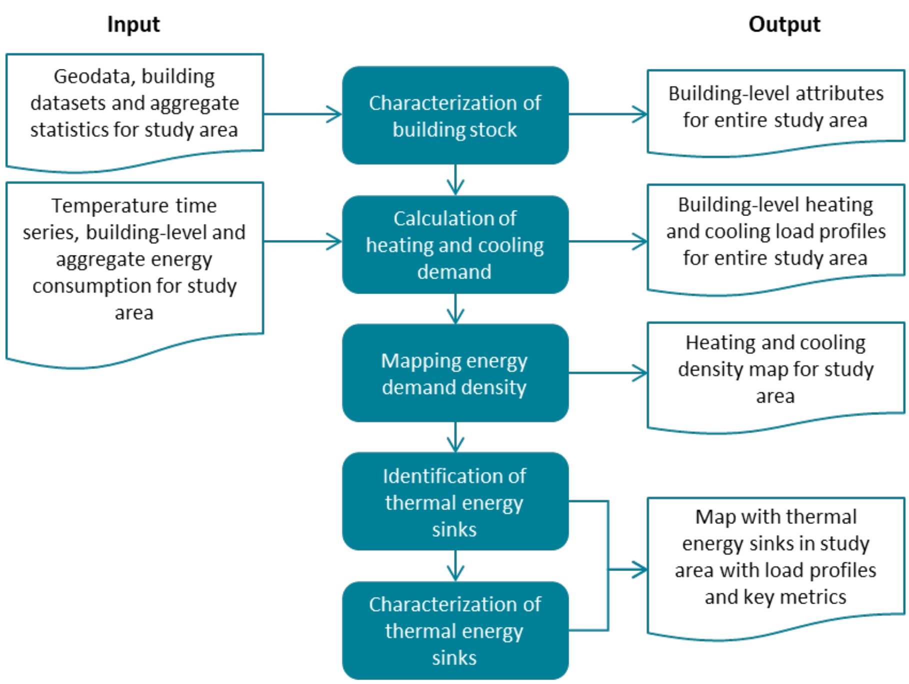


Figure 3. Workflow for mapping and characterization of thermal energy sinks.

[2] A physics-based gray-box model that simplifies the thermal properties of a building using one equivalent resistance (1R) and one capacitance (1C) to represent the heat transfer process.

Characterization of Building Stock

Buildings are parametrized in terms of their physical properties and the behavior of their occupants. Since detailed micro-level data is often incomplete or unavailable for many urban areas, this work proposes the creation of a synthetic building stock. Synthetic building stock modeling addresses the limitations of data availability by generating individual building data from aggregated building stock statistics (Nägeli, Jakob, Catenazzi, & Ostermeyer, 2018). This data is geographically allocated using probabilistic GIS-based methods, ensuring that the synthetic representation mirrors the distribution and urban form of the real area under analysis. As a result, the synthetic building stock approximates the diversity in building characteristics and urban layouts.

The attributes required to calculate heating and cooling loads at the building scale depend on the specific calculation method employed, as detailed in the following subsection. The building and occupant attributes used in this project are summarized in Table 2. The data sources and calculation methods for these attributes for the study area are outlined in Section 5.

Table 2. Building-level attributes used for the calculation of heating and cooling loads.

Attribute	Description/Value
Buildings use	Residential, commercial
Building type	Residential: mobile home, single-family detached, single-family attached, multi-family 2-4 units, multi-family 5+ units Commercial: education, food, healthcare, lodging, office, public, retail, supermarkets, public, warehouse
Building vintage	<1950, 1950-1969, 1970-1989, 1990-2009, >2010
Floor area	Total building floor area
Envelope area	Surface area of building elements (roof, floor, wall, window)
U-value	Thermal transmittance of building elements
Thermal capacity	Thermal capacity of building elements
Ventilation/infiltration rate	Rate of incoming air at ambient temperature
Number of housing units	Total number of housing units in residential building
Number of occupants	Total number of occupants living in residential building
Conditioned floor area	Share of floor area that is heated or cooled
Setpoint temperature	Desired building internal temperature for heating and cooling
Occupancy profile	Schedule, density, and activity patterns of occupants over time
Building orientation	Positioning of building relative to the sun

Calculation of Heating and Cooling Demands

Thermal demands in buildings can be classified into building space conditioning, domestic hot water, industrial process heat and refrigeration, and commercial heating and cooling (e.g. swimming pools, data centers). This analysis focuses on building space conditioning, where heating and cooling loads are defined as the thermal energy required to maintain a set indoor air temperature.

Different modeling approaches for building space conditioning are categorized into white-box, black-box, and gray-box models. White-box models, which rely on a detailed physical description of buildings and occupant behavior, are highly accurate but data-intensive. In contrast, black-box models use statistical or historical consumption data, requiring no building-specific information. Gray-box models combine physical properties with statistical approaches, balancing accuracy and practicality. For estimating space heating and cooling profiles, grey-box models lump and represent the thermal properties of building components through resistances (R) and capacitances (C), analogous to an electrical network. RC models can range from 1R1C (Park, Ruellan, Bouvet, Monmasson, & Bennacer, 2011) to up to 13R9C (Protopapadaki, Reynders, & Saelens, 2014) depending on available building data and modeling application. A condensed literature review on grey-box modeling for space heating can be found in (Sperber, Frey, & Bertsch, 2020).

