Thermal Energy Networks: The Future of Decarbonization and Electrification

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Renewable Thermal Energy Solutions with Ambient Temperature Loops

Thermal Energy Networks (TENs) are revolutionizing energy sharing in cities, helping communities reduce energy costs and greenhouse gas emissions. By leveraging thermal diversity and heat pump technologies, TENs optimize the balance of heating and cooling needs across urban and industrial settings. This system design minimizes infrastructure costs and enhances sustainability by recycling and redistributing thermal energy efficiently. Furthermore, integrating TENs into existing infrastructure transforms energy consumers into active stakeholders in the energy ecosystem, fostering collaboration between utilities and end-users to achieve long-term climate goals.

INTRODUCTION

TENs are the newest generation of district heating and cooling designs, offering efficient and sustainable solutions for urban and industrial areas. By harnessing renewable energy sources like geothermal energy, wastewater heat recovery, and industrial waste heat, TENs create a seamless system where buildings can share and balance thermal loads. This innovative integration of energy sources and sinks is what defines a TEN, paving the way for smarter and greener energy management.

Traditional district energy systems typically rely on 2-pipe or 4-pipe configurations to distribute chilled water, hot water, or steam. In contrast, TENs utilize one-pipe ambient temperature loops (ATL) that use a heat transfer medium ranging ideally between 50°F and 85°F (10°C and 29.44°C). This medium provides a flexible and efficient energy source for various heat pump applications, such as water-to-water, water-to-air, and heat pump chillers.

Unlike air-source heat pumps and air-cooled air-conditioning equipment that struggle to remain efficient in extreme outdoor temperatures or inefficient burning fossil fuel equipment, TENs provide a stable and renewable energy solution. At the core of TENs is the water source heat pump (WSHP), which harnesses the stable, year-round temperatures of the ATL to deliver exceptional energy efficiency and versatility. With a coefficient of performance (COP) rating of 3 - 5 or higher provided by WSHP. ATLs eliminate the need for supplementary electric resistive heating used by air source heat pumps, as the heat exchange efficiency and performance of a WSHP is not affected by low ambient outdoor air temperatures of winter or the extreme highs of summer.

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Core Concepts of Thermal Energy Network

In understanding the theory of TENs, it is essential to first grasp terms associated with these designs. The term *Thermal Energy Network* is used to describe a group of stakeholders and renewable energy resources interconnected by a system of pipes designed to distribute and exchange renewable thermal energy among multiple buildings or districts. These networks rely on a combination of geothermal energy, waste heat recovery, and heat pumps to optimize energy efficiency and decarbonize. TENs are a scalable, sustainable solution for modern energy management. The successful adoption and integration of TENs depends on three stakeholders: consumers, prosumers, and generators.

Consumers are stakeholders connected to the ATL who strictly consume thermal energy, such as residential buildings. *Prosumers* both consume and generate energy, like offices that produce heat and use it for their own needs. *Generators* include industrial sites and natural sources like geothermal wells. which supplies energy to the network for broader distribution.

The process begins by bringing thermal energy utilities directly to the doorsteps of the stakeholders. However, access alone is not enough. To fully utilize TENs, buildings and residences must undergo infrastructure upgrades to manage, store, and redistribute energy, turning them into active stakeholders within the broader energy ecosystem. These upgrades include installing BTU (kW) meters, energy storage systems, and upgrading HVAC equipment. Key to the decarbonization strategy is the replacement of fossil fuel burning equipment, air source heat pumps, and air-cooled air-conditioning equipment with WSHPs. By undergoing this transformation, the energy industry paves the way for a more dynamic and collaborative relationship between energy utilities and stakeholders.

It is the gas utilities companies that possess the infrastructure and business models essential for facilitating and managing the transition to TENs and some are already leading the charge. As the shift towards electrification and decarbonization gains more momentum, fossil fuel utilities are adapting and diversifying to remain competitive in the energy market. Several regulated utility companies in New England recognize this imperative to offer a product aligned with market demand for clean, renewable geothermal energy and are doing so.