A 1R1C model is employed in this study to calculate space heating and cooling demands for individual buildings (Figure 4). While higher-order RC models can provide more detailed thermal behavior, the 1R1C model is sufficient to capture the thermal response of buildings for large-scale urban analyses (Harb, Boyanov, Hernandez, Streblow, & Müller, 2016). This model effectively represents transient heating and cooling demands with limited data requirements and computational effort, making it ideal for regional and national assessments.

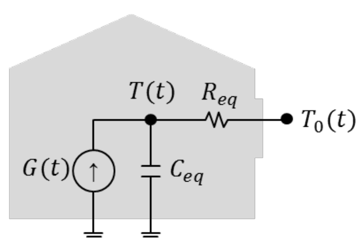


Figure 4. 1R1C representation of a single-zone building.

Assuming a time-dependent ambient temperature $T_0(t)$, the dynamic thermal balance of a building (residential or non-residential) considers the interaction between thermal losses and thermal gains over time. Thermal losses occur through the building envelope due to transmission and ventilation, which depend on the temperature difference between the indoor and outdoor environment and are governed by the equivalent heat transfer coefficient R_{eq}. Thermal gains ($G(t)$ in Figure 4), on the other hand, include internal sources such as occupants and appliances, solar radiation, and external thermal inputs or removals, such as active heating and cooling systems.

In the 1R1C model, the building is treated as a heat accumulator with a uniform internal temperature T and an equivalent heat capacity or thermal mass C_{eq}. The change in indoor temperature over time is determined by the combined effects of heat losses, heat gains, and the thermal properties of the building's components. The equivalent thermal parameters aggregate the properties of building elements, such as the roof, walls, floor, and windows, weighted by their surface area. This framework facilitates the calculation of the building internal temperature under specific external conditions as well as the thermal input needed to maintain a stable indoor temperature following the equation below:

$$\frac{dT}{dt} = \frac{1}{C_{eq}} \cdot \left(\frac{T_0(t) - T(t)}{R_{eq}} + G(t) \right)$$

User behavior is incorporated into the gray-box model by specifying a desired indoor temperature to be maintained when the building is occupied. Additionally, a time-dependent occupancy or activity profile is defined to reflect variations in required external thermal input (heating or cooling) based on occupancy patterns.

Mapping Thermal Energy Demand Density

The spatial aggregation of heating and cooling demands enables the mapping of thermal energy demand density. Aggregation is performed over defined grid sizes depending on the objectives of the study. For identifying potential district and cooling heating systems, demand data is typically aggregated into cells of 0.25 to 1 km^2 (approximately 0.1 to 3.5 square miles) (Lefrère & Cerema, 2019; Gils, Cofala, Wagner, & Schöpp, 2013). These sizes strike a balance between spatial resolution and computational efficiency, capturing localized high-demand clusters while avoiding excessive granularity.

In this study, hexagonal cells around 0.28 square miles are used, aligning with the maximum size of identified potential sites for TEN projects in Framingham, Massachusetts (NSTAR Gas Company, d/b/a Eversource Energy and CDM SMith, 2022) as well as with other EPRI efforts mapping high-resolution energy demand (EPRI, 2024). While further refinement may be needed for the detailed feasibility assessment of individual TEN projects, this level of aggregation provides a valuable initial estimation.

Identification of Thermal Energy Sinks

Thermal energy sinks are characterized based on their thermal energy demand density to ensure sufficient demand density for economic viability and system utilization. These thresholds vary depending on the system configuration and efficiency, as depicted in Figure 2, with typical values ranging from 50 to 150 GWh/km^2/year (approximately 400-1,300 billion

BTU/mi²/year). Following the methodology outlined in (Molar-Cruz, et al., 2022), thermal energy sinks are identified as contiguous areas meeting a minimum energy demand density. Specifically, hexagons with a demand density of at least 400 billion BTU/mi²/year are grouped, and lower-density hexagons are included if they connect high-density zones. Clusters with a total annual thermal demand below 800 billion BTU (100 GWh) are excluded, as they are unlikely to be economically viable for district energy systems (Moller & Werner, 2016).

Characterization of Thermal Energy Sinks

Besides the demand density of thermal energy sinks, other key metrics are necessary to characterize the thermal demand structure and external energy requirements, providing a comprehensive basis for analyzing the feasibility of TEN systems in urban areas. In this study, two metrics are used for describing the thermal balancing potential and the type and size of external thermal sources required to balance the thermal demands of the sink.

Demand Overlap Coefficient

The DOC measures the extent to which heating and cooling demands in a given area overlap, indicating the potential for internal balancing within a thermal sink (Wirtz, Kivilip, Remmen, & Müller, 2020). This metric represents the proportion of heating and cooling demands that can be canceled out in the system as illustrated by the gray area in Figure 5.

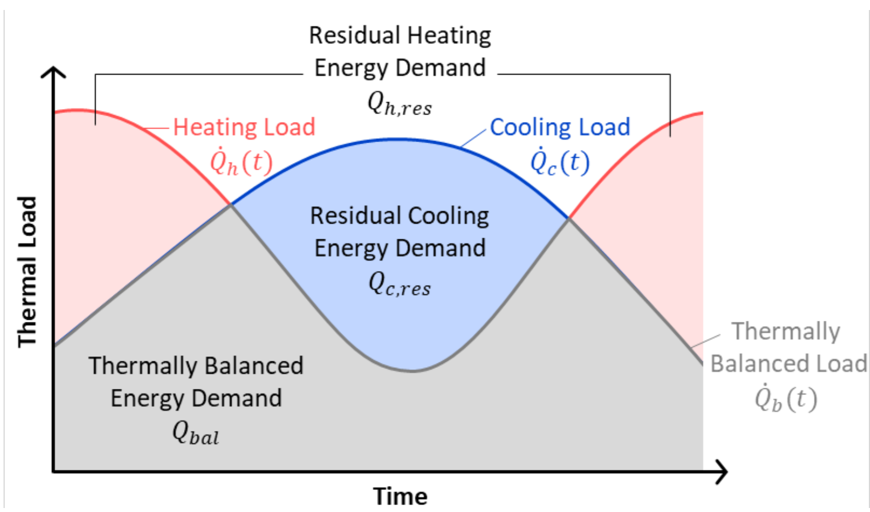


Figure 5. Heating (red) and cooling (blue) load profiles for a given area. The overlap of both load profiles is the thermally balanced energy demand (gray). Adapted from (Wirtz, Kivilip, Remmen, & Müller, 2020).

For a thermal energy sink with B buildings, the DOC is calculated solely on the basis of building energy demands as

$$DOC = \frac{2 \cdot \sum_t \min\left[\sum_{b \in B} \dot{Q}_{h,b,t}, \sum_{b \in B} \dot{Q}_{c,b,t}\right]}{\sum_t \sum_{b \in B} (\dot{Q}_{h,b,t} + \dot{Q}_{c,b,t})}$$

A DOC value of 0 signifies no overlap, meaning heating and cooling demands occur at different times and cannot offset each other. Conversely, a DOC of 1 indicates perfect overlap, where heating and cooling demands align in time and magnitude, maximizing the potential for internal balancing. However, the DOC is an approximation, as the temperature of waste heat from cooling applications often requires adjustment using heat pumps or chillers before it can be used for heating. Residual demands that cannot be balanced internally must be met by external thermal sources, either at the building level or through a network-wide system. By identifying areas with higher DOC values, planners can prioritize regions with greater potential for efficient integration into TEN.

Load Balance Index

The Load Balance Index (LBI) identifies whether a thermal energy sink is heating-dominated, cooling-dominated, or balanced, helping determine the type of external supply required. It is calculated as

$$LBI = \frac{Q_h - Q_c}{Q_h + Q_c}$$

where Q_h and Q_c are the thermal sink annual demands for heating and cooling, respectively.

LBI ranges from -1 to 1, where a value of -1 indicates that the area is entirely cooling-dominated, and a value of 1 signifies complete heating dominance. An LBI of 0 represents a balanced load, suggesting significant potential for recovering waste heat and minimizing reliance on external sources. In contrast, systems with extreme LBI values lack load diversity, reducing their efficiency and increasing the need for external energy inputs. This metric is valuable for evaluating the feasibility of TEN, as it helps identify areas where external sources, such as renewable heating or cooling, might be needed to achieve a balanced thermal load.

The suitability of a thermal sink for integration into a TEN cannot be determined solely from the calculated indices, as additional information about the available thermal sources is required to evaluate their ability to balance the loads. However, the indices provide key insights into the type and size of external thermal sources needed to achieve balance in the area.

5 CASE STUDY: FRAMINGHAM, MASSACHUSETTS

The methodology for the identification and characterization of thermal energy sinks described in Section 4 is applied to Framingham, Massachusetts, selected as a case study as a TEN pilot project is under construction (Eversource, 2024). Existing feasibility studies for the project (NSTAR Gas Company, d/b/a Eversource Energy and CDM SMith, 2022) provide a foundation for high-level validation of the proposed approach.