Essentials for Successful TEN Operation

A TEN relies on two major components and the 1st & 2nd law of thermodynamics to achieve superior energy efficiency. The first component, a *heat source,* refers to where thermal energy is drawn from. The second component, a *heat sink,* is where excess heat is discharged and stored like a battery for use later. Common heat sources in a TEN include geothermal wells, which extract thermal energy from the Earth's subsurface, dewatering, solar thermal, wastewater energy transfer, and waste heat from industrial processes. For heat sinks, examples include underground aquifers, large bodies of water, or even the soil of the Earth itself, which can absorb and dissipate heat effectively.

Thermal load shedding and thermal load sharing are key engineering concepts in the operation and optimization of TENs due to the thermal diversity of the network. *Thermal load shedding* is the intentional reduction of heat rejection during cooling processes or the decrease in fossil fuel or electricity use for generating thermal energy in heating operations. In a TEN, this involves redistributing excess thermal energy, such as heat normally expelled by cooling towers or dry coolers at a data center, to other buildings within the network where it can be used for heating purposes. *Thermal load sharing,* on the other hand, enables multiple heat sources to collaborate in supplying thermal energy or utilizing sinks that store surplus energy generated earlier. This process transfers thermal energy from areas of excess to where it is needed within the network, optimizing energy use, minimizing waste, and improving overall efficiency. Together, these strategies contribute to the flexibility, resilience, and sustainability of TENs, ensuring efficient energy management across urban and industrial systems.

The data center in Figure 1, functions as a thermal energy source, shedding approximately 1,200,000 BTUs (351.2 kW) to the ATL. Under conventional systems, this thermal energy would typically be rejected into the atmosphere using cooling towers, contributing to overall electrical consumption of the TEN. Instead, this thermal load shedding offsets the energy demand of the data center and those connected to the ATL.

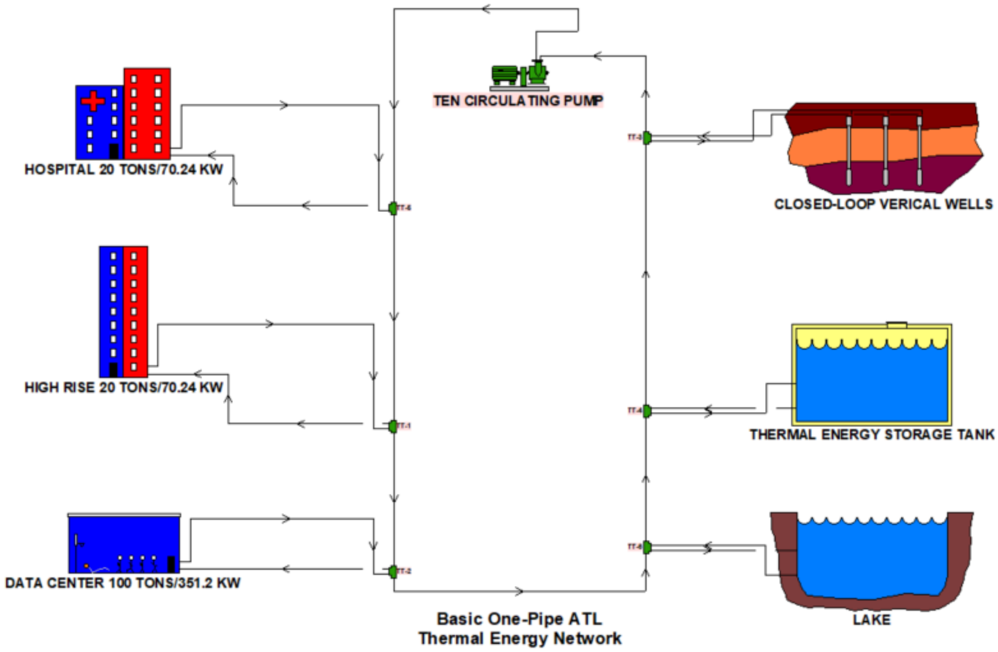

Figure 1 Basic One-Pipe Ambient Temperature Loop. DISCLAIMER: It should be noted that the loads specified are purely hypothetical and for simple explanation and demonstration purposes only. Actual real world values will vary.