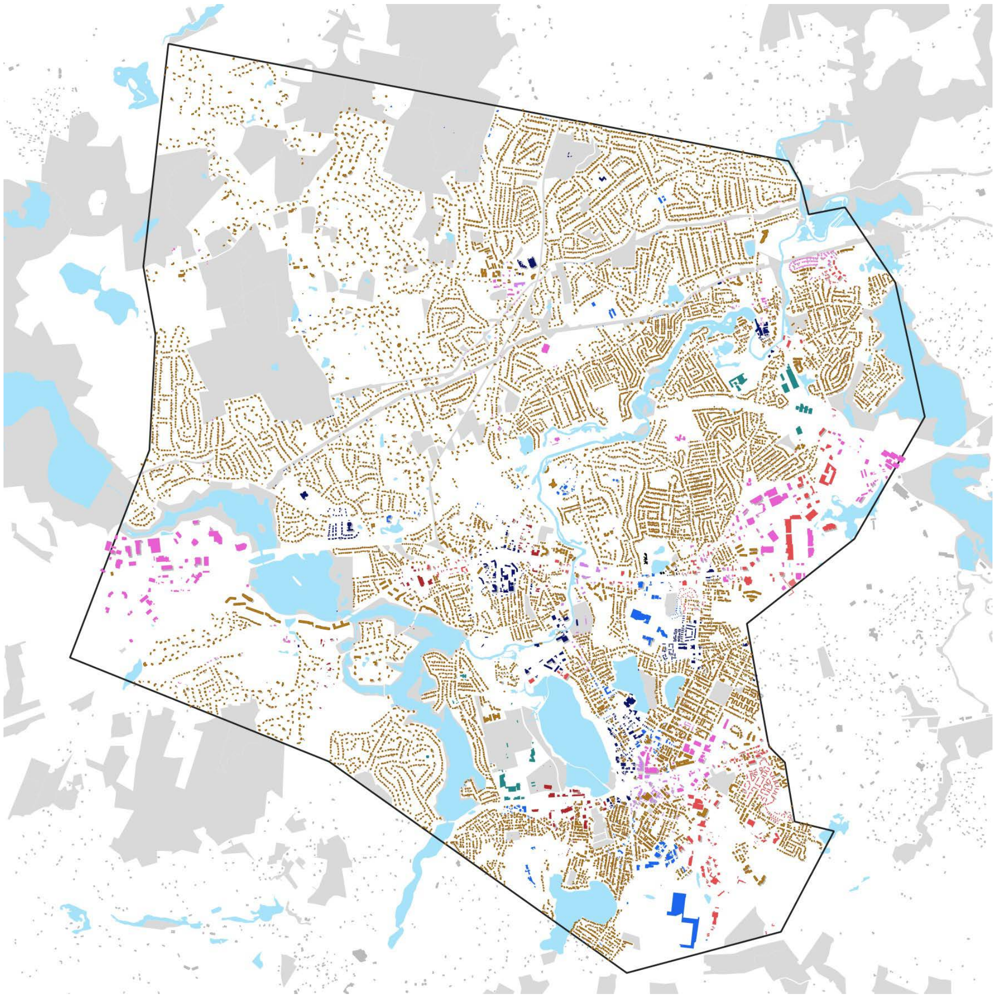
Characterization of Building Stock

The characterization of the building stock in Framingham begins with 18,076 building footprints obtained from the MassGIS portal's Building Structures (2-D) layer, which includes all buildings in Massachusetts larger than 150 square feet (Commonwealth of Massachusetts, 2024). For each building in the study area (see Figure 6), the attributes listed in Table 2 are estimated using publicly available datasets. Table 3 provides a summary of the datasets used for each attribute along with the corresponding calculation methods.

Table 3. Building attributes, calculation approach and publicly available datasets used.

Attribute	Calculation Approach	Sources
Buildings use	Spatial join of building footprints and land use polygons	Building footprints: MassGIS Data: Building Structures (2-D) | Mass.gov Land use: MassGIS Data: 2016 Land Cover/Land Use | Mass.gov
Building type	Spatial join of building footprints, land use polygons and points of interest	Building footprints: MassGIS Data: Building Structures (2-D) | Mass.gov Land use: MassGIS Data: 2016 Land Cover/Land Use | Mass.gov Points of interest: OpenStreetMap (OSM)
Building vintage	Sampled from aggregate statistics of building vintage from gridded census data	Gridded census data: U.S. Census Grids (Summary File 3), 2000 | NASA Earthdata
Floor area	Footprint area multiplied by number of floors. Number of floors determined by dividing the number of housing units by the average housing unit size in Massachusetts.	Average housing unit size in Massachusetts: 2020 RECS microdata

Envelope area	Surface area assuming a simplified representation of the building as a box, with the base corresponding to its footprint and the height calculated based on the number of floors and the floor-to-roof height of 10 feet.	Building footprints: MassGIS Data: Building Structures (2-D) | Mass.gov
U-value	Thermal transmittance value of construction materials from literature. Construction material for walls and roof, and window glazing sampled from aggregate statistics for Massachusetts.	Wall and roof materials, window glazing: 2020 RECS microdata. Thermal transmittance values: Building America Research Benchmark Definition; TABULA WebTool
Thermal capacity	Thermal capacity value of construction materials from literature. Construction material for walls and roof, and window glazing sampled from aggregate statistics for Massachusetts.	Wall and roof materials, window glazing: 2020 RECS microdata. Reference values from TABULA WebTool
Ventilation/ infiltration rate	Literature review	Reference values from TABULA WebTool
Number of housing units	Iterative assignment of number of housing units by building type, ensuring that the total number of housing units in cell matches census totals.	Number of housing units from gridded census data: U.S. Census Grids (Summary File 1), 2010 | NASA Earthdata
Number of occupants	Iterative assignment of number of occupants by housing unit, ensuring that the total number of occupants in cell matches census totals.	Population from gridded census data: U.S. Census Grids (Summary File 1), 2010 | NASA Earthdata
Conditioned floor area	Random fraction of total floor area within range. Residential: 80-100%; commercial: 40-80%	-
Setpoint temperature	Random setpoint temperature within range. Heating: 60-72°F, cooling 75-85°F	-
Occupancy profile	Random daily schedule for occupants in building	-



Number of buildings by type

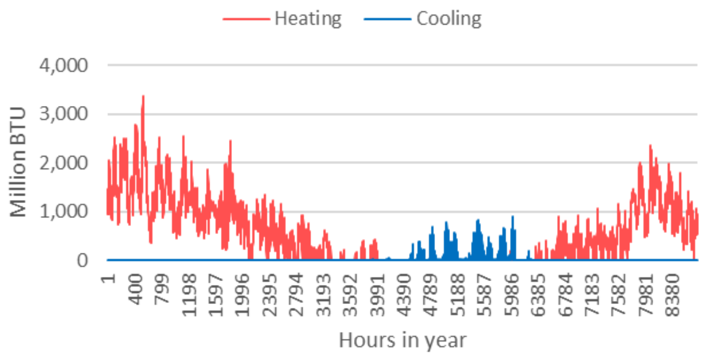
Residential	16,164
Single-family	14,326
Multi-family	1,838

Commercial	1,912
Education	288
Food	440
Healthcare	100
Lodging	11
Office	423
Public	54
Retail	441
Supermarket	141
Warehouse	14

Figure 6. Buildings in Framingham, Massachusetts by building type. Building footprints extracted from the MassGIS Portal and building types estimated from land use and points of interest layers (see Table 3 for data sources). Gray areas represent green spaces.

Mapping Thermal Energy Density

The building attributes in Table 3 are used to calculate heating and cooling demand profiles for each building in Figure 6 using hourly temperature data for year 2015 from the NASA MERRA2 dataset for the climate zone (HDD-2, CDD-5) according to the heating (HDD) and cooling degree days (CDD) classification in US-REGEN (EPRI, 2024). The resulting aggregated heating and cooling load shapes for Framingham are shown in Figure 7.



	Annual demand (billion BTU)	
	Heating	**Cooling**
Residential	3,716	115
Commercial	1,434	17
Total	5,150	132

Figure 7. Aggregated heating and cooling load profiles (left) and annual demand by buildings sector (right) in Framingham, Massachusetts calculated using building-level 1R1C model.

Buildings demands are aggregated into hexagonal cells, each covering approximately 0.28 square miles. The maps in Figure 8 illustrate the spatial distribution of space heating and cooling demands for both the residential and commercial sectors. In Framingham, the heating and cooling demand patterns differ significantly. Space heating is closely aligned with building density, particularly in residential and mixed-use areas, while space cooling is predominantly concentrated in commercial zones. However, the heating demand in the hexagons with the highest values is approximately 13 times greater than the cooling demand.

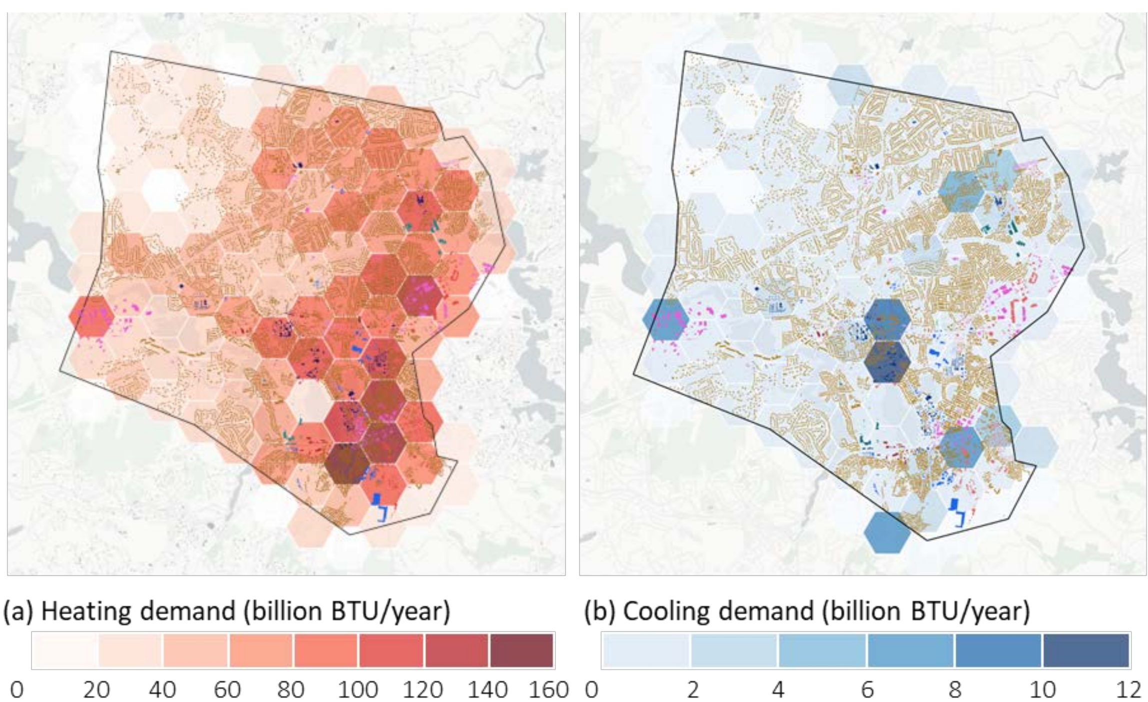


Figure 8. (a) Annual heating and (b) cooling demand for hexagons in Framingham, Massachusetts. Building types are indicated by color (see legend in Figure 6).