During winter, those BTUs (kW) from the data center are distributed through the ATL to other buildings. For instance, 240,000 BTUs (70.24 kW) are utilized by the hospital to meet its heating requirements, while another 240,000 BTUs (70.24 kW) are consumed by the high-rise building. By leveraging the thermal energy supplied by the TEN, both the hospital and the high-rise reduce their dependency on fossil fuels or electricity for heating to nearly zero. This effectively eliminates the need for boilers, reduces electrical consumption, and sheds their respective thermal loads too.

The remaining 720,000 unused BTUs (210.72 kW) are stored in the Earth, a lake, or in a thermal storage tank. These heat sinks enhance the system's overall efficiency by redistributing thermal energy, which reduces fuel costs otherwise required to generate thermal energy. An ideal scenario would involve integrating an industrial consumer, such as a dairy plant, to utilize much of the 720,000 unused BTUs (210.72 kW) to preheat process water for pasteurization. This design maximizes energy efficiency and operating cost for everyone. Thermal energy storage solutions play a significant role in boosting system efficiency by storing surplus energy for future use.

ATLs inherently enable energy recovery and when paired with a geothermal source, it results in reducing the number of geothermal wells by capitalizing on offsets from recirculating recovered energy. Hypothetical, a campus requiring 4,000 tons (14,068 kW) for heating and cooling could meet its needs with just 2,000 tons (7,034 kW) of geothermal wells due to energy recovery and load diversity offsets. This reduces installation first costs and carbon emissions from construction equipment, manufacturing of materials, and supply chain. This approach minimizes the upfront costs for heating and cooling equipment too by reducing its total required capacity to meet demands and ensures a reliable energy supply that can adapt to fluctuations in loads.

Ambient Temperature Loops (ATL)

TEN and ATL are not interchangeable terms. While TEN is a broader concept that encompasses the entire system for distributing and exchanging thermal energy, ATL specifically refers to the physical infrastructure that connects all stakeholders in the network. The one-pipe ATL enables the sharing and transfer of thermal energy by circulating fluid at ambient temperatures. ATLs function differently from condenser water loops which are meant to reject heat. Instead, they redistribute heat between heating or cooling dominant buildings, throughout the year and utilize the earth as a battery for storage of thermal energy.

With ATLs, *diversity* is the variation in heating and cooling demands across interconnected TEN stakeholders, which is key to its performance and energy efficiency. The ATL enables TEN stakeholders to continuously redistribute thermal energy to each other while incorporating geothermal technologies as a renewable energy source. It is the thermal diversity of the ATL that makes this possible as it circulates a heat transfer medium ideally between 50°F to 85°F (10°C to 29.44°C) to the stakeholders. Adhering to the 1st law of thermodynamics, energy is never lost. It is constantly moving around the network and being reused.

For design engineers and operators, a primary concern with one-pipe ATLs is the temperature cascade effect. The cascade effect refers to the progressive temperature change of water as it circulates through a one-pipe loop. Cascading raises doubts about the ability of stakeholders at the end of the loop to meet their heating or cooling demands. Counterintuitively, having more stakeholders connected will improve temperature cascade at the last point due to increased system diversity, creating a smoothing effect on the overall ATL load requirements.

This means that while some stakeholders may require more cooling or heating, others may need less, thereby balancing the total demand. As a result, the system can distribute thermal energy more evenly, preventing any user from being overburdened or underutilized. This balance ensures that the heat transfer medium temperature remains consistent as it travels through the ATL, leading to an optimal temperature by the time it reaches the last stakeholder. Consequently, the stakeholders HVAC systems are more efficient as ATLs reduce energy waste.