The total thermal energy demand represents the combined heating and cooling requirements. Figure 9. This map highlights energy corridors that align closely with the urban structure (i.e. the spatial distribution of buildings, infrastructure, and land use patterns) of the study region.

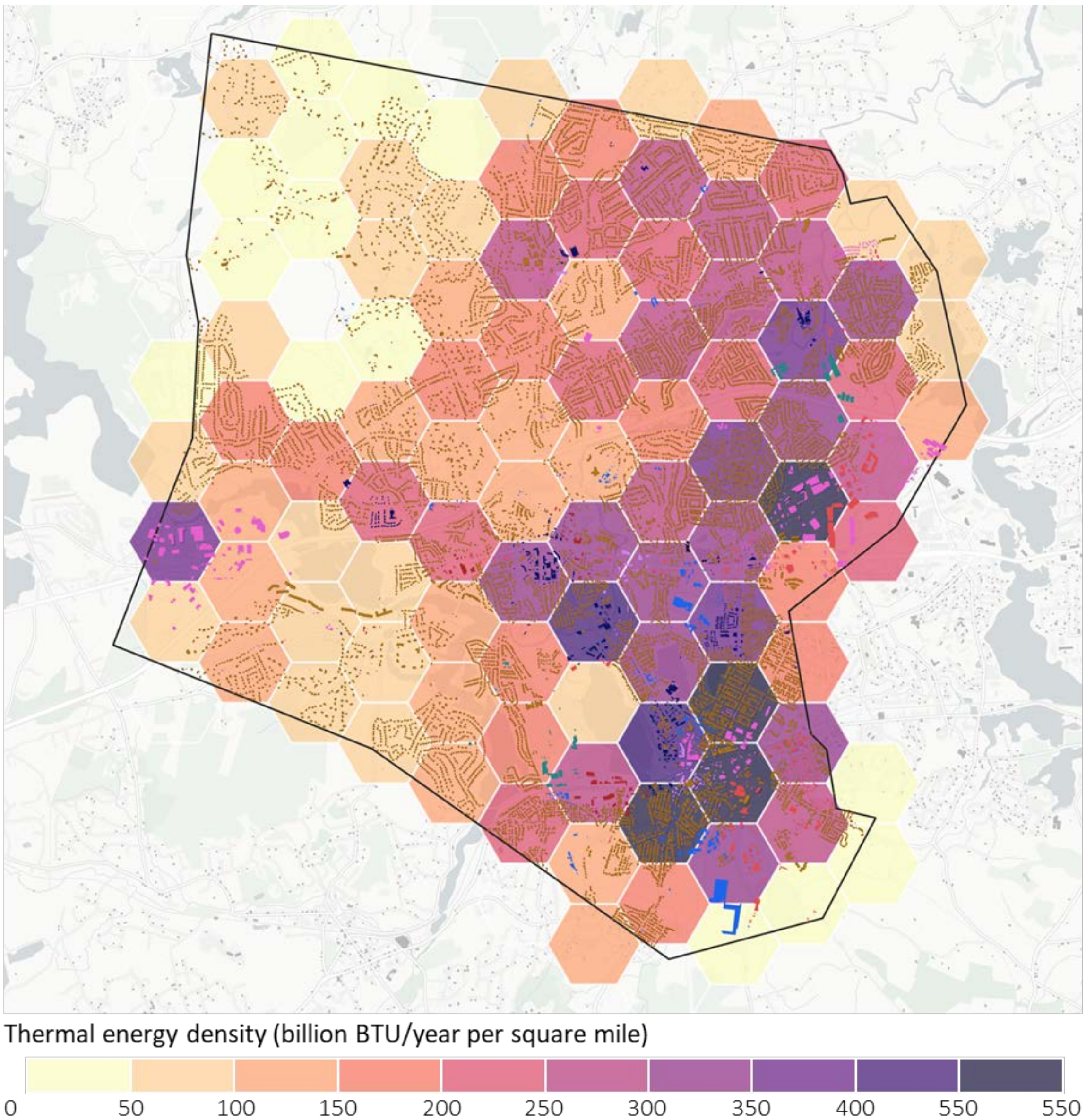


Figure 9. Thermal energy density map for Framingham, Massachusetts. Building types are indicated by color (see legend in Figure 6).

Identification and Characterization of Thermal Sinks

Thermal energy sinks are identified by clustering contiguous areas with an annual thermal energy density exceeding 400 billion BTU per square mile. Additionally, lower-density hexagons near the threshold (300–400 billion BTU per square mile) are included if they serve to connect high-density zones. Clusters with a total annual thermal demand of less than 800 billion BTU are excluded. As a result, the analysis identifies a single thermal energy sink for the study area, as highlighted in the map shown in Figure 10, with an aggregate annual thermal demand of 1,985 billion BTU.