Efficient Temperature Cascade

Efficient temperature cascade in an ATL ensures precise thermal energy management, leading to optimal performance across all TEN stakeholders. Good temperature cascade achieves consistent temperature drops or rises in a sequential manner, allowing each user to receive the appropriate thermal energy without excessive under or over delivery . In a well-designed one-pipe ATL with many stakeholders, the temperature of the water decreases or increases (climatic dependent) progressively as it moves from one building to another transferring thermal energy, ensuring that the last stakeholder still heats and cools sufficiently. (Taco Comfort Systems 2019)

In contrast, poor temperature cascade fails to maintain these sequential temperature changes. This can occur due to improper pipe sizing, inadequate thermal insulation of pipes and equipment, insufficient thermal diversity or incorrect flow rates. This results in a temperature at the final user that may drop or rise significantly, making it difficult to maintain desired temperatures of a stakeholder's house loop. Such inefficiencies compromise thermal performance and leads to increased energy consumption as the system compensates for the temperature disparities. Ensuring a balanced and well-maintained temperature cascade is crucial for the reliability and efficiency of an ATL.

One-pipe systems

The streamlined design of one-pipe ATL systems delivers significant advantages. The label "one-pipe system" specifically describes the ATLs physical layout. This design uses a single pipe to circulate a heat transfer medium, such as water or a water/propylene glycol mixture, maintaining a uniform pipe size throughout the loop. For installers, this translates into reduced complexity, as only one consistent pipe size is needed—eliminating the need for fittings like reducers. One-pipe systems are inherently self-balancing (Cunniff, G., Zerba, B 2006), which simplifies expansion when integrating new buildings into the network. Unlike two-pipe systems, there is no need to rebalance the entire network, saving time and further reducing costs. The lack of balance valves simplifies installation and minimizes start-up requirements, making the one-pipe ATL system an efficient and cost-effective solution across multiple sectors.

Optimizing Pump Performance: The True Advantage of One-Pipe ATLs

The system is pump controlled instead of valve controlled, allowing the elimination of control valves, which reduces costs and simplifies installation. One-pipe ATL designs operate as a series circuit with a compound pumping arrangement (ASHRAE 2020). Unlike two-pipe systems, which regulate comfort indirectly by controlling the flow rate (GPM or L/s) of a medium of a constant temperature, one-pipe systems focus on directly managing BTU (kW) delivery (Taco Comfort Systems 2008) by modulating the flow of a medium with a variable temperature. The ATL primary circuit incorporates multiple secondary loops, which are decoupled to allow independent operation in each secondary circuit. Circulators in these secondary circuits are accurately sized for their specific flow and head requirements (Taco Comfort Systems 2008), ensuring they maintain the precise conditions needed to meet building demands without the need for balancing or control valves. This design approach also prevents flow from being redirected between buildings, improving reliability and performance.

Pump affinity laws validate the efficiency of one-pipe ATL systems by demonstrating how precise adjustments to pump parameters such as flow rate, head, and power consumption can significantly enhance performance. The streamlined design, centered on a single, constant pipe size, minimizes complexity and reduces required piping by nearly half compared to traditional two-pipe systems that rely on separate supply and return lines. By eliminating both balance and control valves further reduces pump horsepower by eliminating the pressure drop associated with these components. Because pump power consumption decreases with the cube of its speed, operating at lower speeds not only achieves substantial energy savings but also extends the pump's lifespan and reduces maintenance costs.

The ATL design aligns directly with the 50/90 guideline in HVAC design, which emphasizes efficiency and reliability under varying load conditions. By designing pumps to operate at 50% of their workload under normal conditions, one-pipe ATL systems minimize energy waste while maximizing performance. During peak load situations, these systems seamlessly scale up to 90% of their capacity, leveraging pump affinity laws to maintain reliability without over-sizing equipment. Using variable speed drives to control pumps provide precise flow modulation, ensuring peak thermal energy delivery.

Key Principles of System Management

In both heating and cooling modes, the mixed water temperature is crucial for calculating ΔT, flow rates, and pipe sizing. The primary loop operates on variable primary flow, determined by the ΔT across heat exchange points, such as an intermediary heat exchanger (HX) that hydraulically separates the ATL from the geothermal heat source (Figure 2).

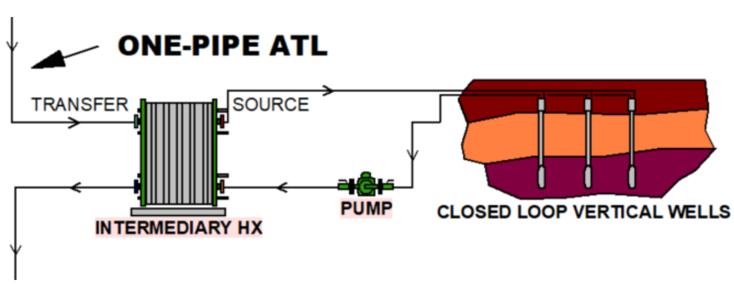

Figure 2 Hydraulically separated ATL from the geothermal HX. In this example there is one geothermal HX connected to the ATL where other scenarios may have multiple. The ATL is piped directly through the HX as opposed to "teeing" into the ATL if multiple HXs were utilized.

Managing the temperature cascade in one-pipe ATLs is the primary challenge. As the heat transfer medium circulates through the loop, its temperature shifts, raising concerns about the ability of end-loop stakeholders to fulfill heating or cooling requirements effectively.

The steady state heat transfer formula helps optimize system performance by calculating how much thermal energy is transferred at any given point. It is useful for ensuring that heat transfer is adequate across all HXs, especially at end-loop stakeholders where there are greater ΔTs. By adjusting variables like surface area or improving insulation to control the heat transfer coefficient, engineers can enhance efficiency and maintain consistent thermal performance throughout the entire TEN.

To maintain consistent heat transfer of the intermediary HX at each building despite the varying ΔTs between the ATL and building house loop, adjustments are necessary. Specifically, the heat transfer coefficient, the heat transfer area, or a combination of both must be increased for smaller ΔTs. The heat transfer coefficient of the intermediary HX depends on fluid velocity. The heat transfer area, on the other hand, is determined by factors such as the number of rows in the HX.

The solution to this challenge involves increasing the flow rate through the HX, adding more rows to expand the heat transfer area, or employing a combination of both strategies. These adjustments ensure the HX continues to operate effectively despite varying ΔTs. Another concern is that many stakeholders connected to an ATL might adversely affect the temperature cascade. (Taco Comfort Systems 2005)

Thermal Management Demonstrated

Figure 3 (a) SI units, (b) I-P units, illustrates a hypothetical one-pipe ATL that optimizes temperature cascade, thermal diversity, and energy distribution in a dynamic environment. The thermal energy content (Btu/kW) of the ATL and designed ΔT of the heat exchanger (HX-1) govern the flow of the heat transfer medium, ensuring load demands are met effectively. Even the user furthest along the loop can reliably operate heating and cooling systems when these parameters are maintained. This system includes three distinct types of thermal energy needs; a cooling-dominant data center, a mixed-load apartment building, and a heating-dominant industrial plant. While the themal loads are purely hypothetical and simple for demonstration only, a commercially available software was utilized to model actual anticipated pipe size, flows and temperatures of the demonstration design. The ATL is sized at 3 inches (DN 80) across its entire length. Each building utilizes an intermediary HX (not shown for clarity) between its house loop and the ATL.