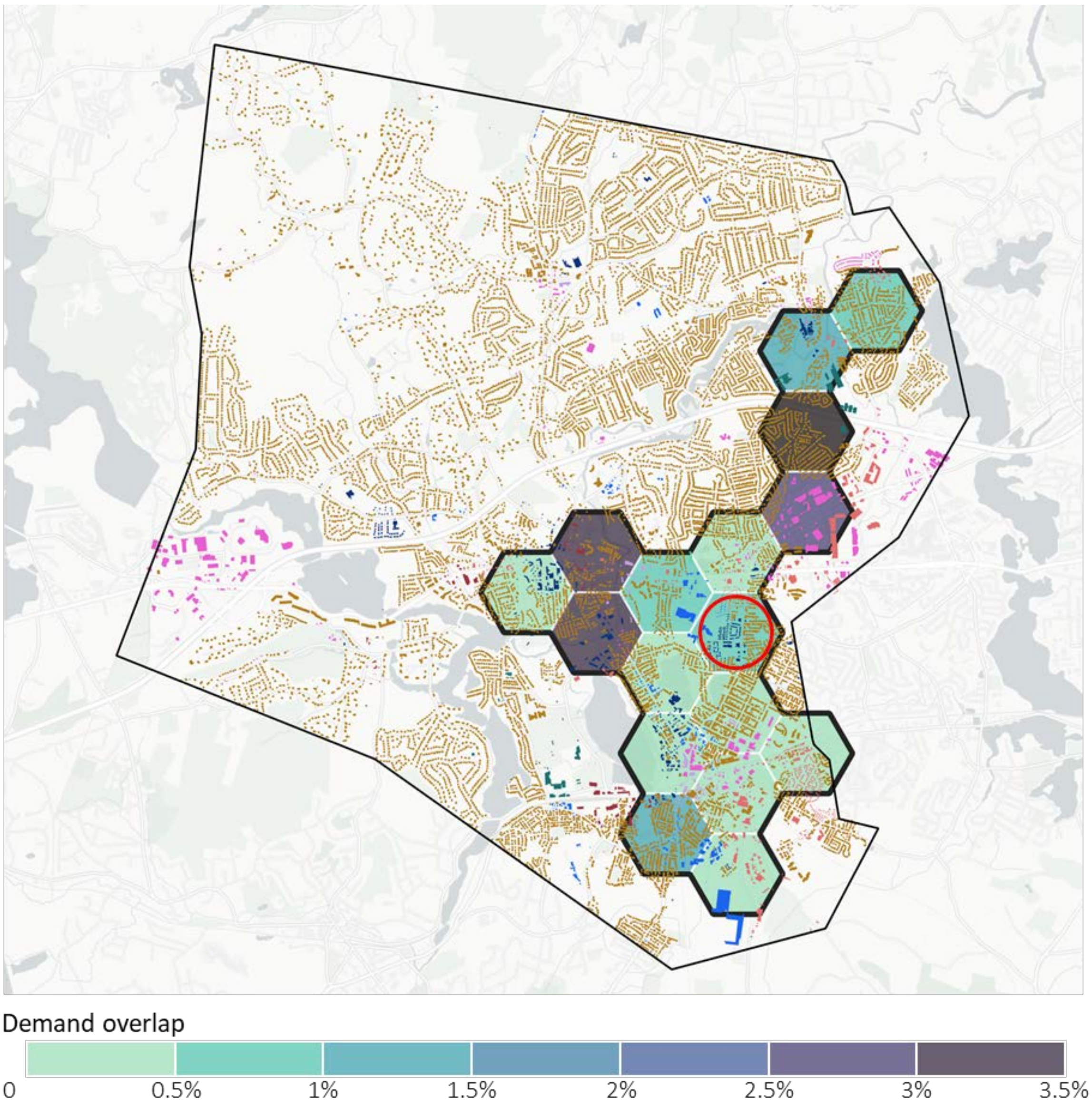


Figure 10. Demand overlap coefficient for identified thermal energy sink in Framingham, Massachusetts. The red circle highlights the area where four potential sites for the development of a TEN pilot project were identified (NSTAR Gas Company, d/b/a Eversource Energy and CDM SMith, 2022). Building types are indicated by color (see legend in Figure 6).

The DOC and LBI metrics were calculated for the identified thermal sink and its constituent hexagons. The DOC, which measures the proportion of thermal loads that are balanced, is shown in Figure 10. Values range between 0.3% and 3.4%, with an average of 1.5% for the entire sink. This low average indicates a significantly unbalanced system dominated by heating loads, as also reflected in the LBI value of 0.98.

Considering only space heating demands, as done in this study, this sink would require an external heat source to meet most of the heating and cooling loads, as only a small fraction of the loads can balance each other. However, this picture could change if other heating and cooling demands in buildings, such as domestic hot water and commercial cooling (e.g., data centers, ice rinks, supermarkets), were included in the analysis. Incorporating these additional loads could result in a more balanced thermal profile.