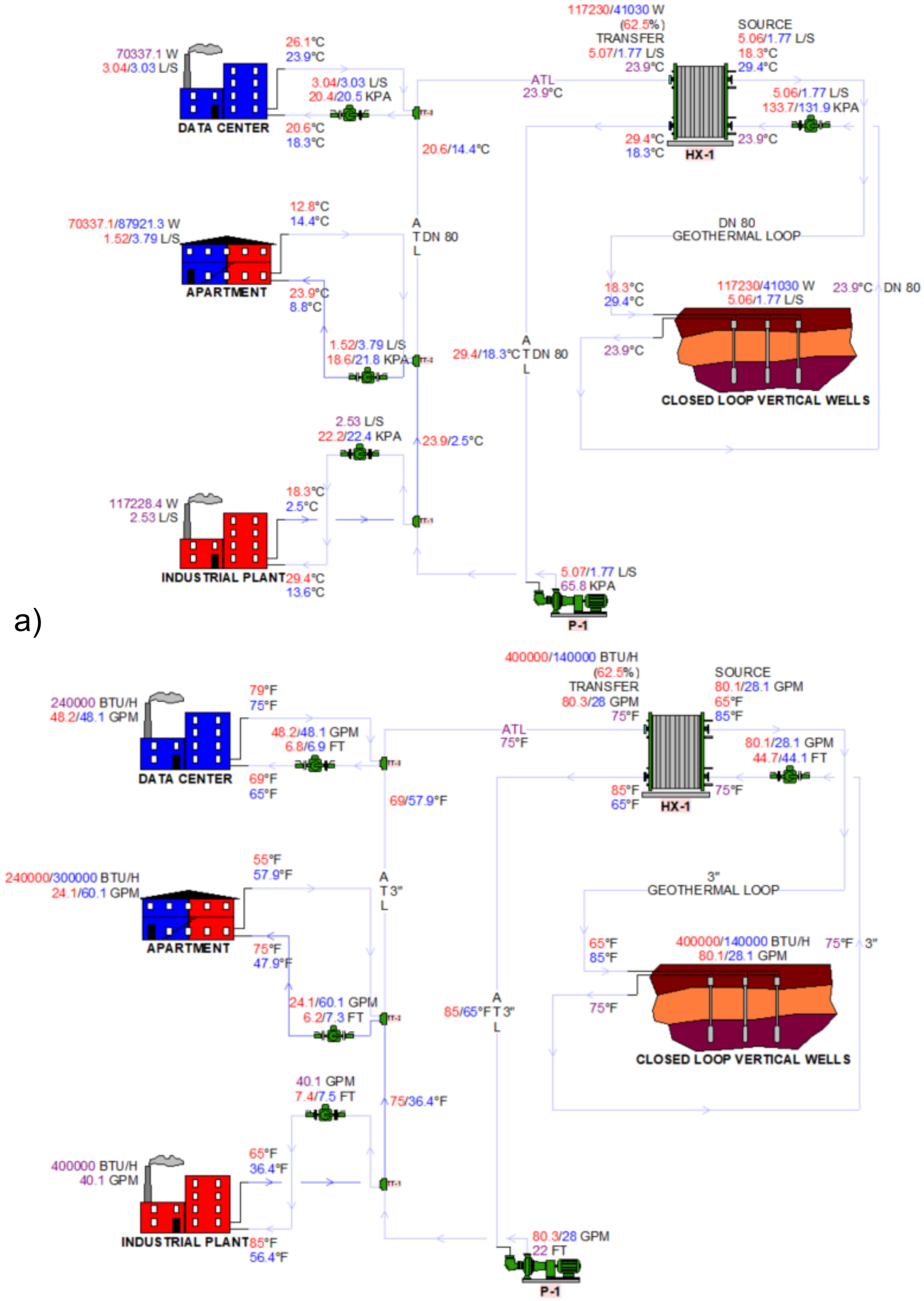

Figure 3 (a) SI units, (b) I-P units. The figure illustrates the cascade effect, diversity, and thermal distribution across a one-pipe ATL. Highlighted values in red pertain to heating loads, with red-labeled buildings being heating-dominant. Conversely, blue values represent cooling loads, and blue-labeled buildings are cooling-dominant.

This TEN consists of a geothermal source/sink, a main loop intermediary heat exchanger, a main loop distribution pump, and the three stakeholders. During the summer, the network manages a total heat rejection of 540,000 BTU/h from the apartment building and the data center. However, only 140,000 BTU/h is transferred to the geothermal sink via the heat exchanger (HX-1). This reduction occurs because the network redirects excess heat to the industrial plant, utilizing it for productive purposes rather than rejecting it to the ground. In winter, the network requires a total of 640,000 BTU/h to meet the heating demands of the apartment building and the industrial plant. Of this, 400,000

BTU/h is supplied by the geothermal source through HX-1, while the remaining 240,000 BTU/h is provided by the data center, offsetting the geothermal demand.

Temperature annotations along the ATL highlight the cascade effect, demonstrating how thermal diversity smooths temperature and load requirements. Seasonal and climatic variations dictate whether the ATL operates in cooling or heating dominant modes. Each stakeholder manages its own decoupled secondary loop using a circulator pump, dynamically controlling flow to sustain the desired ΔT of their house loop at the intermediary HX. Meanwhile, the ATL circulator pump (P-1) adjusts flow based on real-time demands across the loop, promoting efficient energy use.

ATLs are easily scalable, enabling seamless future expansions without requiring substantial redesigns. Limits on the number of TEN stakeholders connected, are dictated by the total designed loop load and ΔT which also determines loop pipe sizing. When a new user connects to an existing ATL system, the additional diversity that stakeholder provides improves cascade effects, ensuring minimal impact on other stakeholders. For systems with high thermal loads, splitting the loop into smaller, more manageable circuits with appropriately sized pipes is a practical and efficient solution. (Cunniff, G., Zerba, B 2006)

Legislation, Feasibility, Implementation

Recent years have seen remarkable progress in overcoming political barriers to the adoption and legislation of TENs. By 2022, U.S. policymakers increasingly acknowledged the substantial economic and environmental benefits of these systems, prompting the creation of supportive legislative frameworks to expedite their implementation and drive decarbonization. Currently, TENs are active in 13 states, with 8 states—including Massachusetts, New York, Colorado, Washington, Maryland, Vermont, California, and Minnesota enacting legislation since 2021 that mandates or permits regulated utilities to develop these networks. Pennsylvania, New Jersey, and New Mexico have enacted measures to explore the potential of geothermal energy projects (Buildingdecarb.org 2024).

The Department of Energy (DOE) has also played a pivotal role, allocating $13 million in 2023 (U.S. Department of Energy 2023) to fund community based TEN projects across 11 communities in 10 states. Building on this momentum, in December 2024, the DOE's Geothermal Technologies Office (GTO) announced the selection of five projects for the second phase of its Community Geothermal Heating and Cooling Initiative. These projects will receive over $35 million collectively to install community-scale geothermal systems in Illinois, Michigan, Massachusetts, Vermont, and Oklahoma (U.S. Department of Energy 2024).

TENs are particularly cost-effective in scenarios requiring high thermal load density and high annual operating ratios. Dense thermal loads justify significant upfront investments, as infrastructure for energy transmission and distribution often accounts for over half of initial costs. High utilization rates further enhance the return on investment, making TENs ideal for industrial complexes, urban centers, and large mixed-use developments like university campuses, airports, and office districts.

One prime example of this innovation is Eversource Energy's TEN project in Framingham, Massachusetts. Launched in July 2024, it became the nation's first utility-operated ATL TEN, delivering sustainable heating and cooling to approximately 135 residential and commercial customers. The purpose of the system is to eliminate fossil fuel dependency by its stakeholders. By November 2024, the project served 16 residential properties, two commercial buildings, and 108 units managed by the Framingham Housing Authority (Eversource Energy 2024). At the time of the publishing of this paper, performance metrics have not been published by Eversource Energy.

Similarly, National Grid is leading its second TEN project in Dorchester, Massachusetts. Breaking ground in early 2024, this initiative replaces outdated gas boiler systems with geothermal heating and cooling while transitioning gas-powered appliances to electric alternatives. It serves 129 units across seven public housing buildings and supports the Franklin Field community's fossil-free goals for 2030 (National Grid 2024). At the time of the publishing of this paper, performance metrics have not been published by National Grid.

These efforts represent just a fraction of the growing commitment within the U.S. and globally to advance TEN solutions for a sustainable future.

CONCLUSION

Thermal Energy Networks are a game-changer for sustainable energy and clearly still in their infancy and somewhat experimental but gaining in popularity. While real world metrics are yet to be realized and published, modeling shows a number of favorable benefits. By reusing and sharing renewable heat, these systems cut costs, reduce emissions, and pave the way for a cleaner energy future. This significantly reduces energy-intensive pumping systems and reduces HVAC equipment sizes due to the ability ATLs to offset system capacity through energy recovery. This not only cuts operating costs but also lowers first costs by minimizing the infrastructure required. The result is intelligent energy management that collectively decarbonizes, optimizes thermal performance, and supports long-term sustainability.

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NOMENCLATURE

ΔT = is the temperature difference driving the heat exchange process.

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