In the U.S., TENs typically aim for balanced systems, as this approach minimizes the need for external sources to supplement thermal loads. Despite its thermal imbalance, the identified thermal sink remains a promising candidate for a community-level networked energy solution, if local heat sources are available to fully or partially meet the sink's demand (e.g., geothermal energy, waste heat). Developing the entire sink is not necessary; feasibility depends on the scale and compatibility of local thermal sources and location-specific factors, which require detailed technical and economic assessments beyond this study's scope.

To validate the methodology, the identified thermal sink was compared to actual potential sites. The proposed framework successfully highlighted a sink that includes the areas selected by New England utility Eversource for a TEN pilot project (NSTAR Gas Company, d/b/a Eversource Energy and CDM SMith, 2022). While the selection criteria for the pilot project site are far more detailed, leveraging additional data and conducting in-depth analyses for construction planning, the framework in this study effectively identified a compatible thermal sink. The four potential areas in Framingham chosen for the pilot project are within the red circle in Figure 10. These areas are relatively small, reflecting the project's goal to demonstrate the technology's feasibility. The larger sink identified by this study highlights significant potential for future expansion if the pilot project proves successful.

6 GUIDELINES FOR ASSESSING THE ENERGY SYSTEM VALUE OF THERMAL ENERGY NETWORKS

Establishing a methodology for identifying and characterizing thermal energy sinks is a foundational step toward evaluating the TEN's value proposition to decarbonize the U.S. buildings sector at scale. This section outlines a roadmap for advancing the assessment of TENs by addressing key aspects of their identification, evaluation, and integration into broader energy systems. The next steps include:

- **Scaling the identification and characterization of thermal sinks**
  Expand the methodology proposed in this study to cover larger regions and incorporate additional heating and cooling demands beyond space conditioning, such as hot water and commercial or industrial applications.
- **Identification and characterization of thermal energy sources**
  Map and assess thermal energy sources, such as geothermal resources, waste heat (e.g. from power generation, industrial processes, data centers), water bodies, sewage systems, among other sources. This step involves assessing their technical potential, compatibility with TENs, cascading uses, and aggregation of smaller sources to support larger networks.
- **Spatial matching of thermal sinks and sources**
  Optimize TEN designs by spatially matching thermal sinks and sources, prioritizing proximity and connectivity to reduce thermal losses and costs. This step requires analyzing infrastructure needs, identifying feasible corridors for pipelines, and considering land-use and geographic constraints.
- **Technical and economic evaluation of potential TEN sites**
  Conduct detailed site-specific evaluations, refining load calculations to account for current and projected thermal demands, including potential changes driven by population growth and climate change. Estimate total project costs, encompassing infrastructure development, equipment installation, and building upgrades. Additionally, consider critical factors such as permitting requirements, stakeholder engagement, and other operational challenges.
- **Integration of TENs into energy system models**
  Incorporate TENs into broader energy system models to evaluate their competitiveness as a decarbonization strategy for buildings under different TEN deployment scenarios and net-zero pathways. Evaluate cross-sectoral impacts, such as effects on peak electricity demand, gas infrastructure utilization, carbon emissions reductions, and the affordability of energy services.

7 CONCLUSIONS

Thermal energy networks (TEN) offer a potential neighborhood-scale decarbonization strategy, using shared infrastructure to efficiently transfer thermal energy among interconnected buildings and shifting the focus from individual building-level solutions. While pilot projects have demonstrated localized benefits, the broader impacts and value proposition of scaling TEN in the U.S. remain underexplored. Assessing their full potential requires a systematic approach to identifying feasible deployment sites, assessing their technical and economic potential, and their integration into long-term energy system models.

This work lays the foundation for scaling TENs by establishing criteria for assessing feasibility and developing a GIS-based methodology to map thermal energy sinks. Applied to a case study in Framingham, Massachusetts, the methodology uses publicly available geodata and introduces scalable tools to characterize building stock, calculate heating and cooling demands, and identify high-density thermal load centers. Building-level thermal load profiles, calculated with a 1R1C model, are aggregated into a thermal energy demand density map to identify thermal sinks.

The analysis identified a single sink with an annual thermal demand of 1,985 billion BTU, aligning closely with sites selected for a potential TEN pilot project and validating the methodology. The Demand Overlap Coefficient (DOC) and Load Balance Index (LBI) metrics highlight the sink's heating-dominated profile, with low internal balancing potential of space heating and cooling loads. Incorporating additional loads, such as domestic hot water and commercial cooling, could result in a more balanced thermal profile.

Finally, guidelines to expand the current methodology and advance the assessment of the system-wide value of large-scale TEN deployment. These include scaling the location of thermal sinks, the mapping and characterization of thermal energy sources, the identification of potential TEN sites by the spatial matching of thermal sinks and sources as well as their detailed technical and economic evaluation, and the integration of TENs into energy system models to evaluate their competitiveness as a decarbonization strategy for buildings under different scenarios. This comprehensive approach enables the analysis of TEN impacts on cross-sectoral impacts, such as effects on peak electricity demand, gas infrastructure utilization, carbon emissions reductions, and the affordability of energy services.

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